Communication Networks

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Material inspired from Scott Shenker & Jennifer Rexford

Last week on

Communication Networks

Communication Networks

Part 1: General overview

#1 What is a network made of?

#2 How is it shared?

#3 How is it organized?

#4 How does communication happen?

#5 How do we characterize it?

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Part 1: General overview

What is a network made of?

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How do we characterize it?

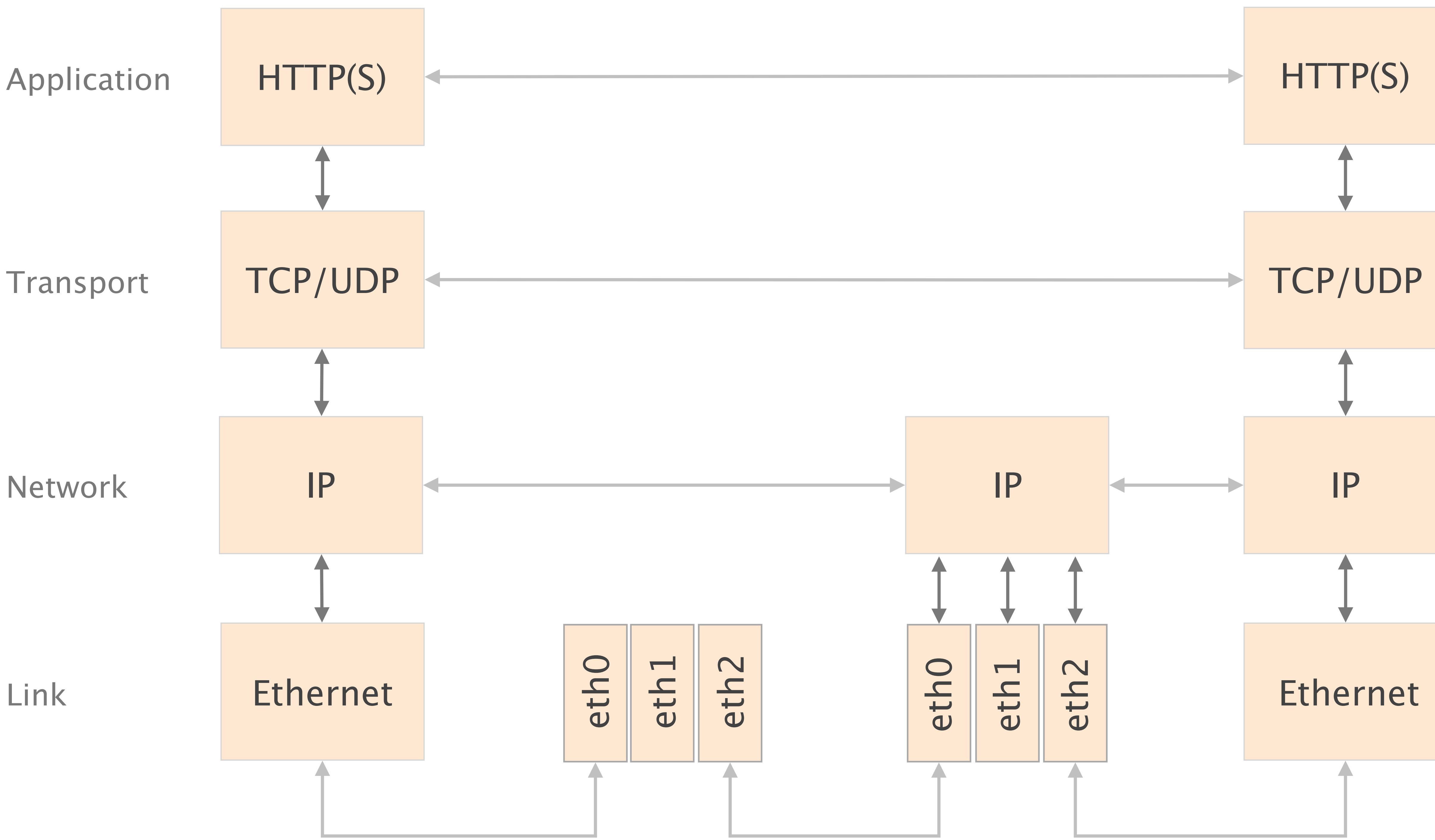
Internet communication can be decomposed in 5 independent layers (or 7 layers for the OSI model)

	layer
L5	Application
L4	Transport
L3	Network
L2	Link
L1	Physical

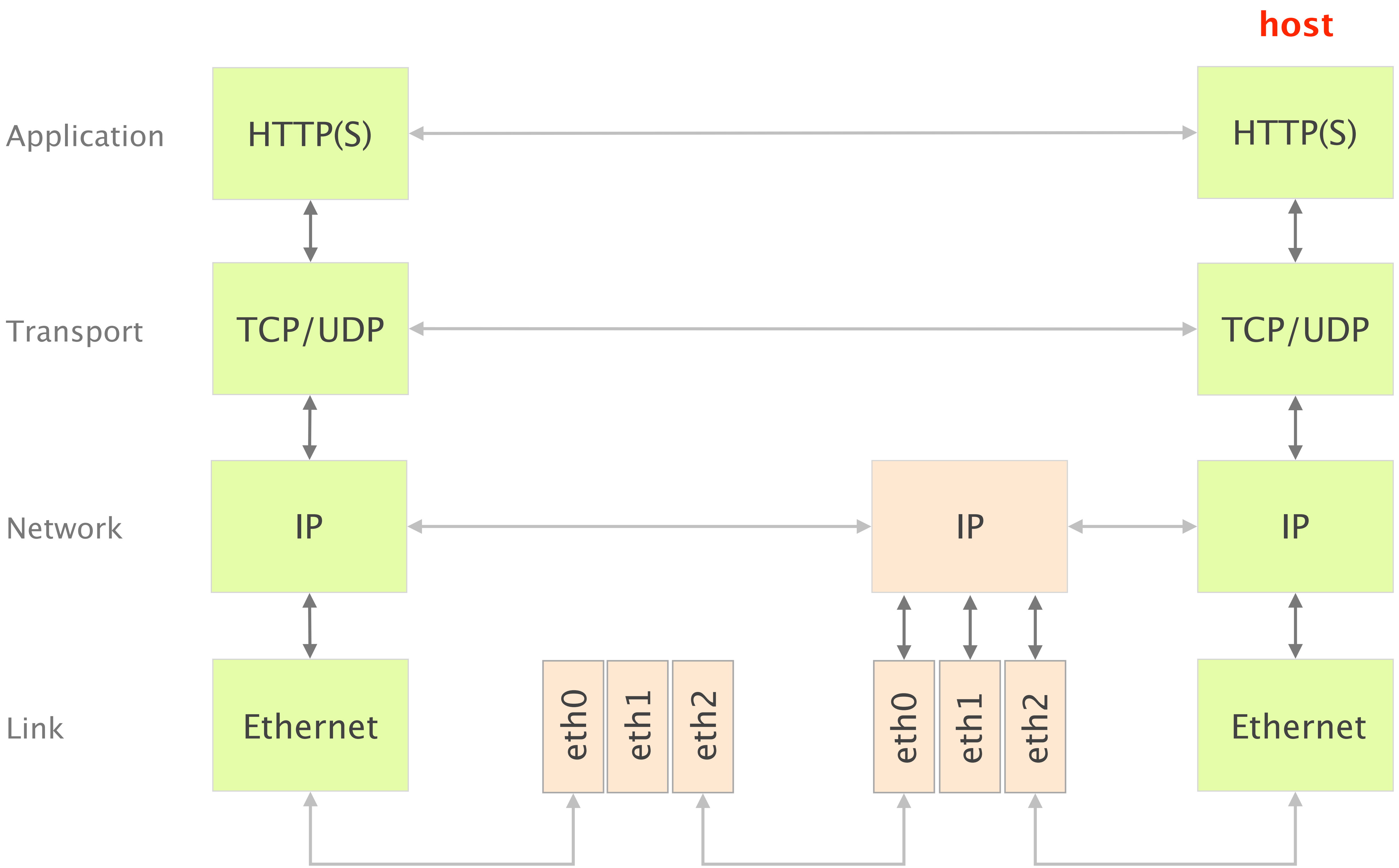
Each layer provides a service to the layer above

	layer	service provided:
L5	Application	network access
L4	Transport	end-to-end delivery (reliable or not)
L3	Network	global best-effort delivery
L2	Link	local best-effort delivery
L1	Physical	physical transfer of bits

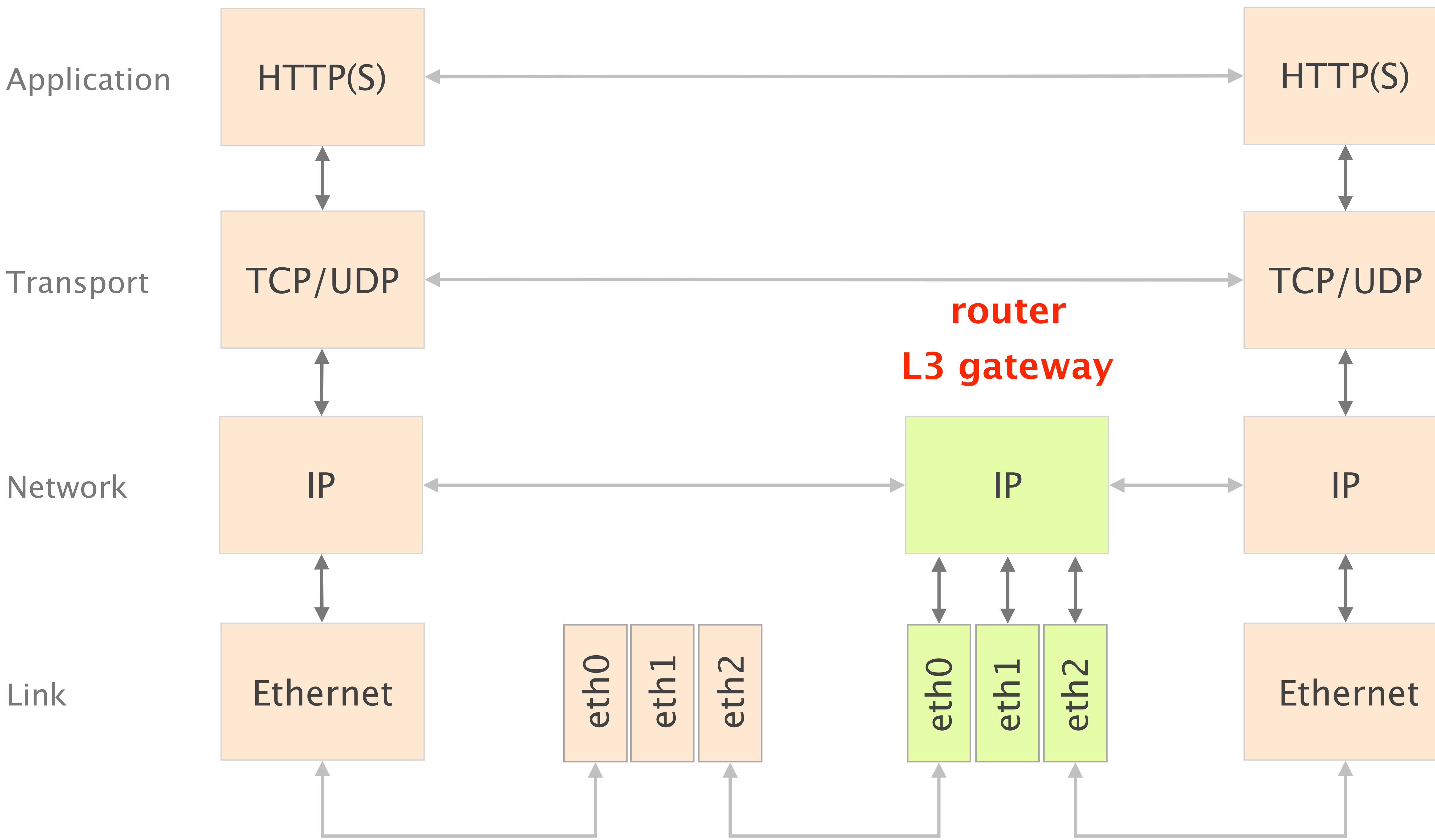
In practice, layers are distributed on every network device



Since when bits arrive they must make it to the application, all the layers exist on a host



Routers act as L3 gateway
as such they implement L2 and L3



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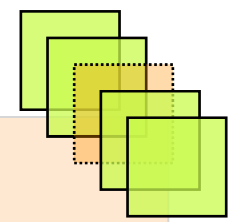
A network *connection* is characterized by its delay, loss rate and throughput

delay

loss



throughput

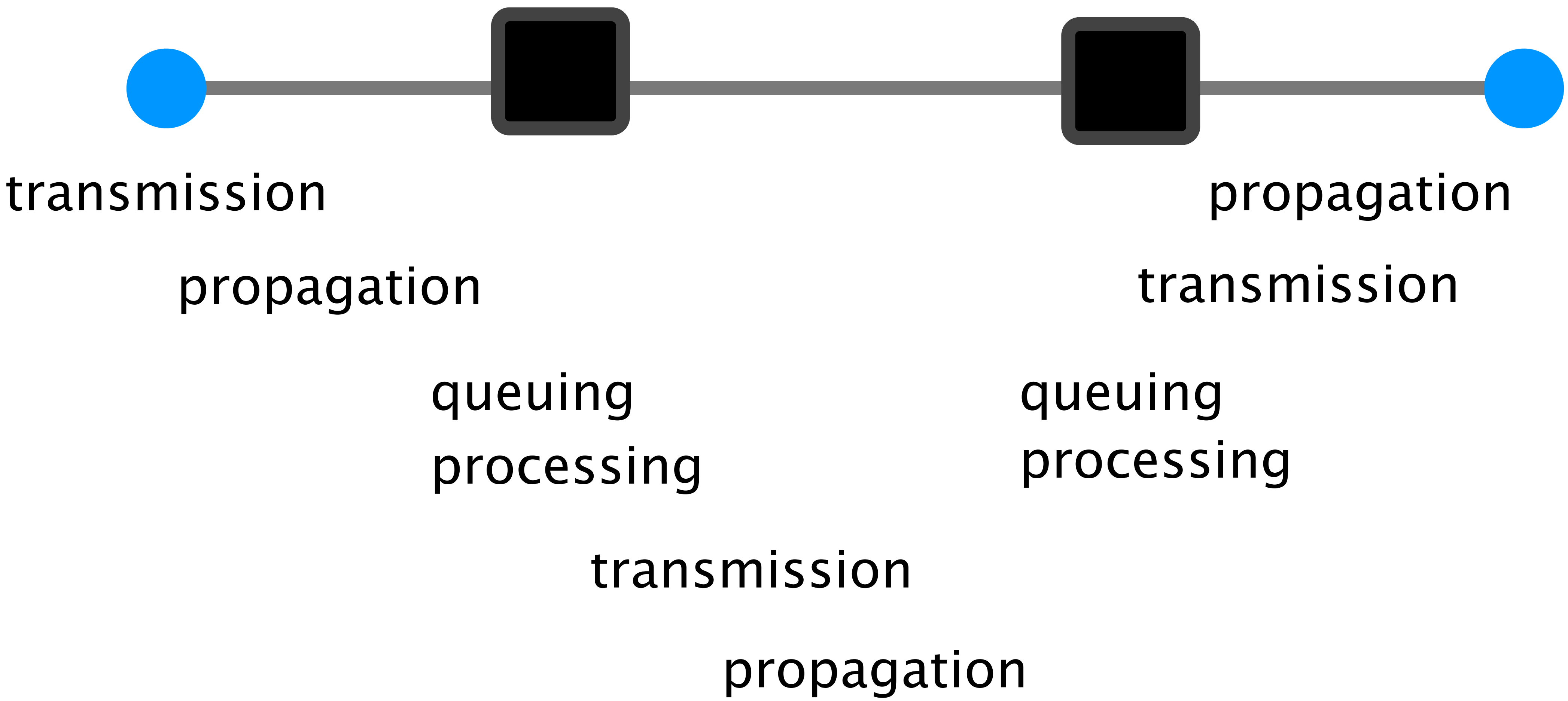
How long does it take for a packet to reach the destination

What fraction of packets sent to a destination are dropped?

At what rate is the destination receiving data from the source?

Each packet suffers from several types of delays at *each node* along the path

	transmission	delay	due to link properties
⊕	propagation	delay	
⊕	processing	delay	due to traffic mix & switch internals
⊕	queuing	delay	
=	total	delay	


transmission
propagation
queuing
processing
transmission
propagation
queuing
processing
propagation
transmission

The queuing delay is the amount of time a packet waits (in a buffer) to be transmitted on a link

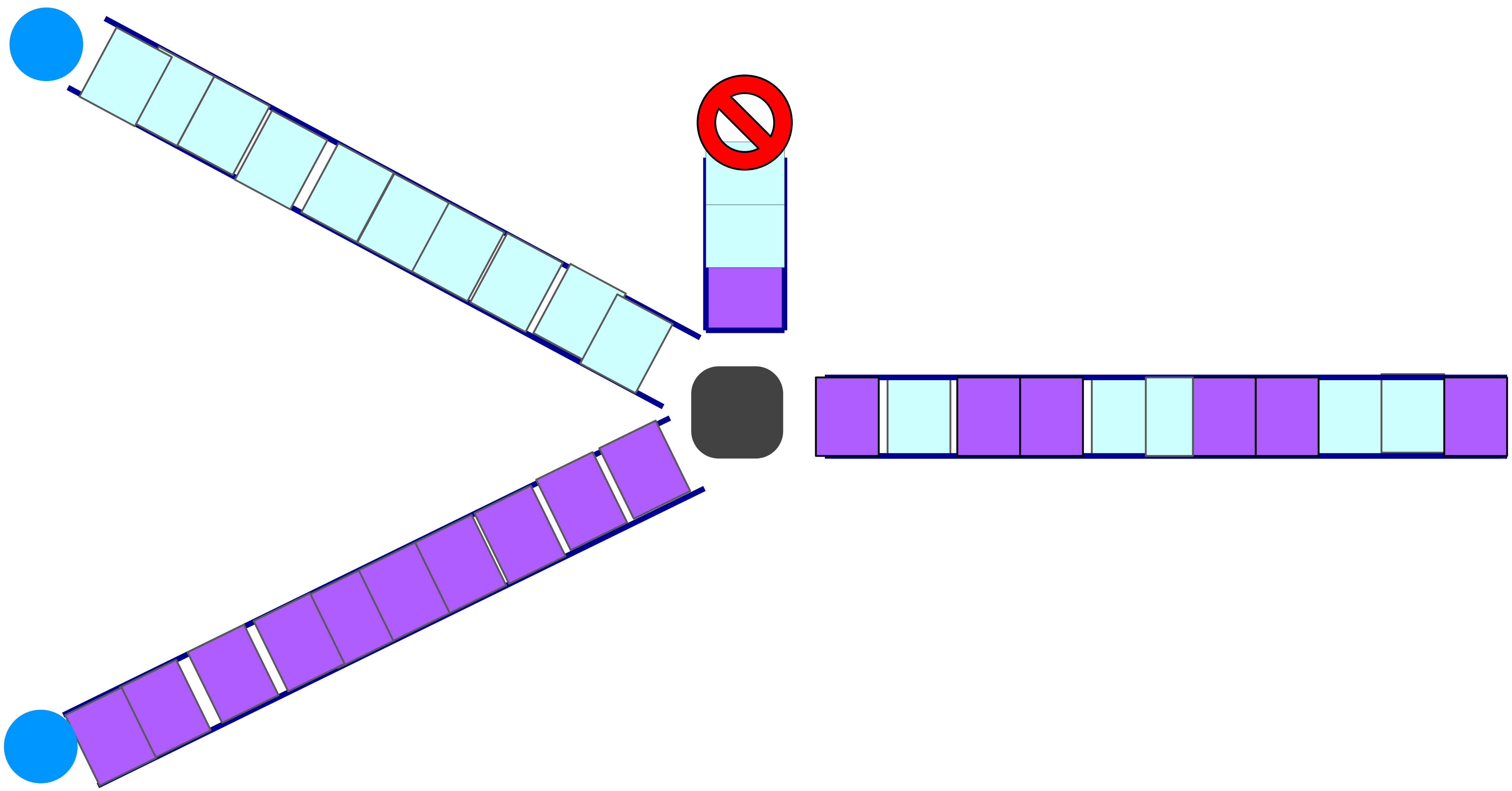
Queuing delay is the hardest to evaluate

as it varies from packet to packet

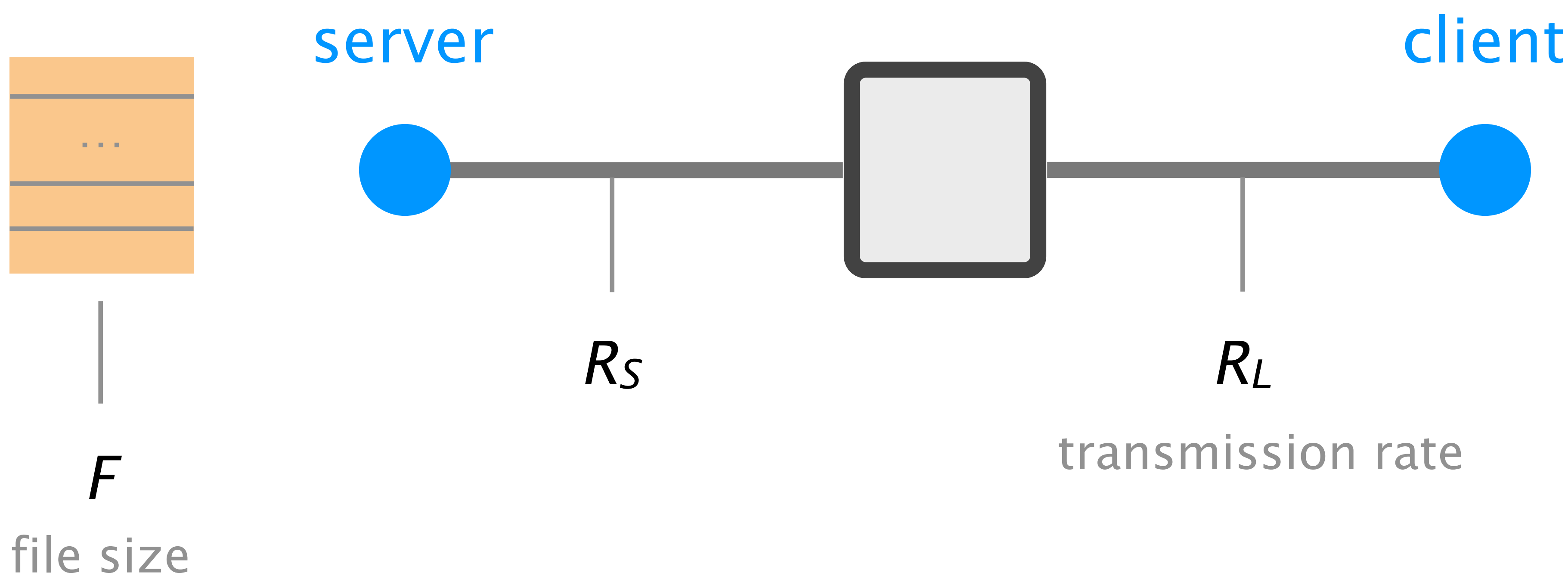
It is characterized with statistical measures

e.g., average delay & variance, probability of exceeding *x*

If the queue is persistently overloaded,
it will eventually drop packets (loss)



To compute throughput, one has to consider the bottleneck link



Average throughput $\min(R_S, R_L)$

= transmission rate of the bottleneck link

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This week on

Communication Networks

We will dive

into two fundamental networking challenges

routing

reliable
delivery

routing

reliable delivery

How do you guide IP packets from a source to destination?

How do you ensure reliable transport on top of best-effort delivery?

This week

routing

Next week

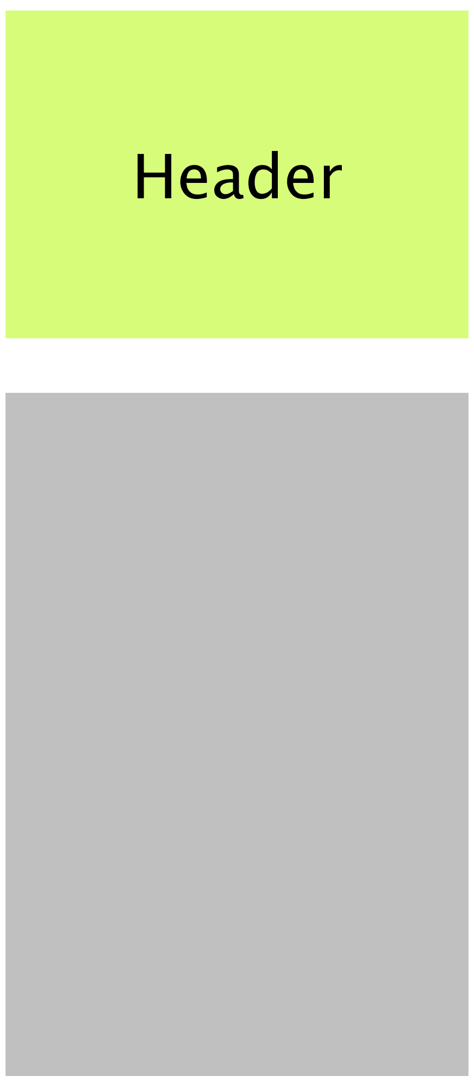
reliable delivery

How do you guide IP packets from a source to destination?

Think of IP packets as envelopes

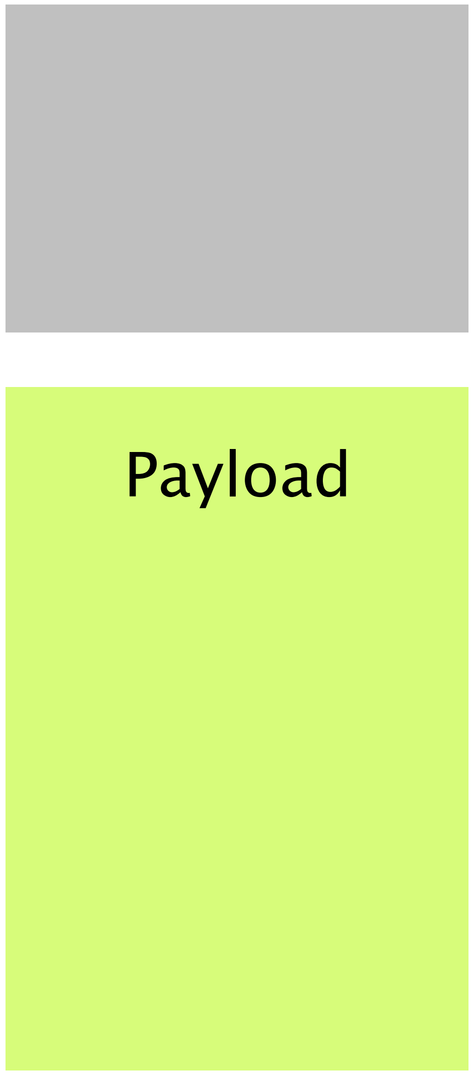
Like an envelope,

packets have a header

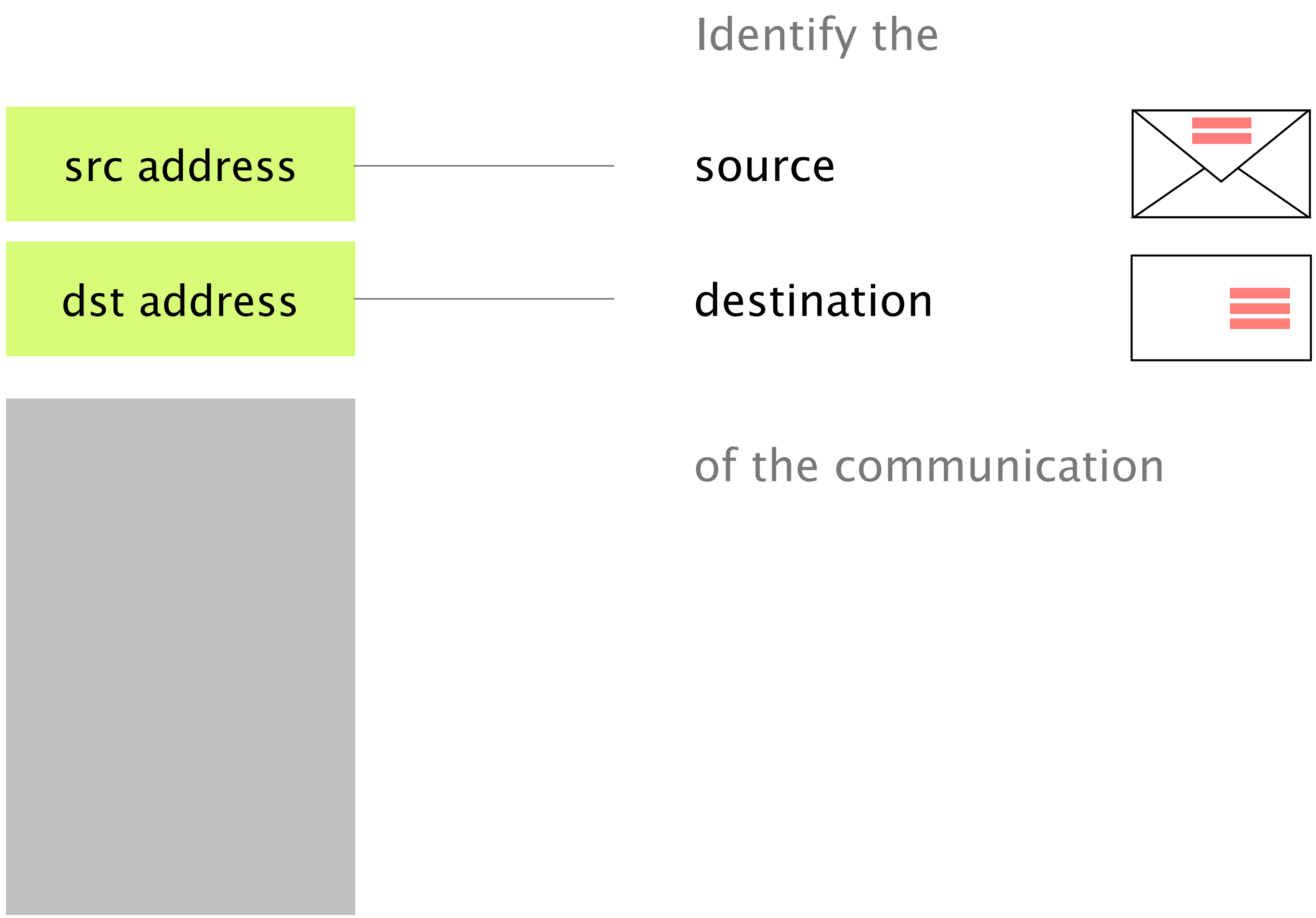


Like an envelope,

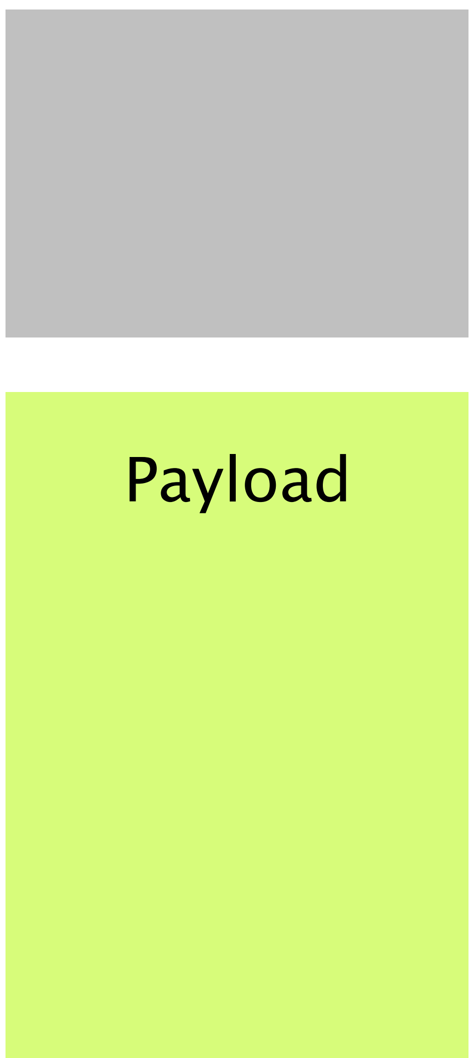
packets have a payload



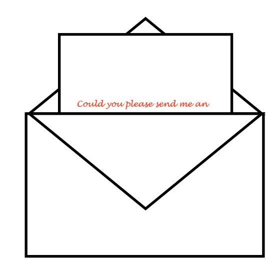
The **header** contains the **metadata** needed **to forward** the packet



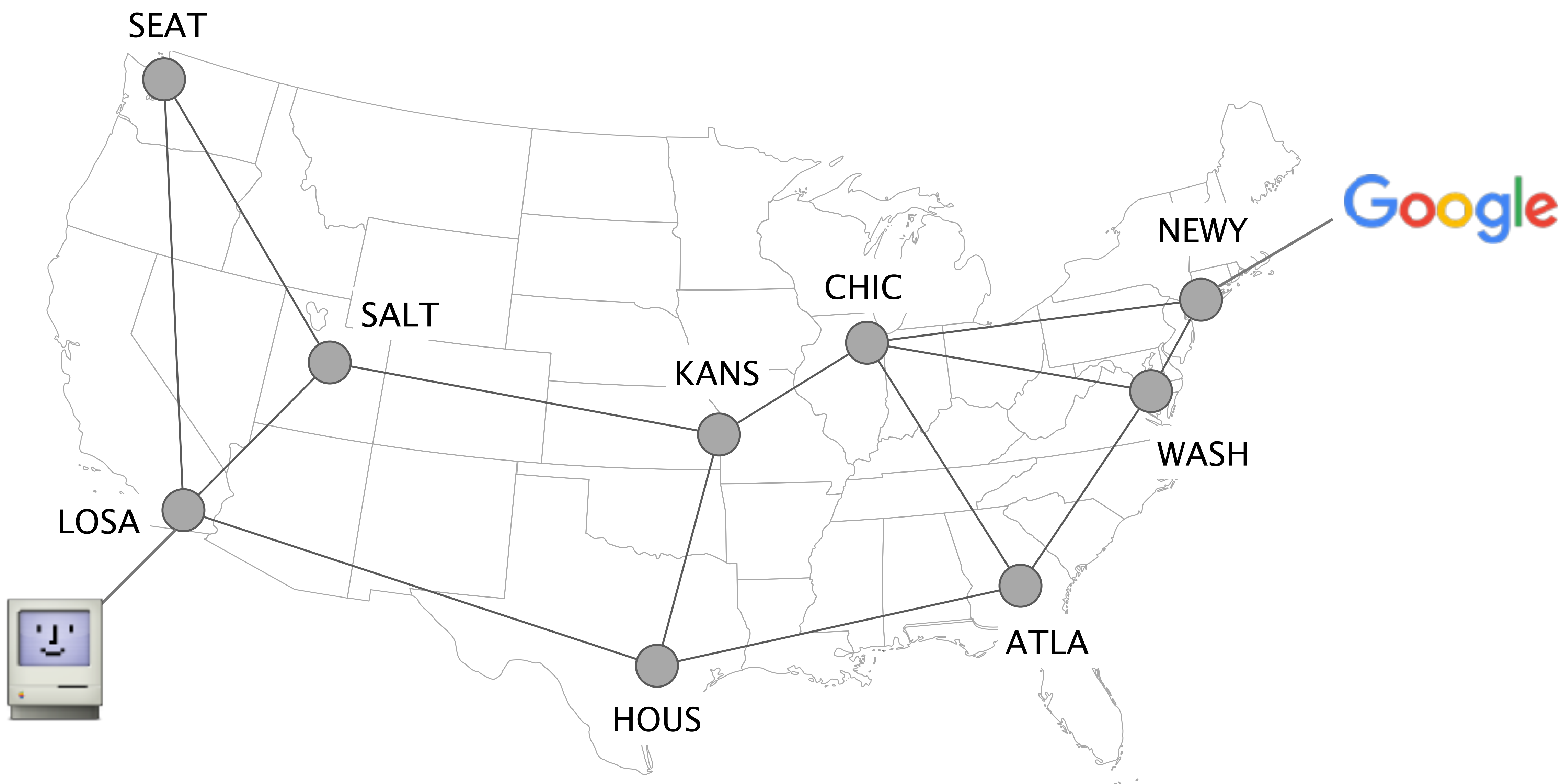
The payload contains the data to be delivered

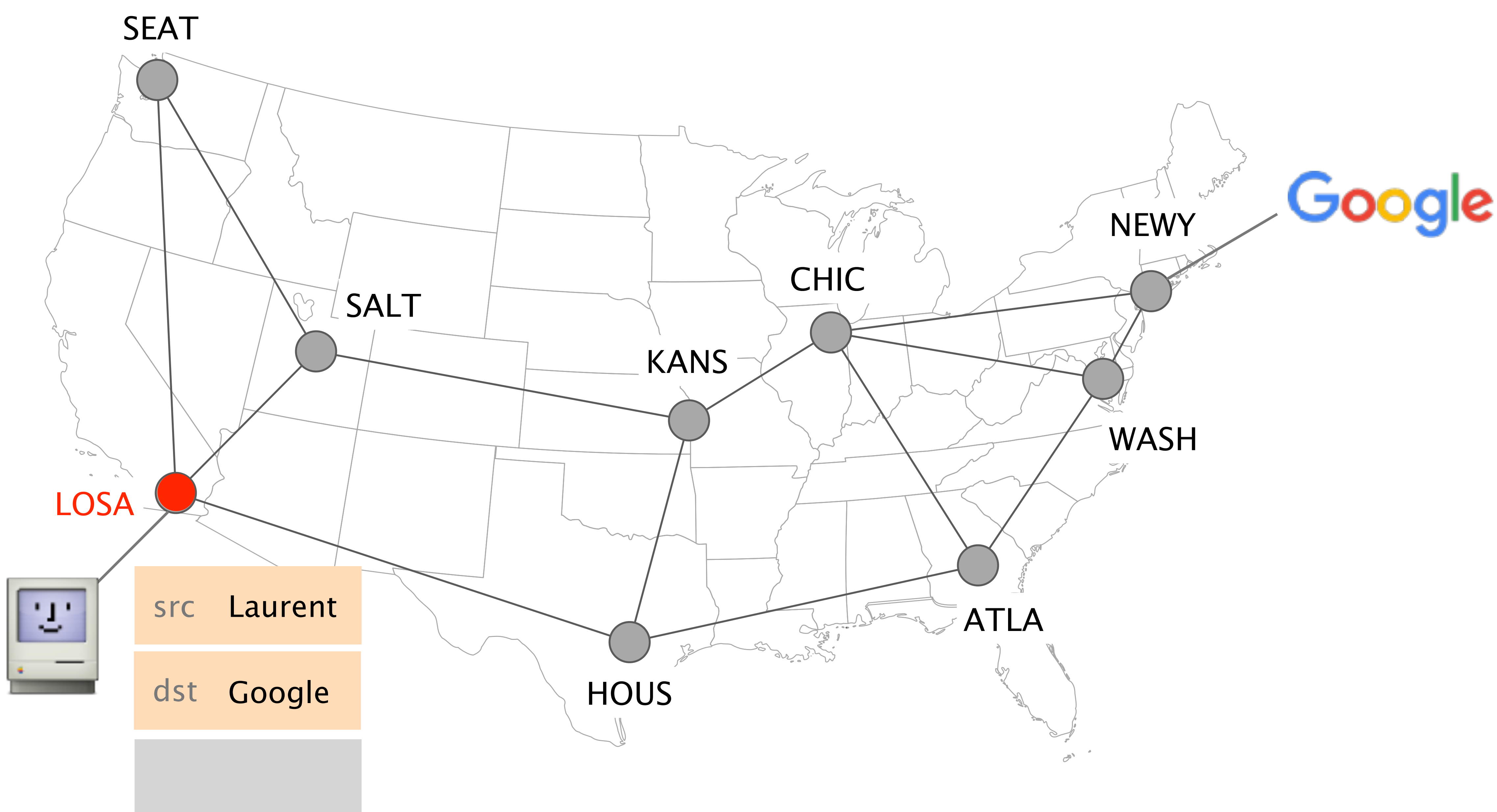


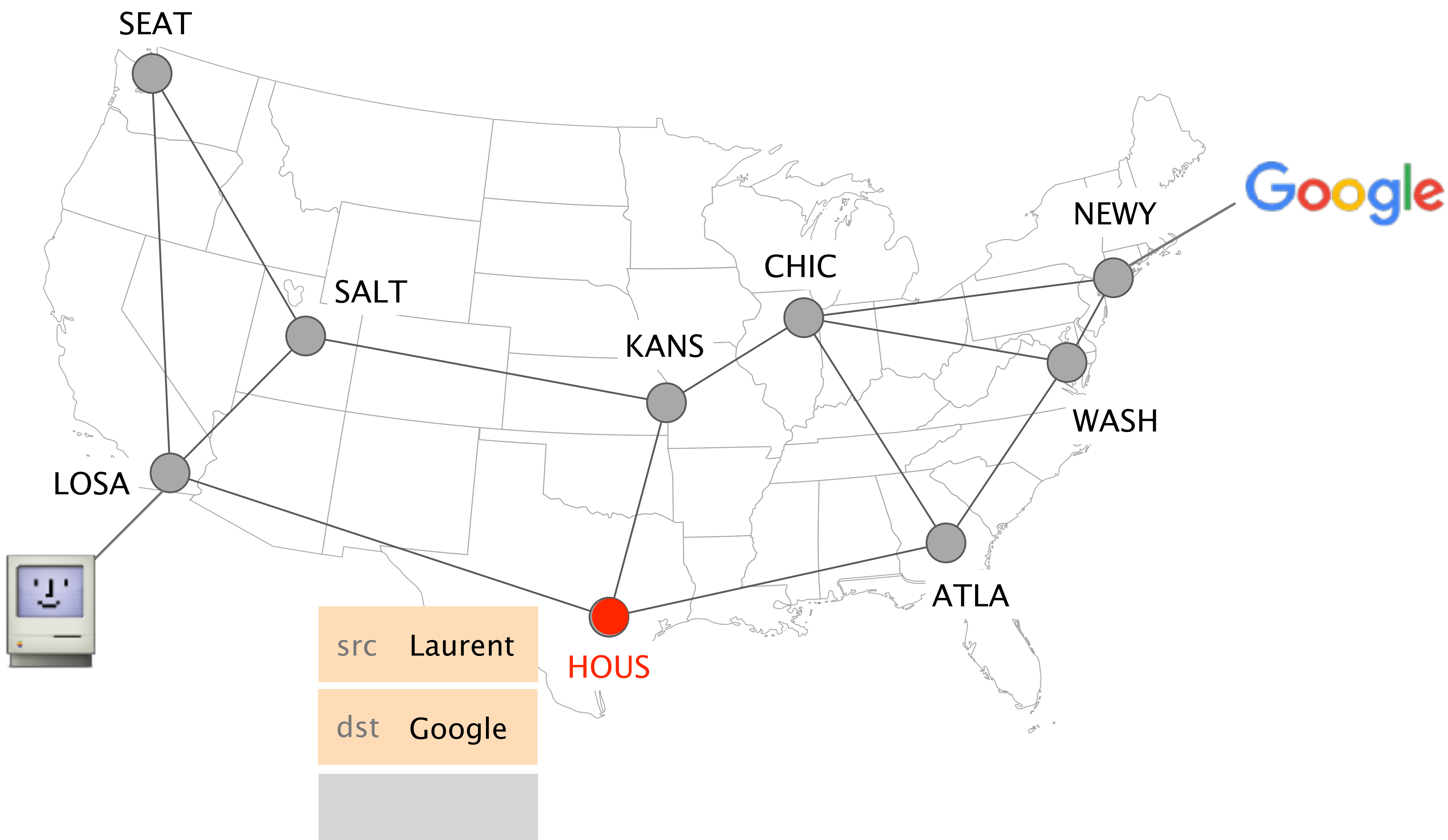

```
<html><head>
<meta http-equiv="content-type" content="text/html; charset=UTF-8">
<title>Google</title>
</head><body>
  <img alt="Google" height=110 src="images/logo.gif" width=276>
  <form action="/search" name=f>
   <input name=hl type=hidden value=en>
   <input name=q size=55 title="Google Search" value="">
   <input name=btnG type=submit value="Google Search">
   <input name=btnI type=submit value="I'm Feeling Lucky">
 </form>
</body></html>
```



Routers forward IP packets **hop-by-hop** towards their destination




SEAT
SALT
KANS
CHIC
NEWY
Google
WASH
LOSA
ATLA
HOUS
src Laurent
dst Google



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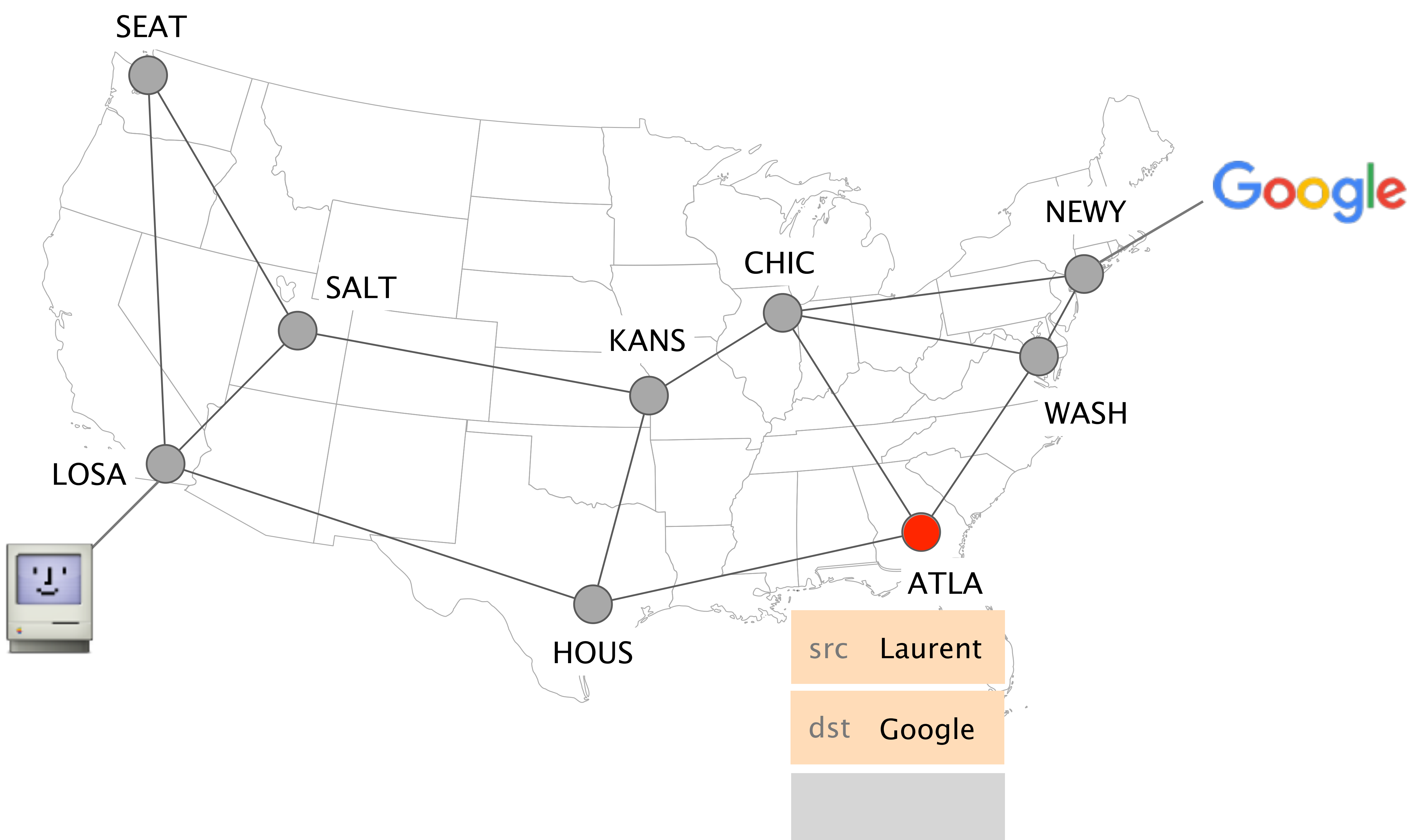

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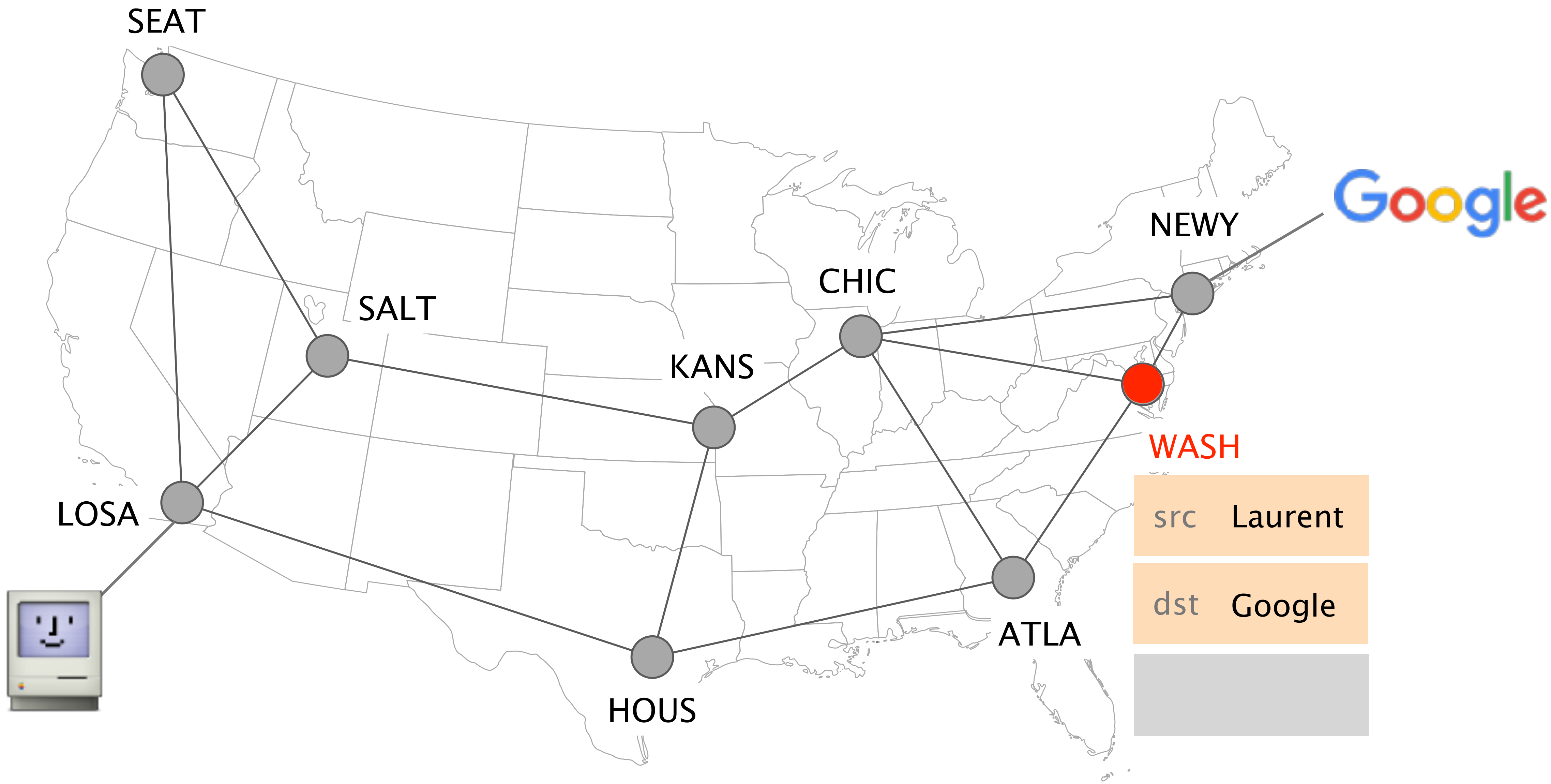
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dst Google
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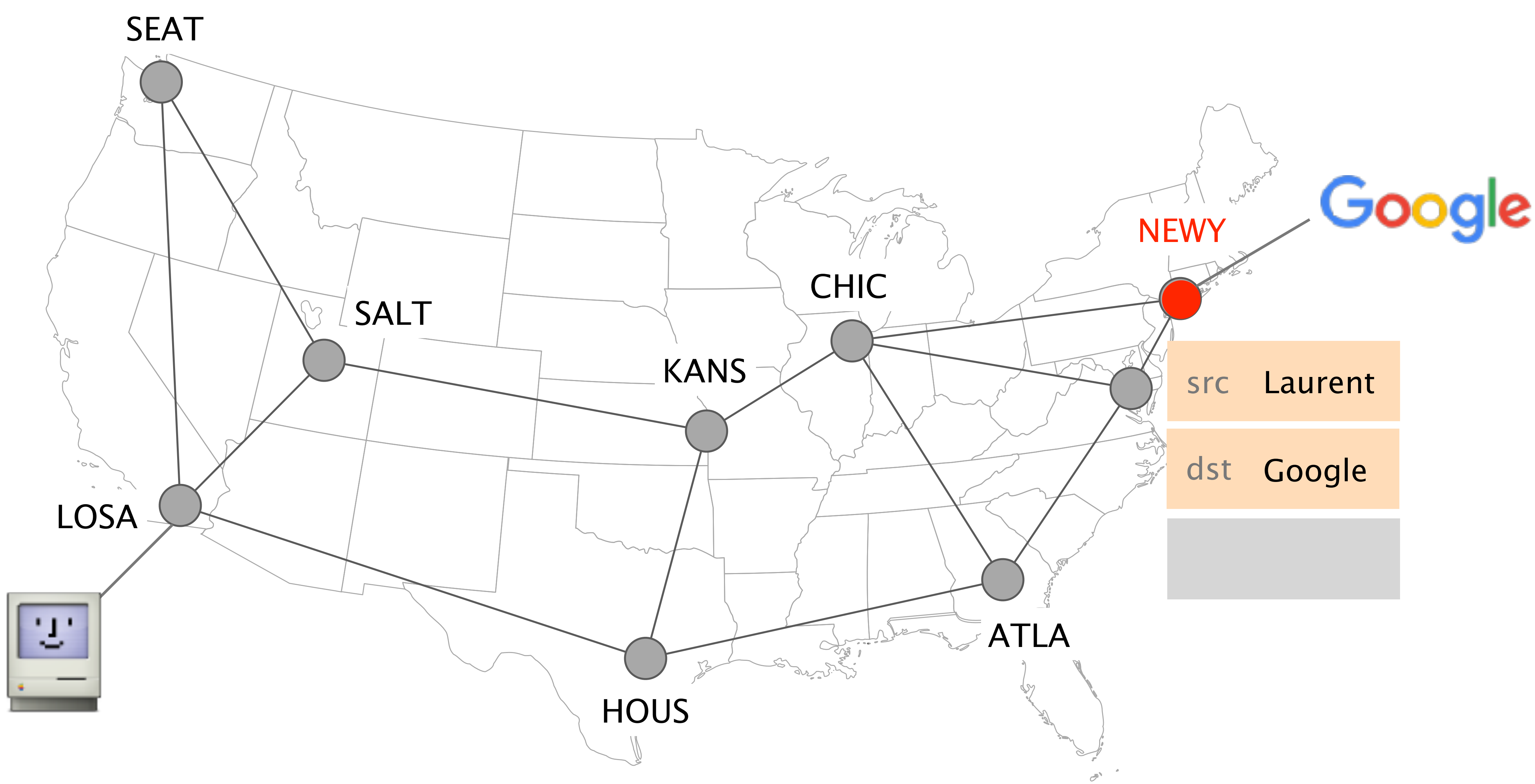
ATLA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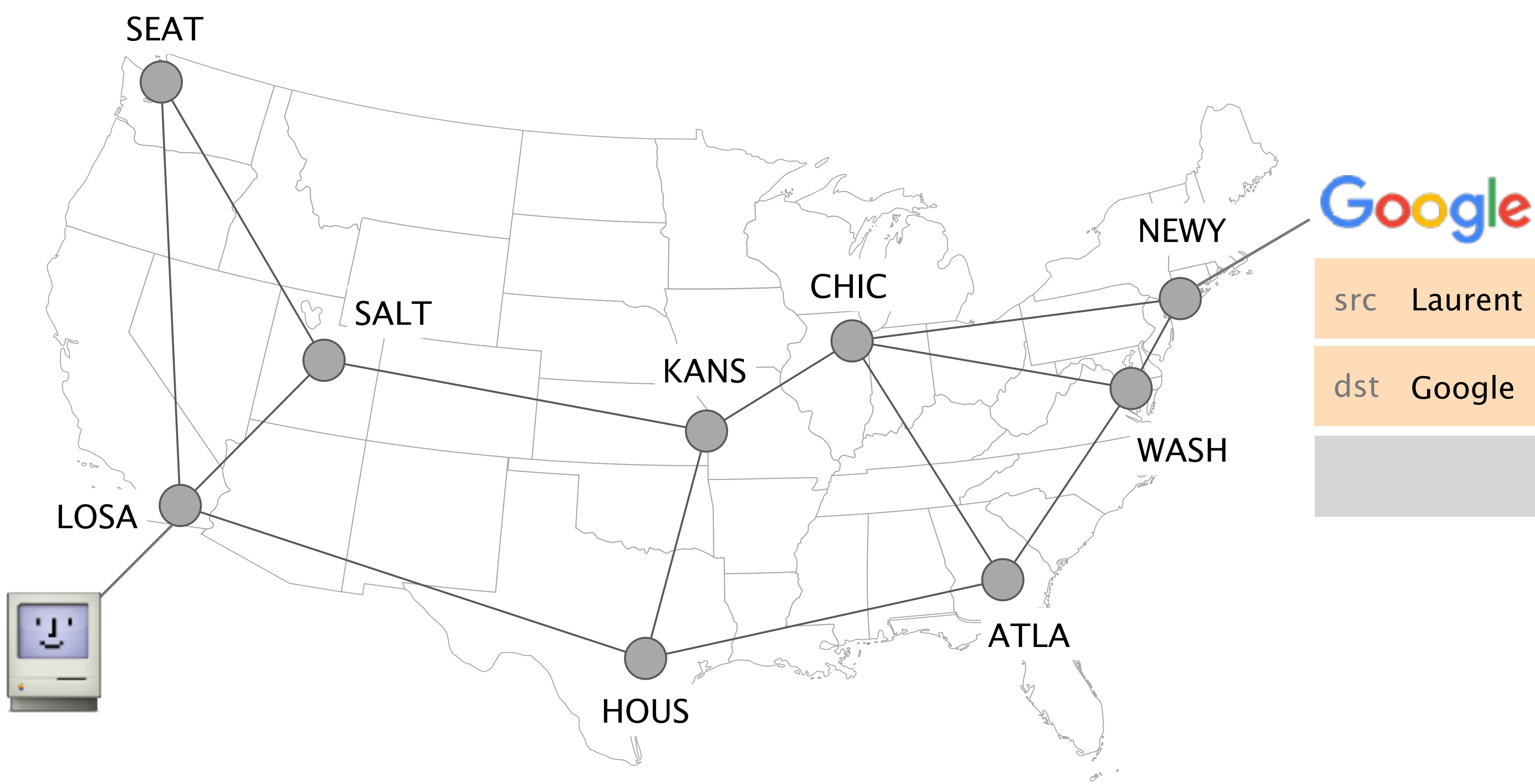
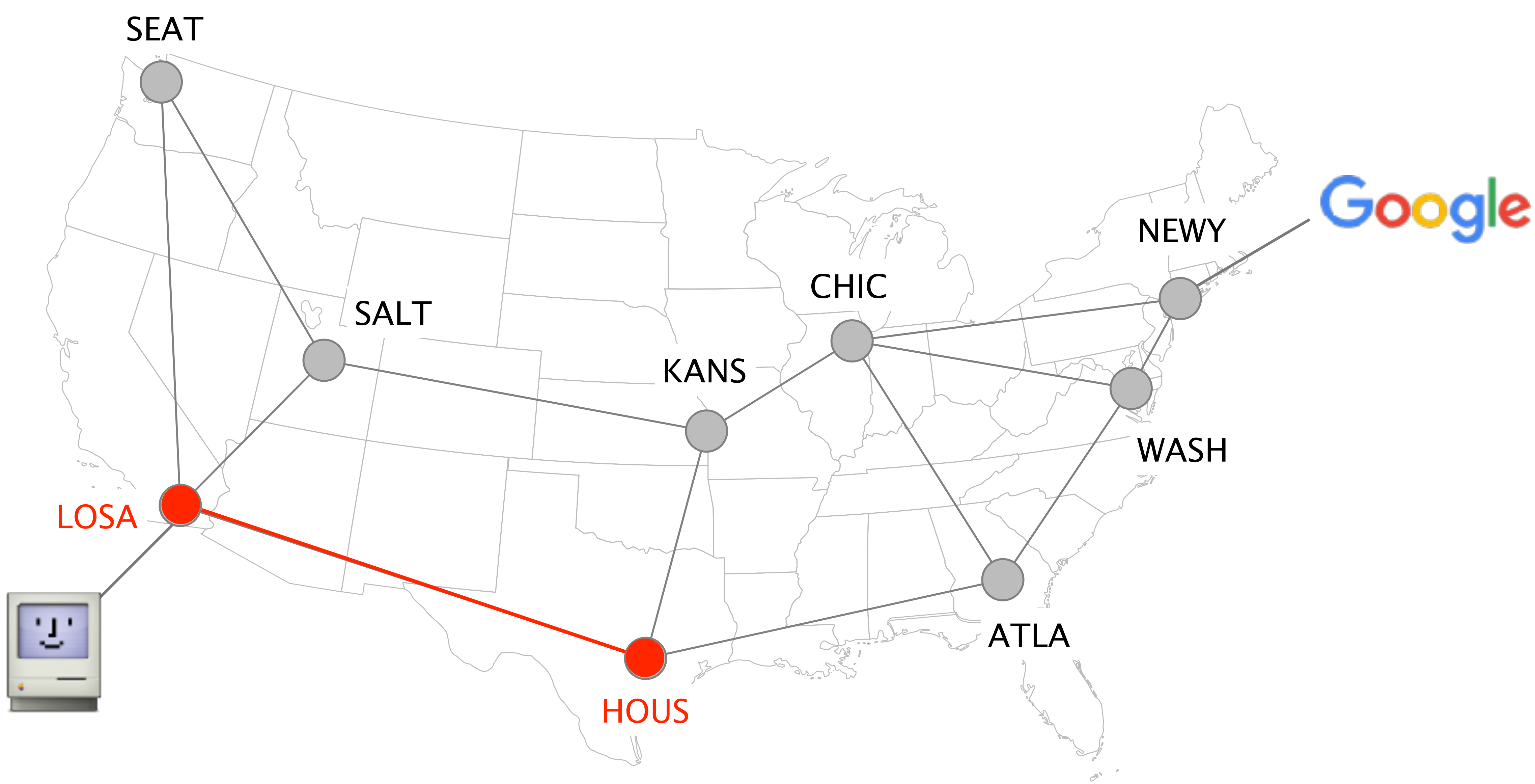


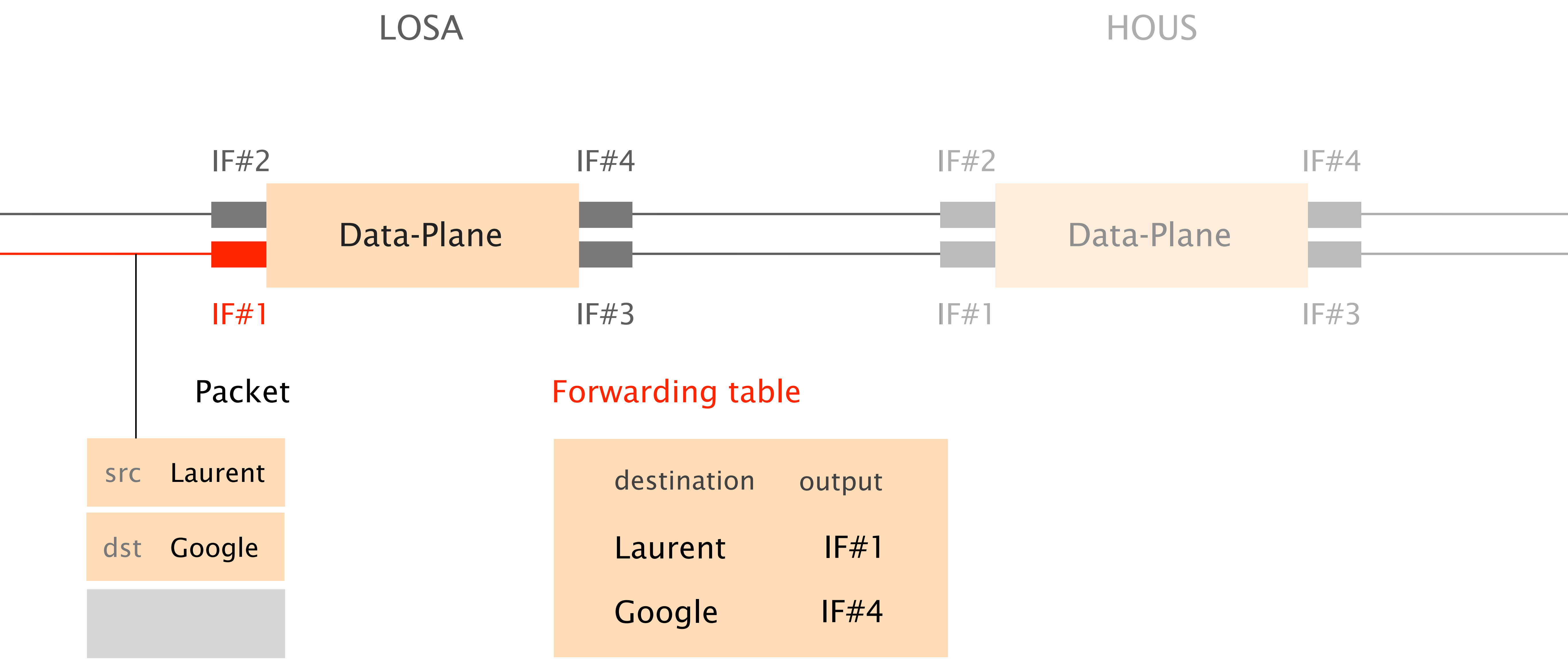
SEAT
SALT
LOSA
KANS
CHIC
NEWY
WASH
HOUS
ATLA
Google
src Laurent
dst Google

Let’s zoom in on what is going on between two adjacent routers

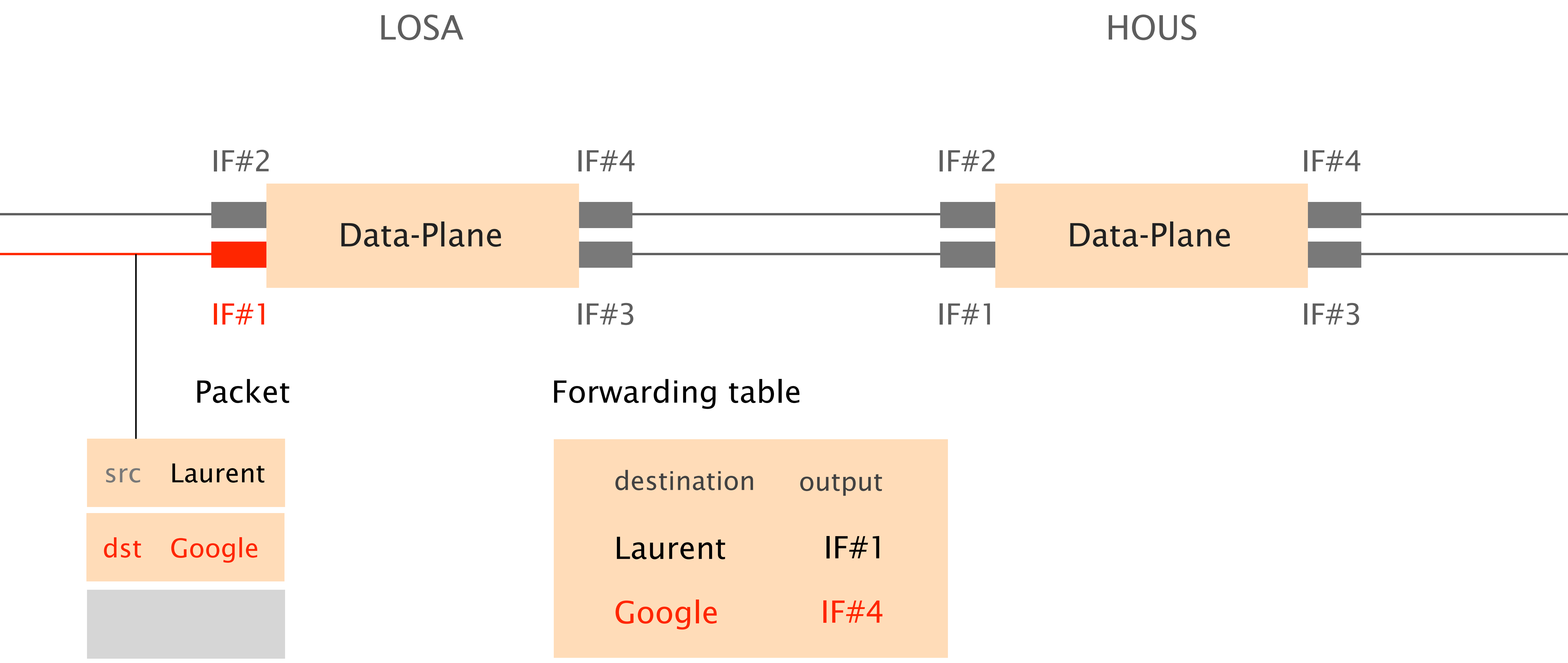


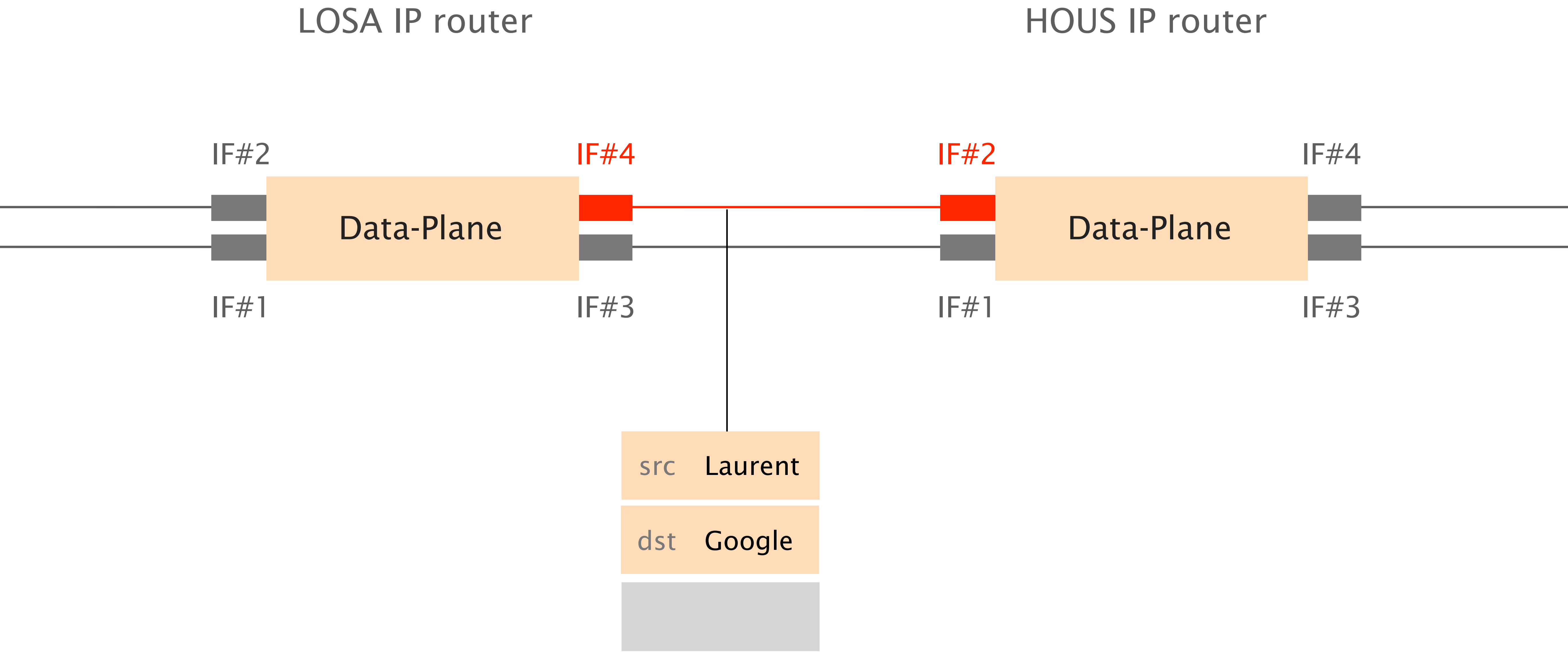

LOSA
HOUS
IF#2
IF#4
Data-Plane
IF#1
IF#3
IF#2
IF#4
Data-Plane
IF#1
IF#3

Upon packet reception, routers locally look up their forwarding table to know where to send it next

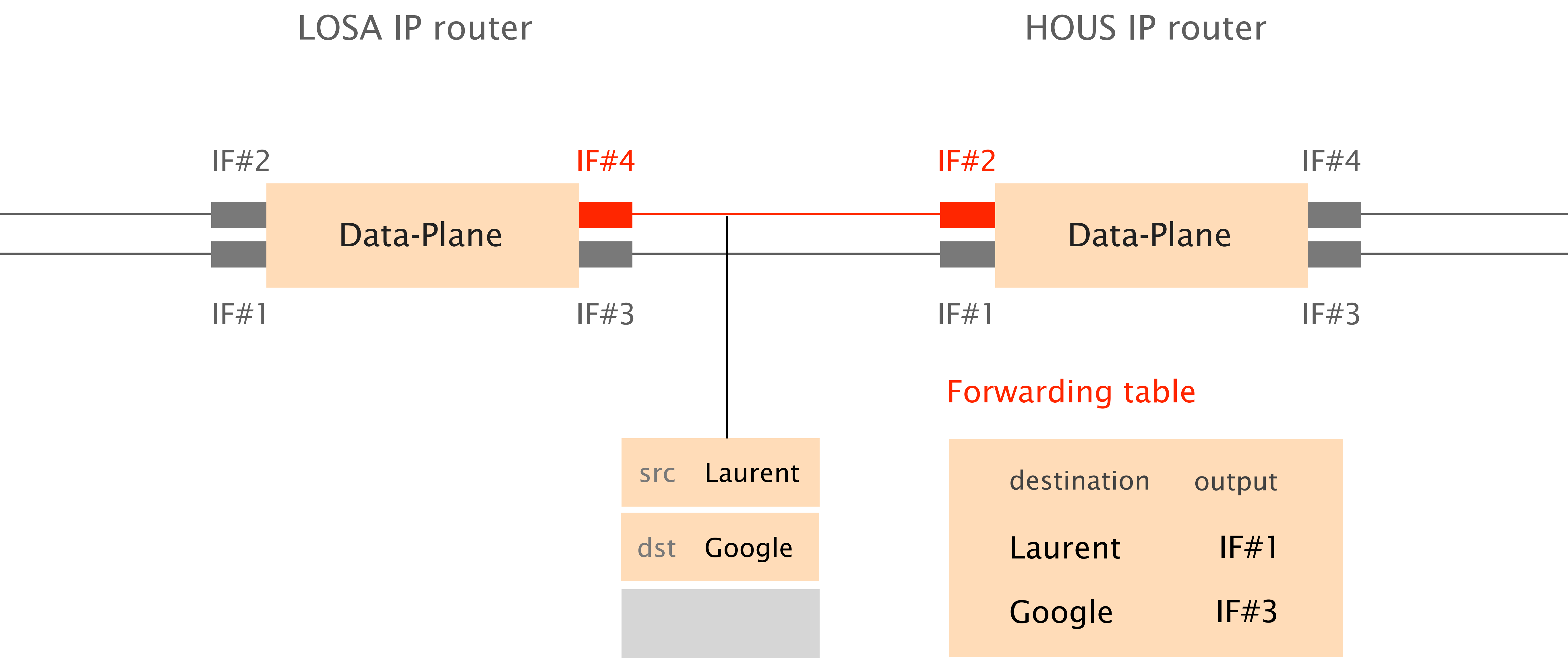


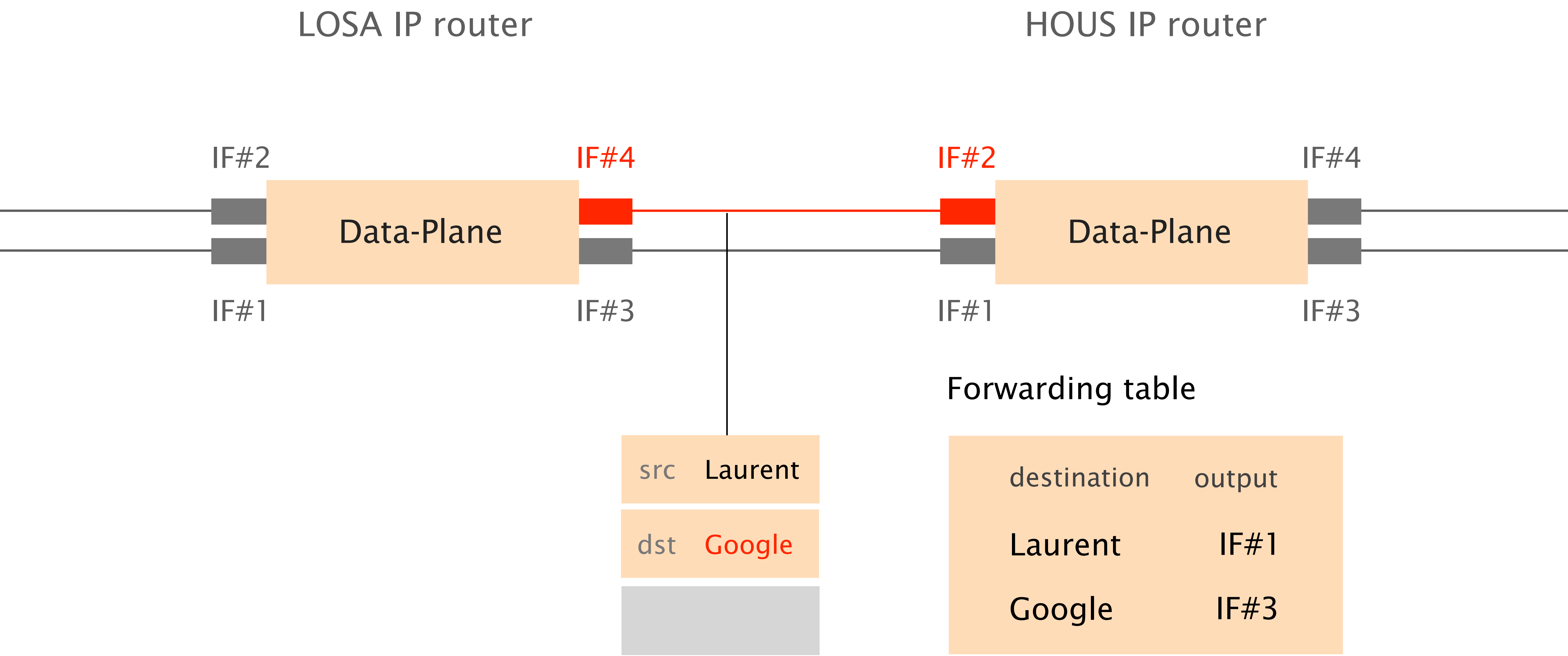
Here, the packet should be directed to IF#4



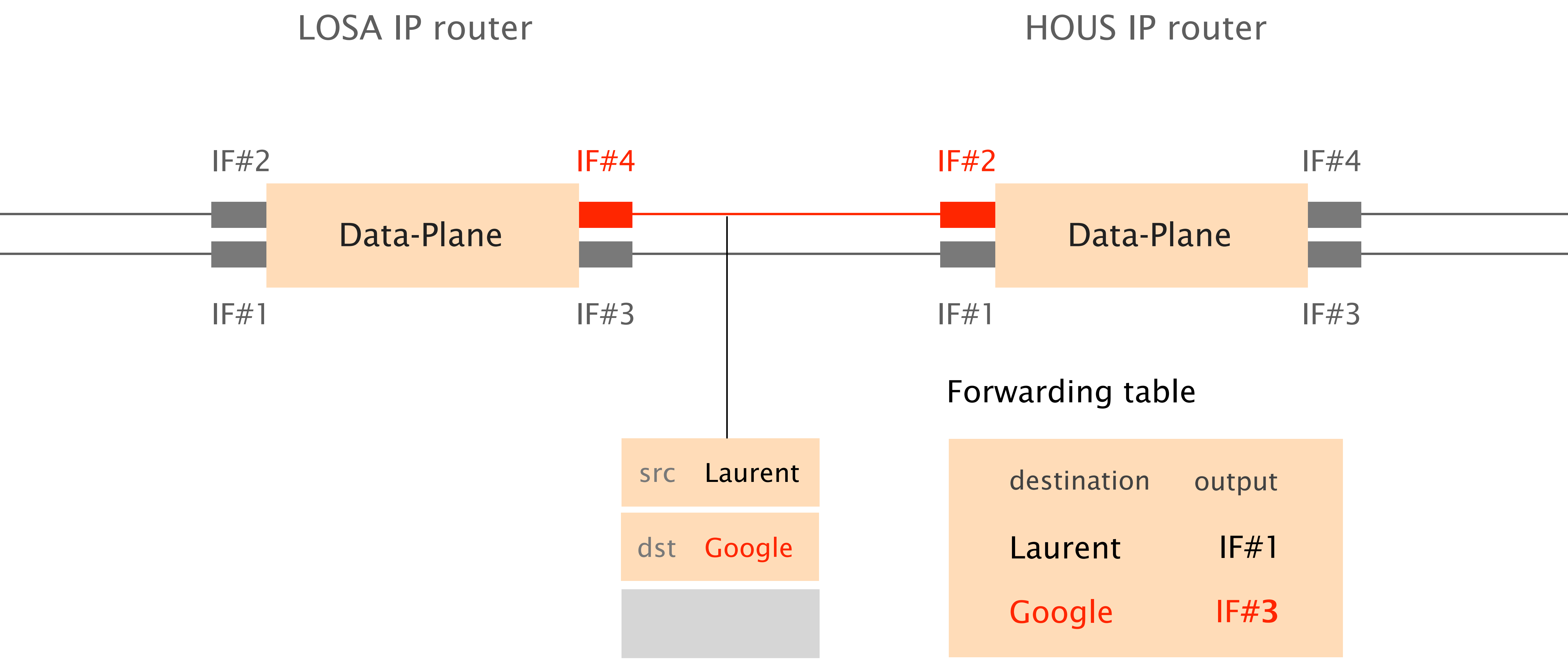

LOSA IP router
HOUS IP router
IF#2
IF#4
IF#2
IF#4
Data-Plane
Data-Plane
IF#1
IF#3
IF#1
IF#3
src Laurent
dst Google

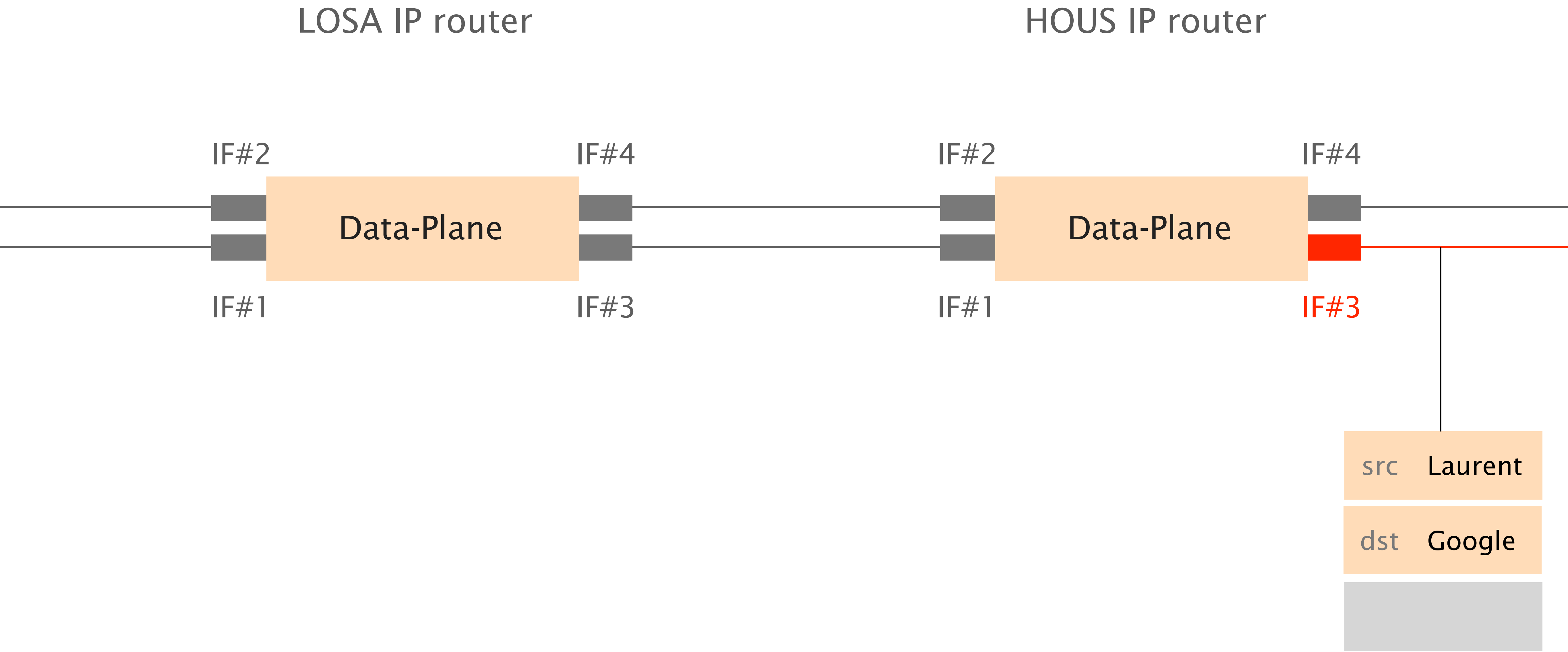
Forwarding is repeated at each router, until the destination is reached





LOSA IP router
HOUS IP router
IF#2
IF#4
IF#2
IF#4
Data-Plane
Data-Plane
IF#1
IF#3
IF#1
IF#3
Forwarding table
src Laurent
dst Google
destination output
Laurent IF#1
Google IF#3


LOSA IP router
HOUS IP router
IF#2
IF#4
IF#2
IF#4
Data-Plane
Data-Plane
IF#1
IF#3
IF#1
IF#3
Forwarding table
src Laurent
dst Google
destination output
Laurent IF#1
Google IF#3



LOSA IP router
HOUS IP router
IF#2
IF#4
Data-Plane
IF#1
IF#3
IF#2
IF#4
Data-Plane
IF#1
IF#3
src Laurent
dst Google

Forwarding decisions necessarily depend on the destination, but can also depend on other criteria

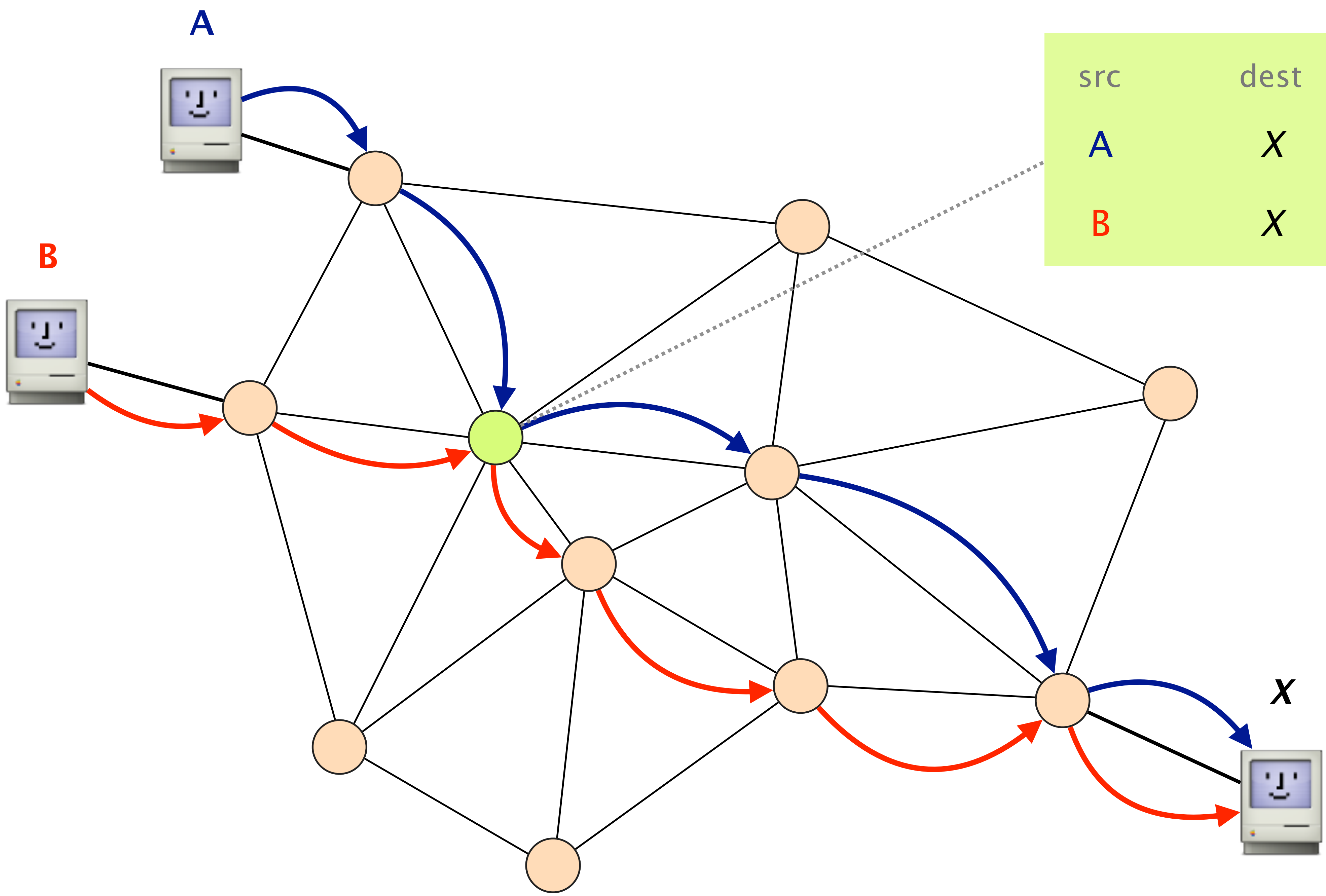
criteria	destination	mandatory (why?)
	source	requires n^2 state
	input port	traffic engineering
	other header	

destination

source

Let’s compare these two

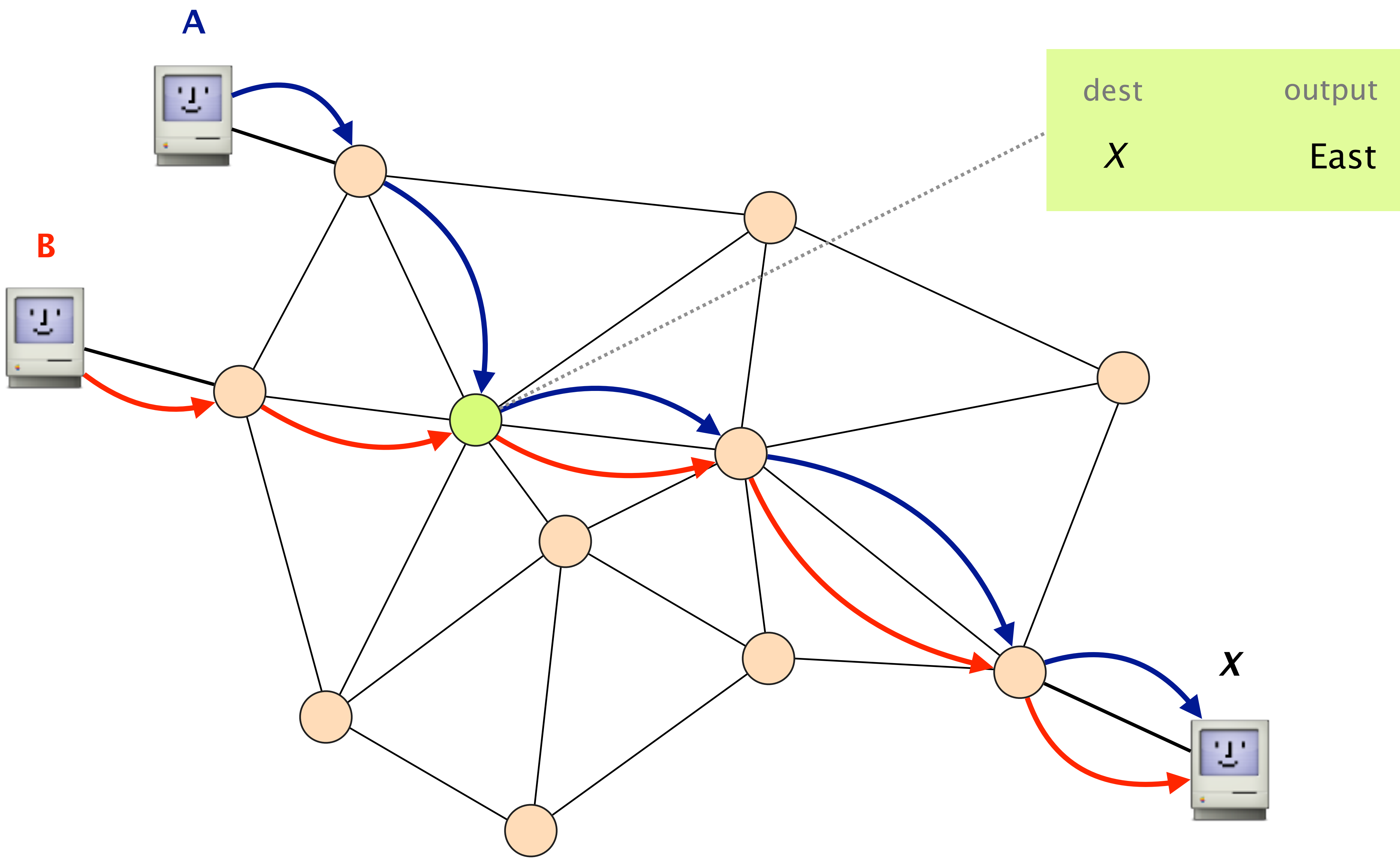
With source- & destination-based routing, paths from different sources can differ



src	dest	output
A	X	East
B	X	South-East

With **destination-based routing**,

paths from different source coincide once they overlap

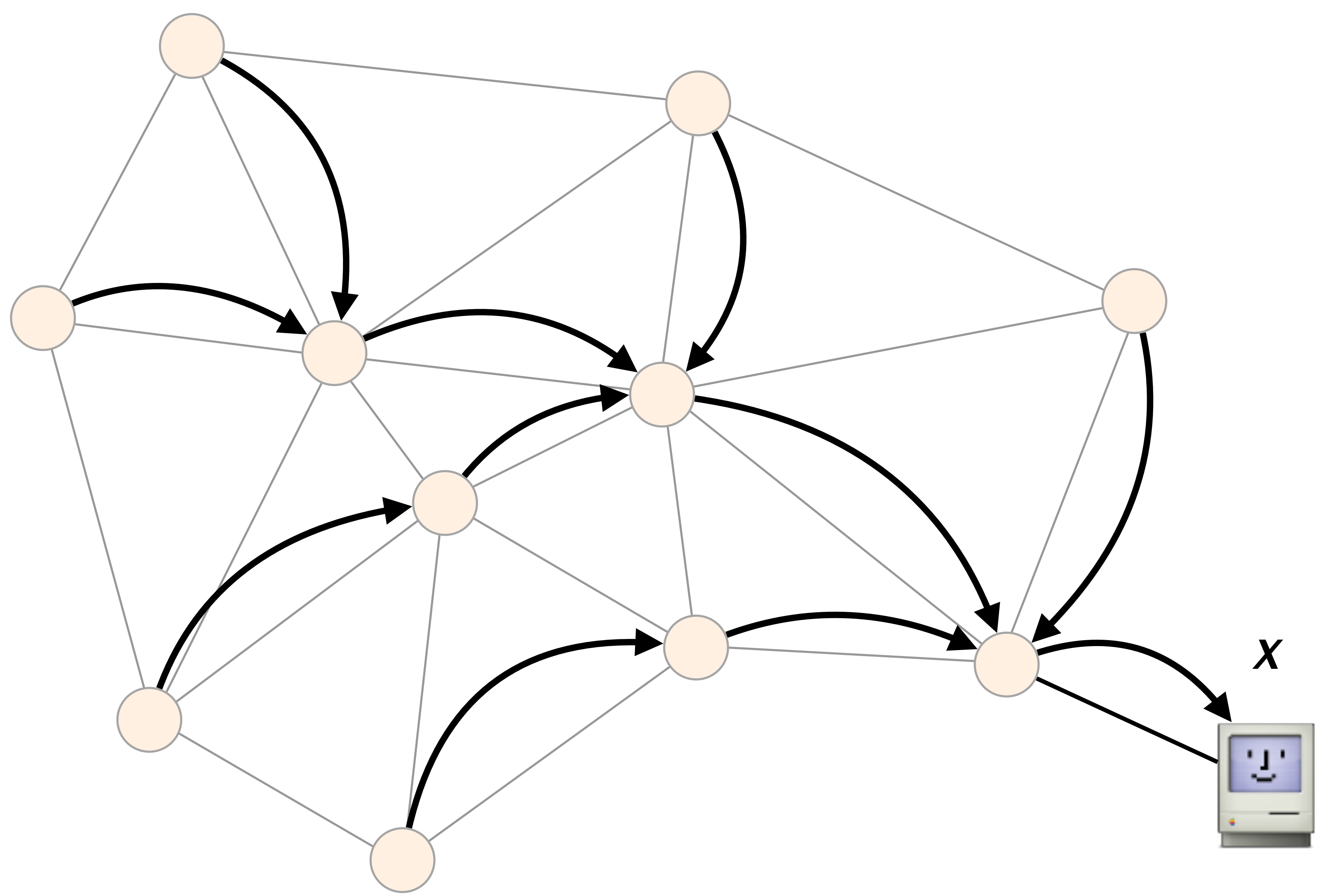


Once path to destination meet, they will *never* split

Set of paths to the destination
produce a **spanning tree** rooted at the destination:

- cover every router exactly once
- only one outgoing arrow at each router

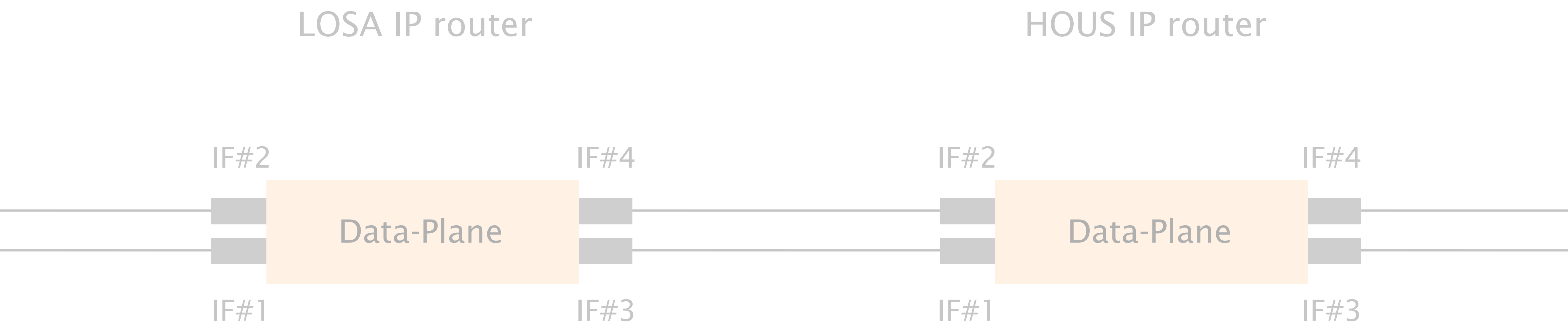
Here is an example of a spanning tree for destination *X*



In the rest of the lecture,
we'll consider destination-based routing

the default in the Internet

Where are these forwarding tables coming from?



Forwarding table

destination	output
Laurent	IF#1
Google	IF#4

Forwarding table

destination	output
Laurent	IF#1
Google	IF#3


Data-Plane
Data-Plane

In addition to **the data-plane**,
routers are also equipped with **a control-plane**

Think of the control-plane as the router's brain

Roles

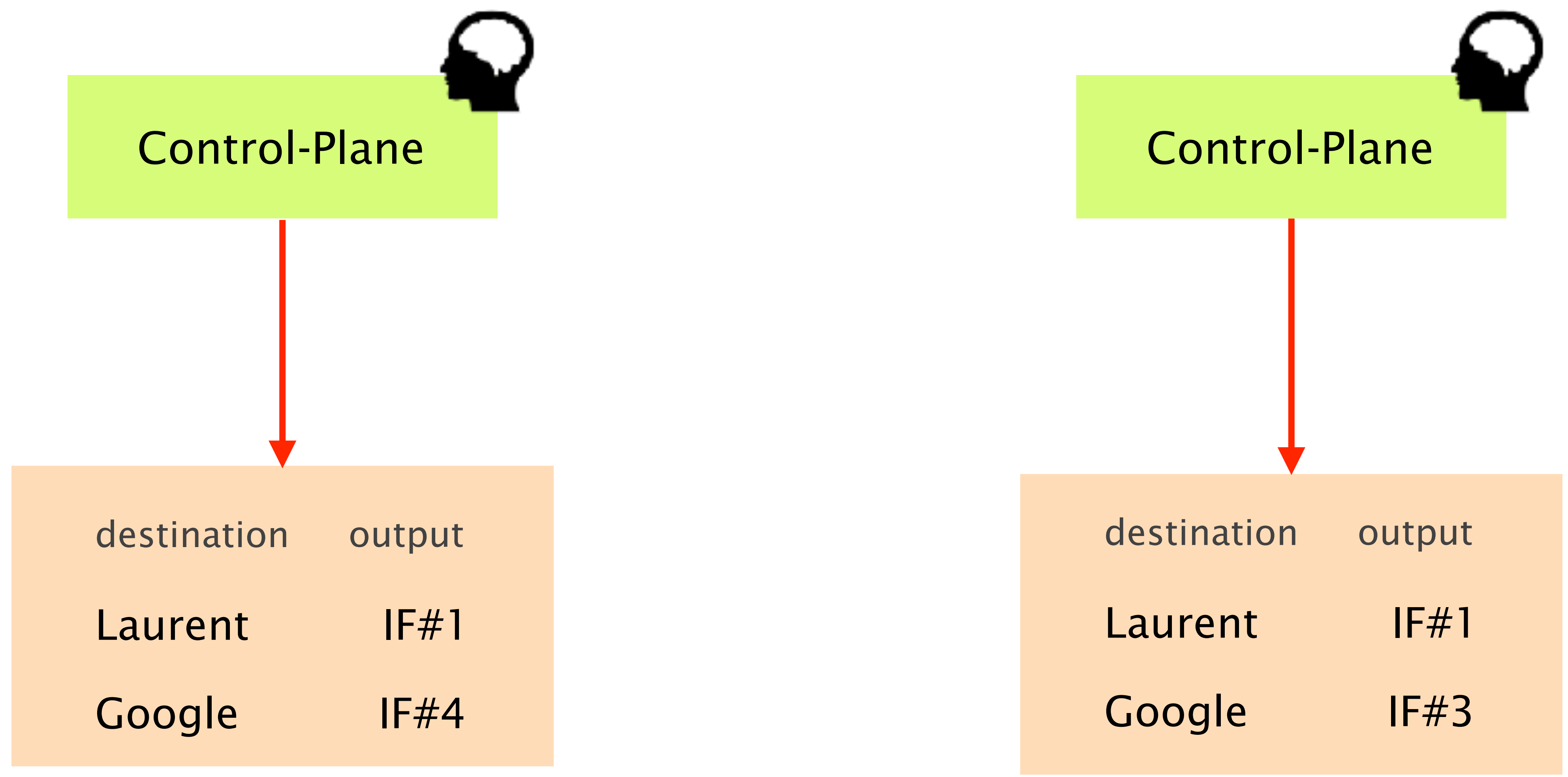
Routing

Configuration

Statistics

…

Routing is the control-plane process that computes and populates the forwarding tables



While forwarding is a *local* process,
routing is inherently a *global* process

How can a router know
where to direct packets
if it does not know what
the network looks like?

Forwarding *vs* Routing

summary

	forwarding	routing
goal	directing packet to an outgoing link	computing the paths packets will follow
scope	local	network-wide
implem.	hardware usually	software always
timescale	nanoseconds	10s of ms hopefully

The goal of routing is to compute
valid global forwarding state

definition

a global forwarding state is valid if

it always delivers packets
to the correct destination

sufficient and necessary condition

Theorem

a global forwarding state is valid if and only if

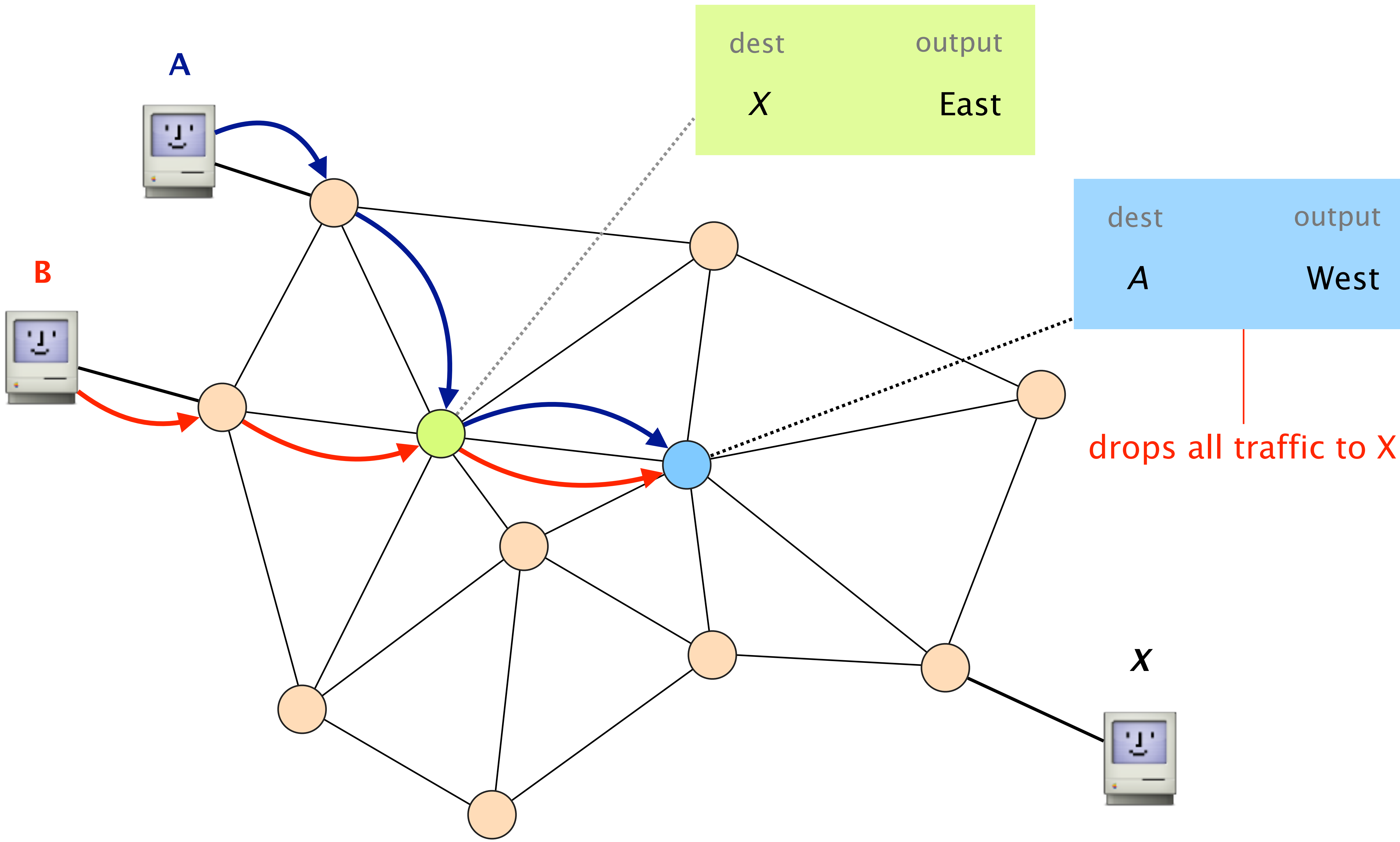
- there are no dead ends

  no outgoing port defined in the table

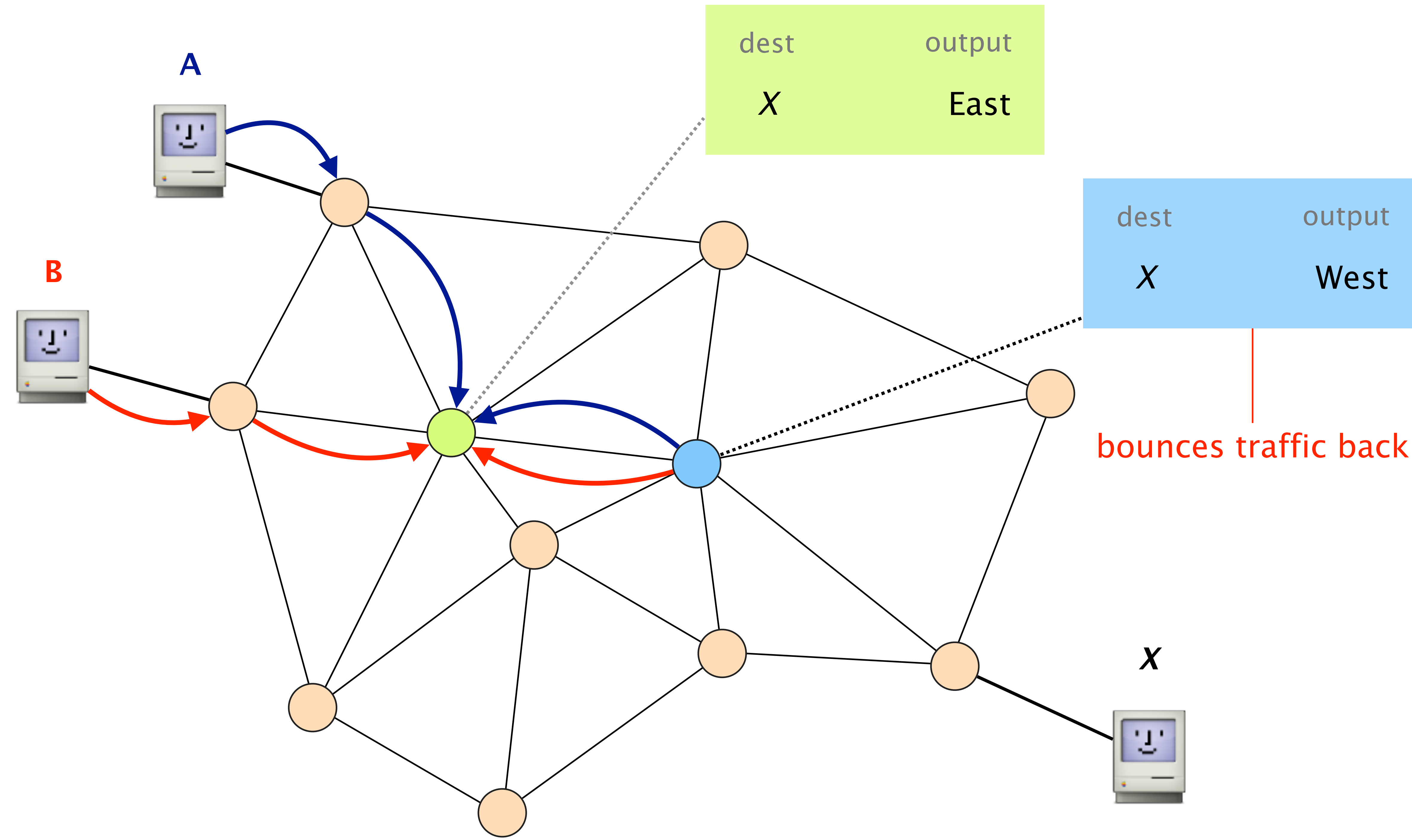
- there are no loops

  packets going around the same set of nodes

A global forwarding state is valid if and only if there are no dead ends



A global forwarding state is valid if and only if there are no forwarding loops



sufficient and necessary condition

Theorem

a global forwarding state is valid if and only if

- there are no dead ends

  i.e. no outgoing port defined in the table

- there are no loops

  i.e. packets going around the same set of nodes

No dead ends and no loops are a **sufficient *and* necessary condition** for forwarding validity

statement 1

A *if* B means B *implies* A

if B is true, then A is true

statement 2

A *only if* B means A *implies* B

if A is true, then B is true

statement 3

A *if and only if* B means both

if A is true, then so is B and vice-versa

To prove statement 3, we must prove statement 1 *and* statement 2

statement 1	A *if* B means B *implies* A if B is true, then A is true
statement 2	A *only if* B means A *implies* B if A is true, then B is true
statement 3	A *if and only if* B means both if A is true, then so is B and vice-versa

Proving the **necessary** condition is **easy**

Theorem

If a routing state is valid

then there are no loops or dead-end

Proof

If you run into a dead-end or a loop

you'll never reach the destination

so the state cannot be correct (contradiction)

Proving the sufficient condition is more subtle

Theorem

If a routing state has no dead end and no loop
then it is valid

Proof

There is only a finite number of ports to visit

A packet can never enter a switch via the same port, otherwise it is a loop (which does not exist by assumption)

As such, the packet must eventually reach the destination question 1 How do we verify that a forwarding state is valid?

question 2 How do we compute valid forwarding state?

question 1 How do we verify that a forwarding state is valid?

How do we compute valid forwarding state?

Verifying that a routing state is valid is easy

simple algorithm

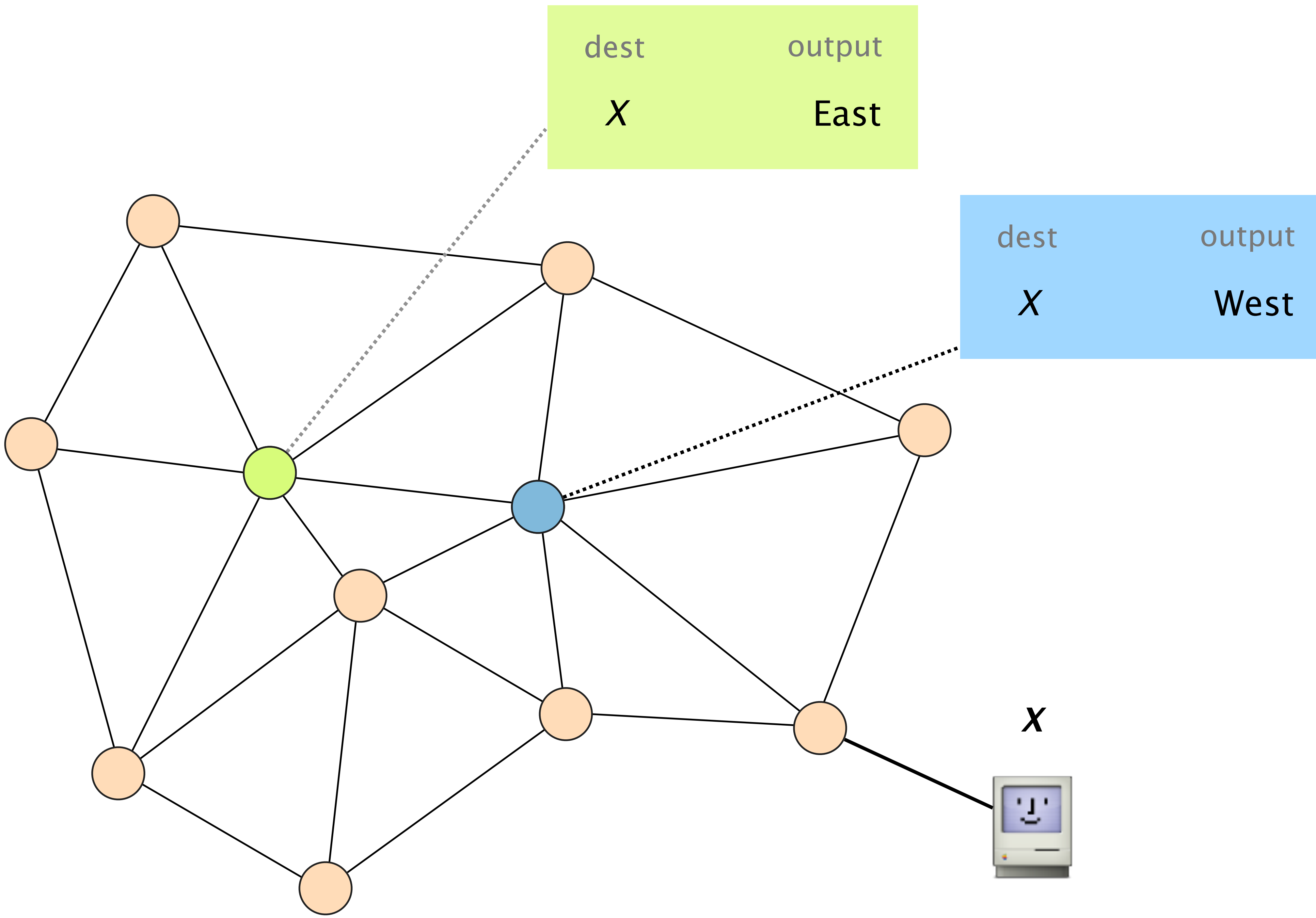
for one destination

Mark all outgoing port with an arrow

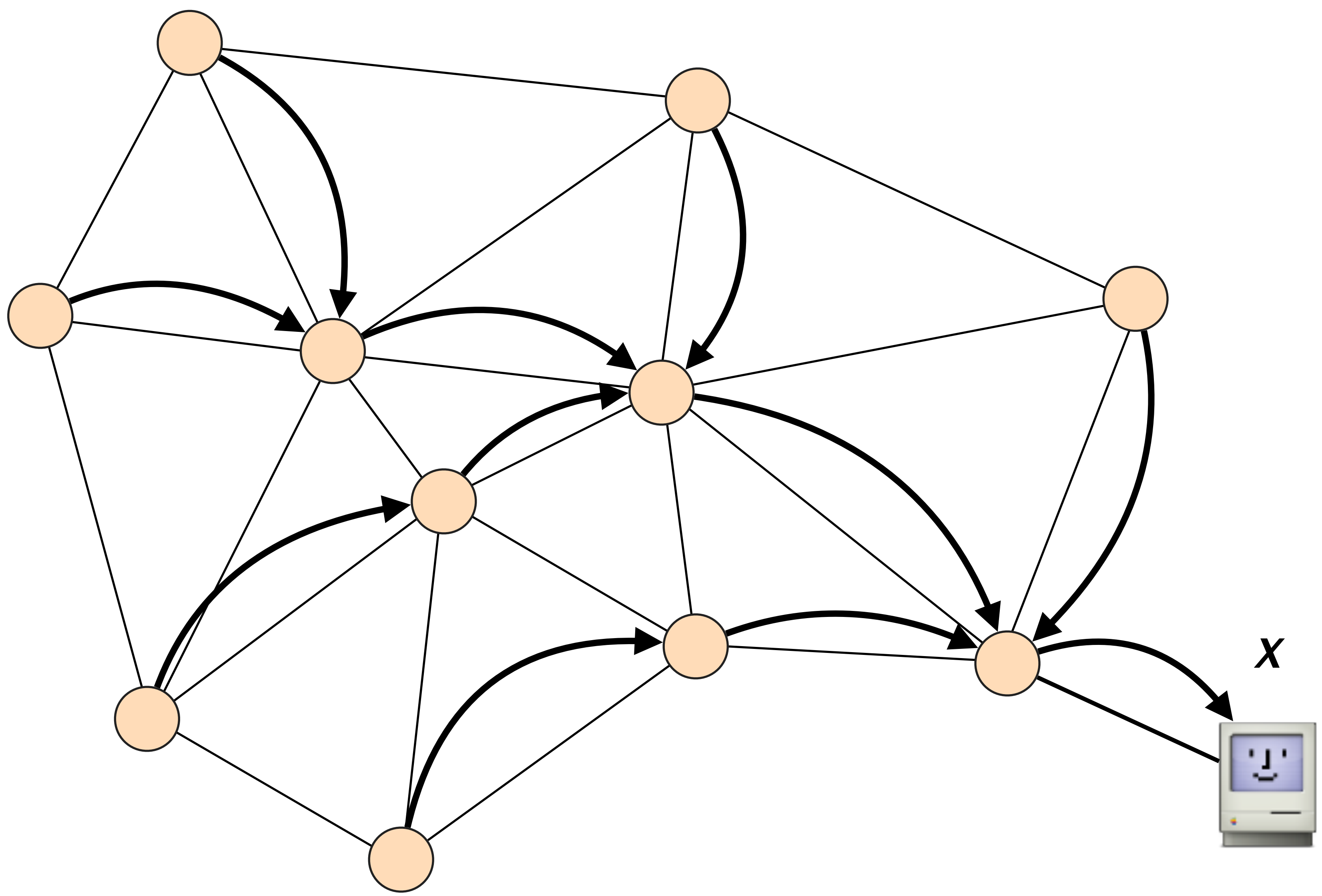
Eliminate all links with no arrow

State is valid *iff* the remaining graph is a spanning-tree

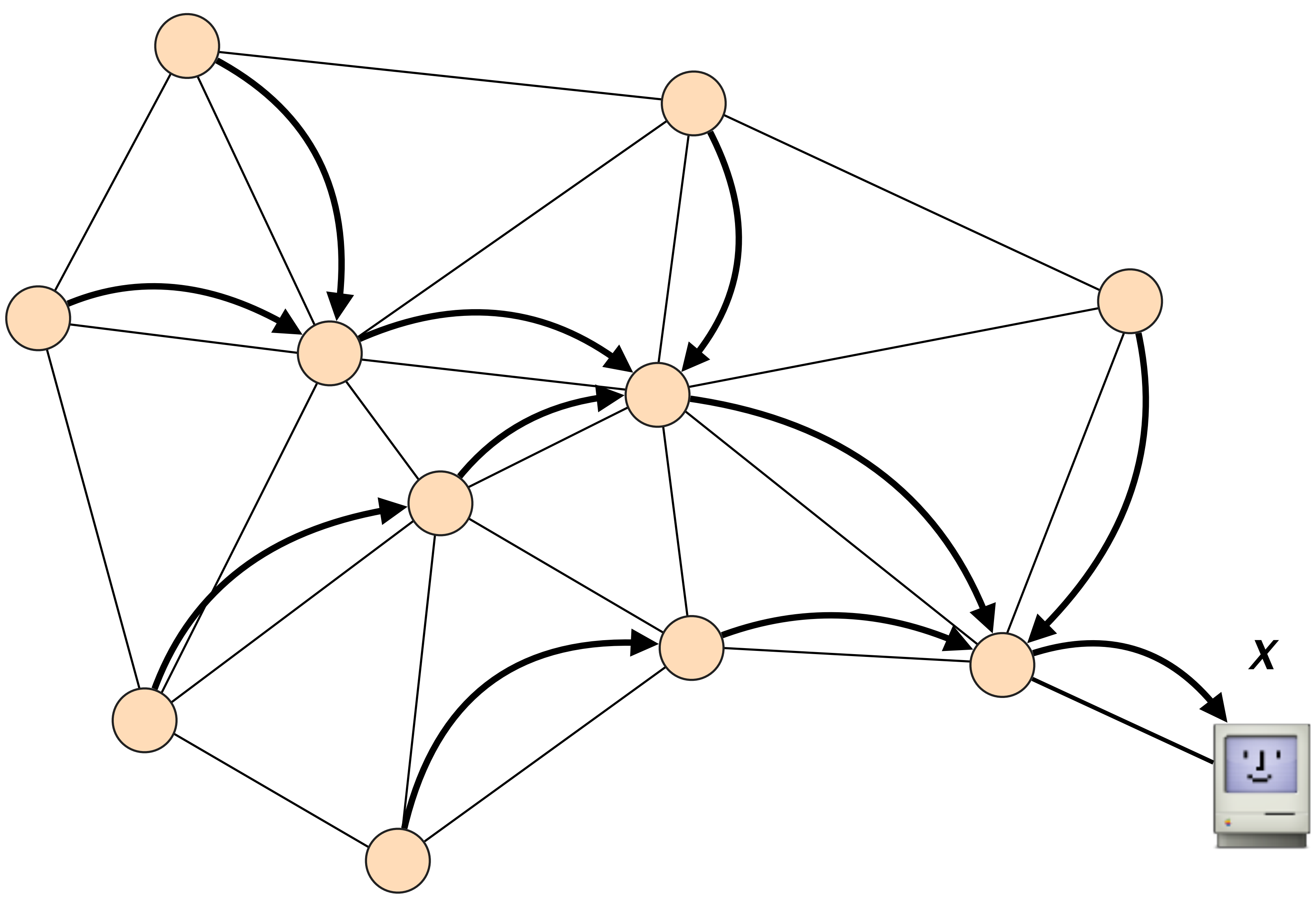
Given a graph with the corresponding forwarding state

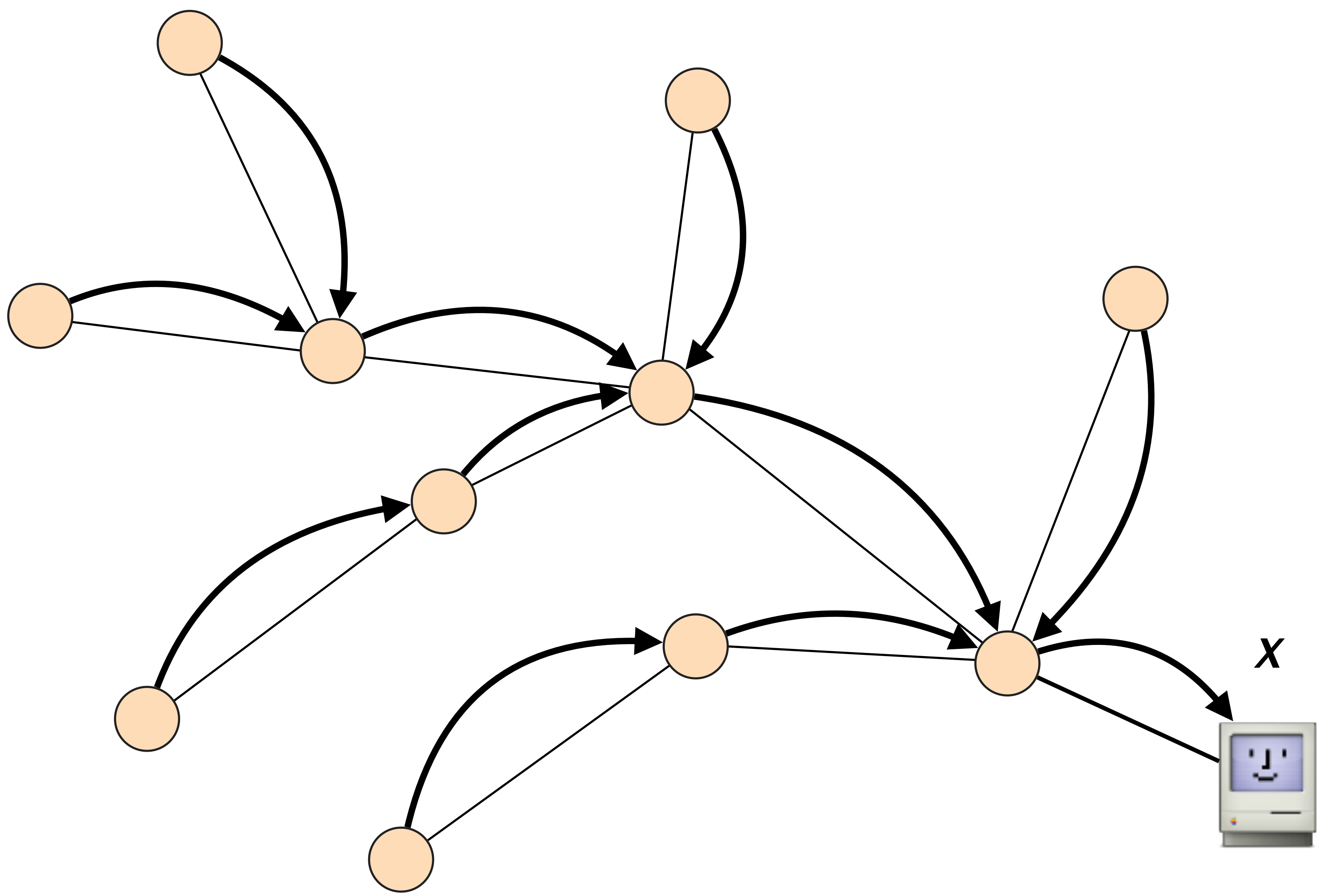


Mark all outgoing ports with an arrow



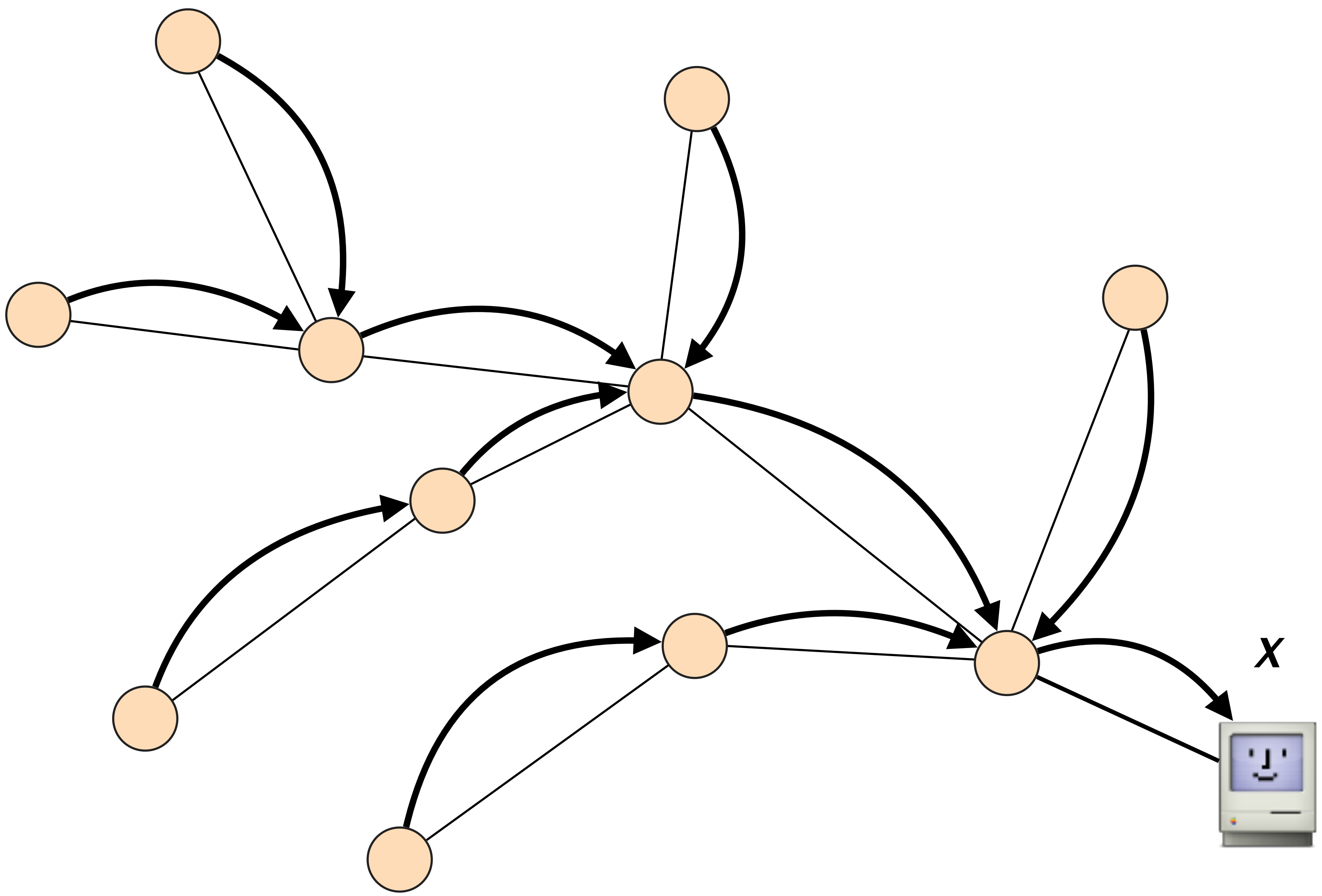
Eliminate all links with no arrow



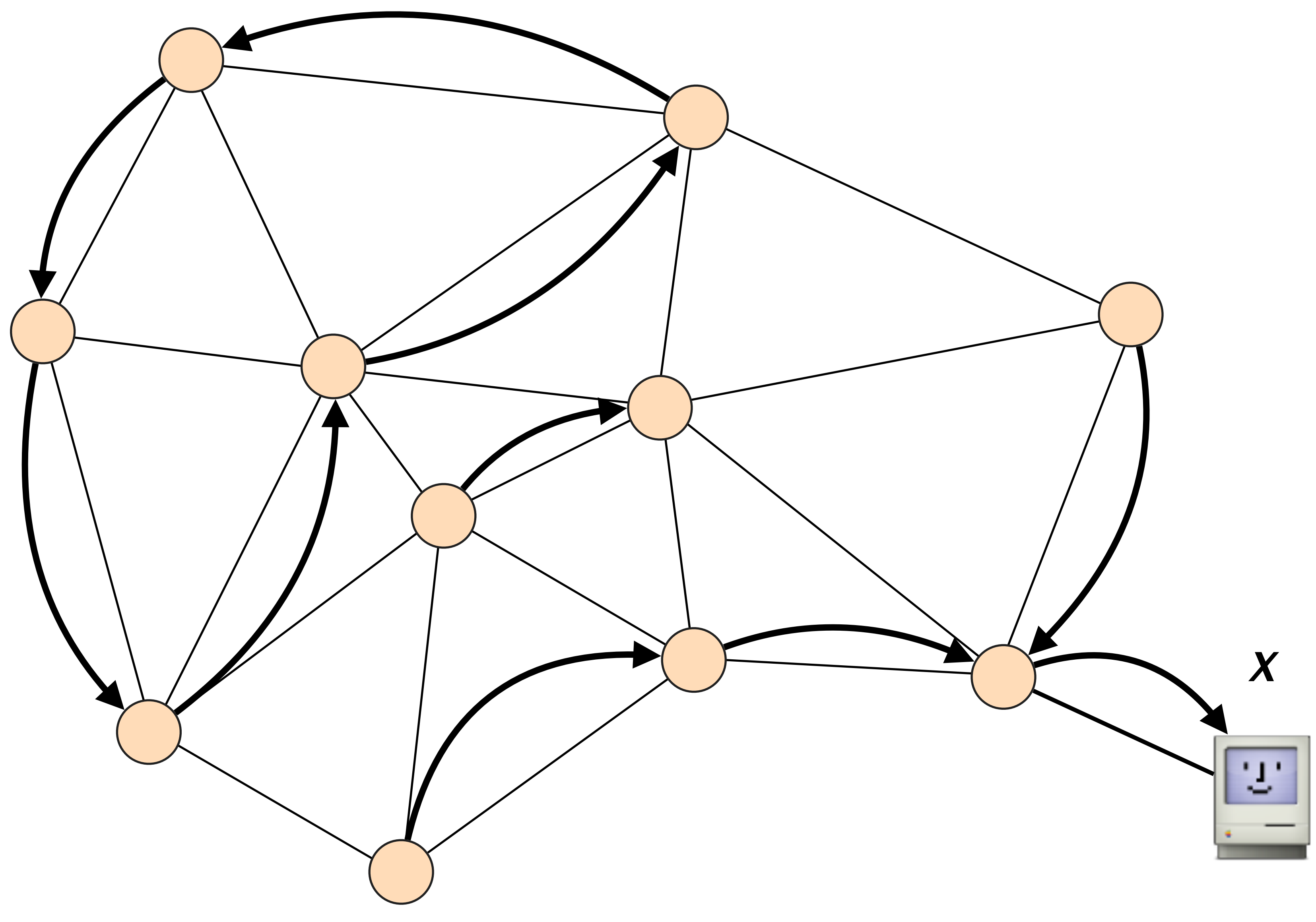

X

The result is a spanning tree.

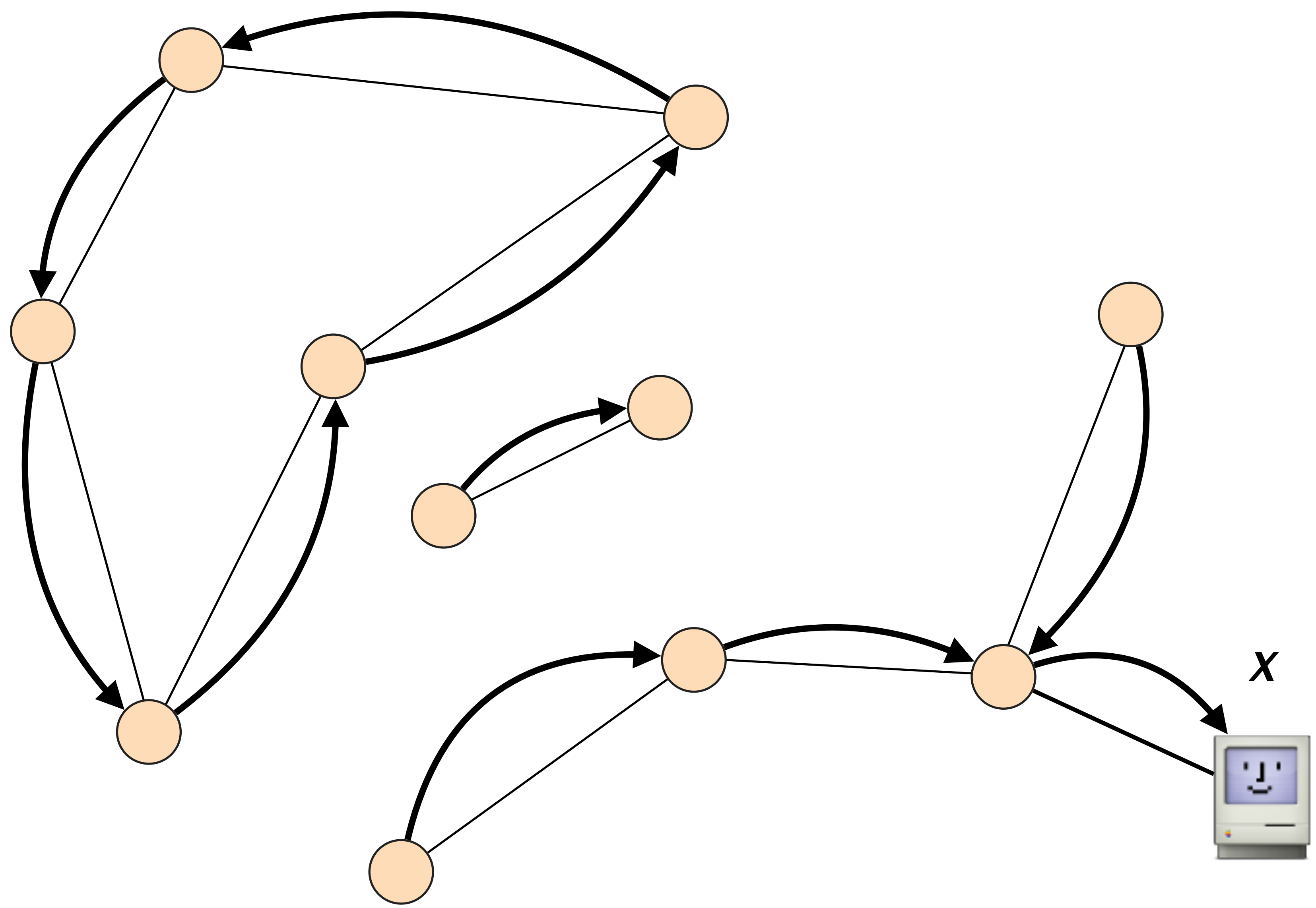
This is a valid routing state



Mark all outgoing ports with an arrow

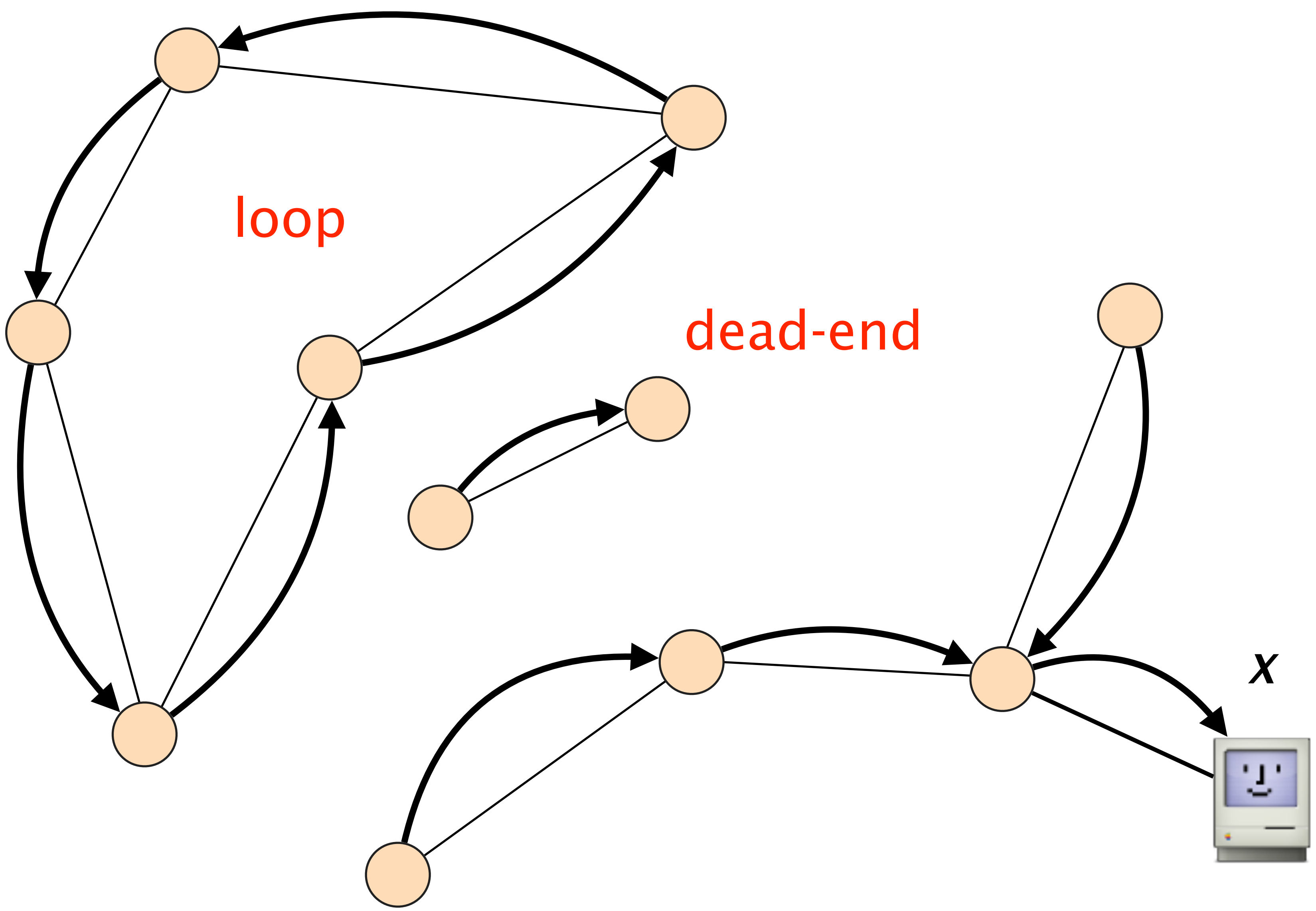


Eliminate all links with no arrow



The result is not a spanning-tree.

The routing state is not valid



How do we verify that a forwarding state is valid?

question 2 How do we compute valid forwarding state?

Producing valid routing state is harder

prevent dead ends easy	prevent loops hard

Producing valid routing state is harder
but doable

prevent dead ends

easy

prevent loops

hard

This is the question
you should focus on

Most routing protocols out there differ in
how they avoid loops

prevent loops
hard

Before I give you all the answers

it's your turn

…to figure out a way to route traffic in a network

instructions given in class

Essentially,
there are **three ways to compute** valid routing state

	Intuition	Example
#1	Use tree-like topologies	Spanning-tree
#2	Rely on a global network view	Link-State SDN
#3	Rely on distributed computation	Distance-Vector BGP

Essentially,
there are three ways to compute valid routing state

#1	Use tree-like topologies	Spanning-tree
	Rely on a global network view	Link-State SDN
	Rely on distributed computation	Distance-Vector BGP

The easiest way to **avoid loops** is to
use a topology where loops are impossible

simple algorithm

Take an arbitrary topology

Build a spanning tree and
ignore all other links

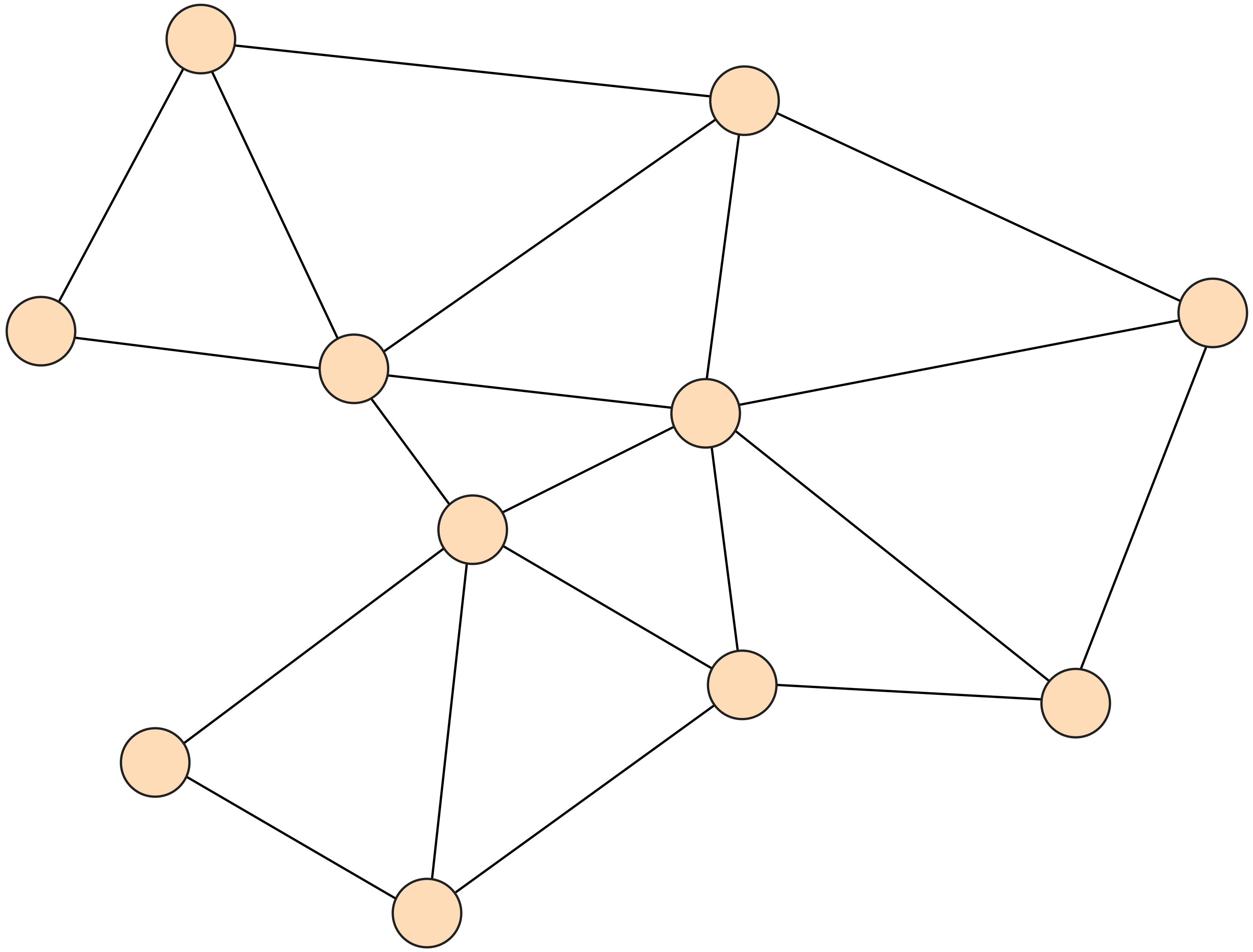
Done!

Why does it work?

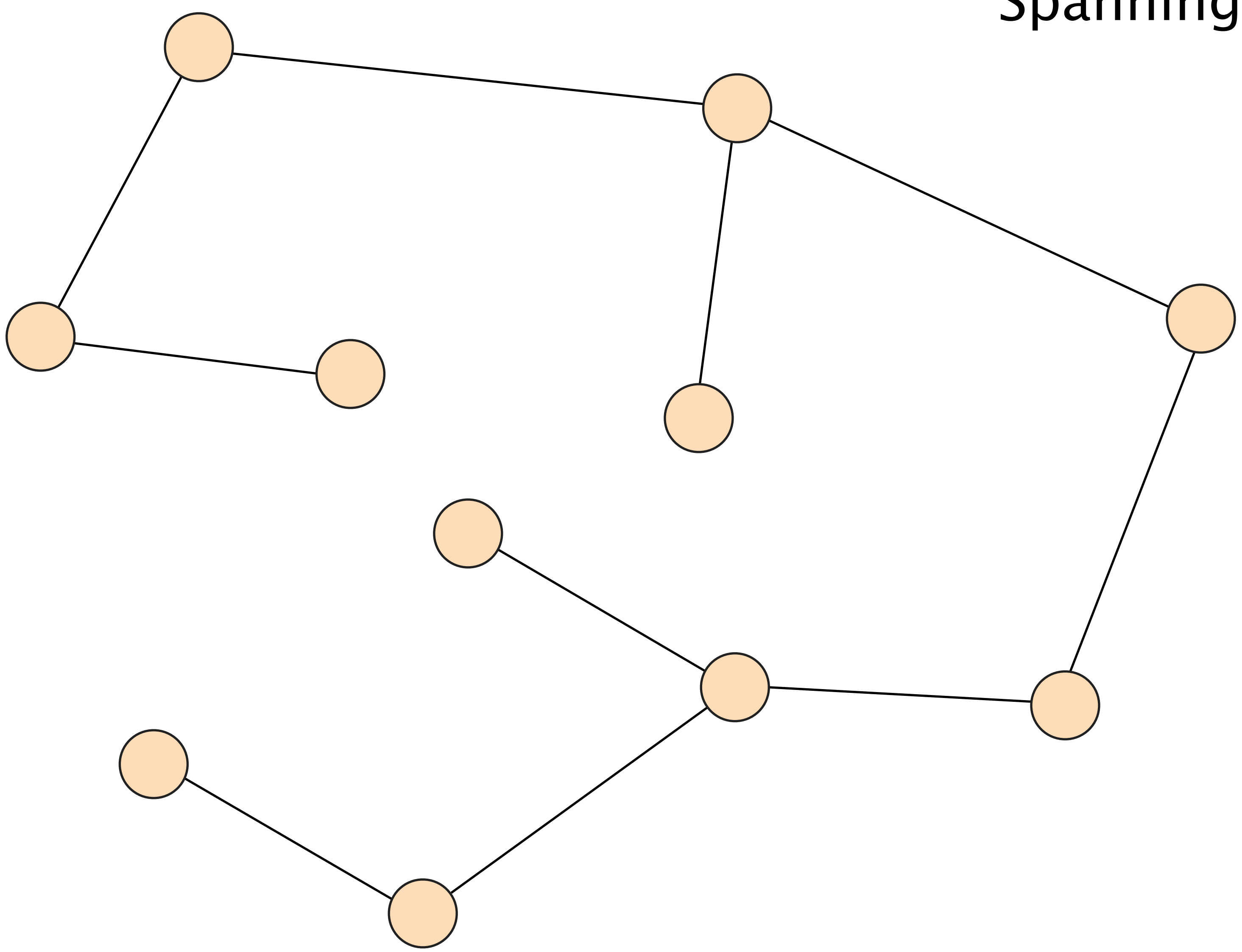
Spanning-trees have only one path
between any two nodes

In practice,

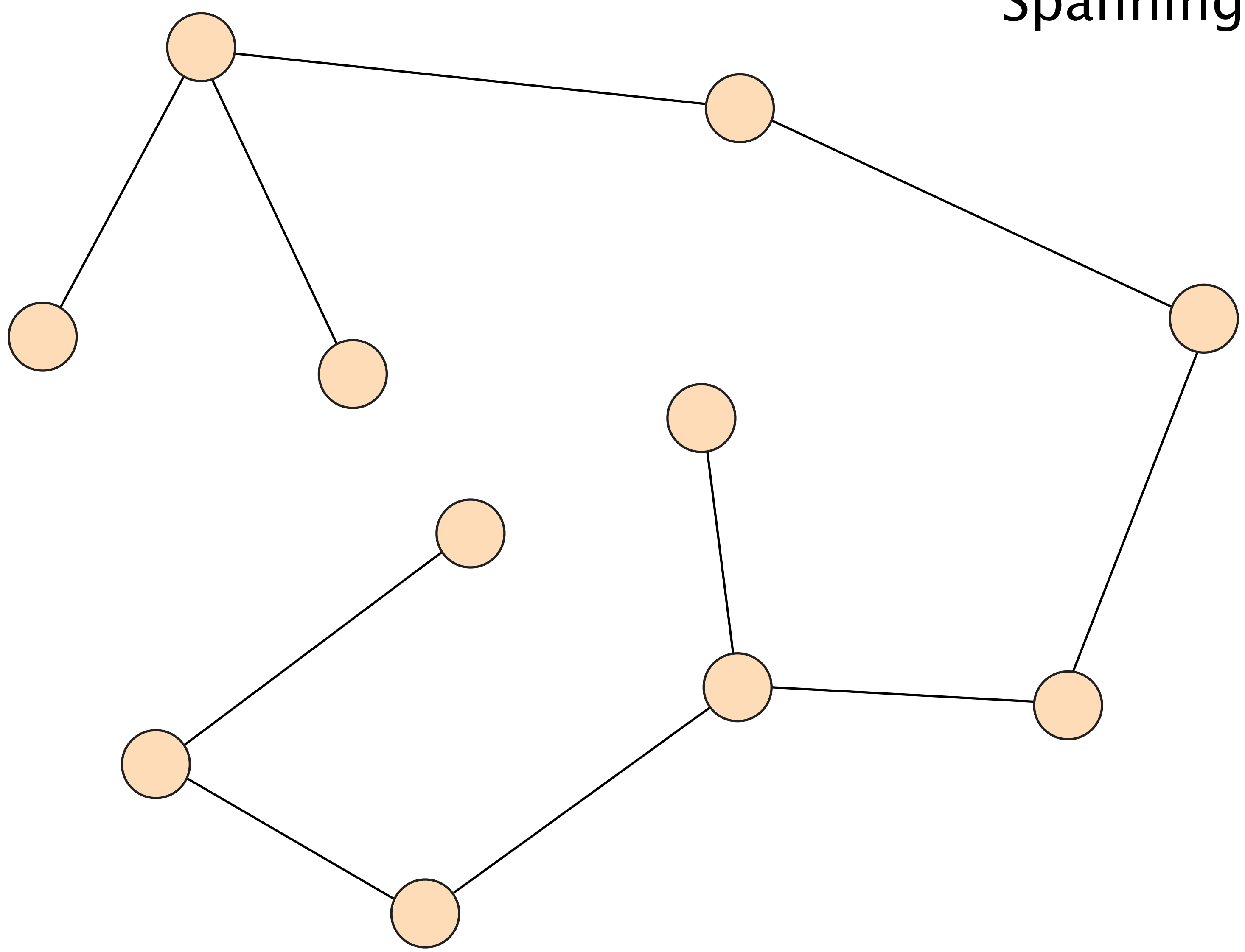
there can be *many* spanning-trees for a given topology



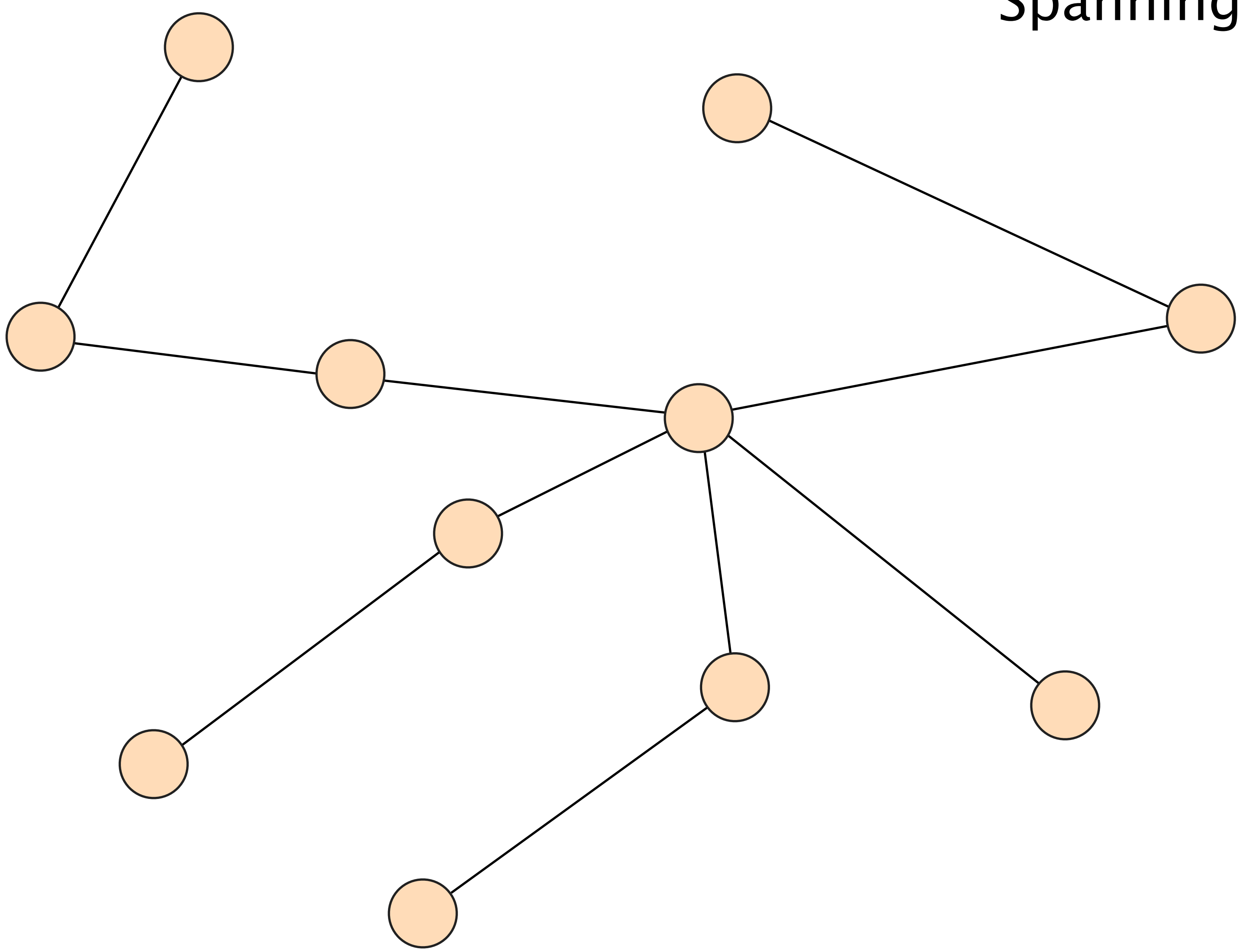
Spanning-Tree #1



Spanning-Tree #2



Spanning-Tree #3



We’ll see how to compute a spanning-tree in two weeks. For now, assume it is possible

Once we have a spanning tree,

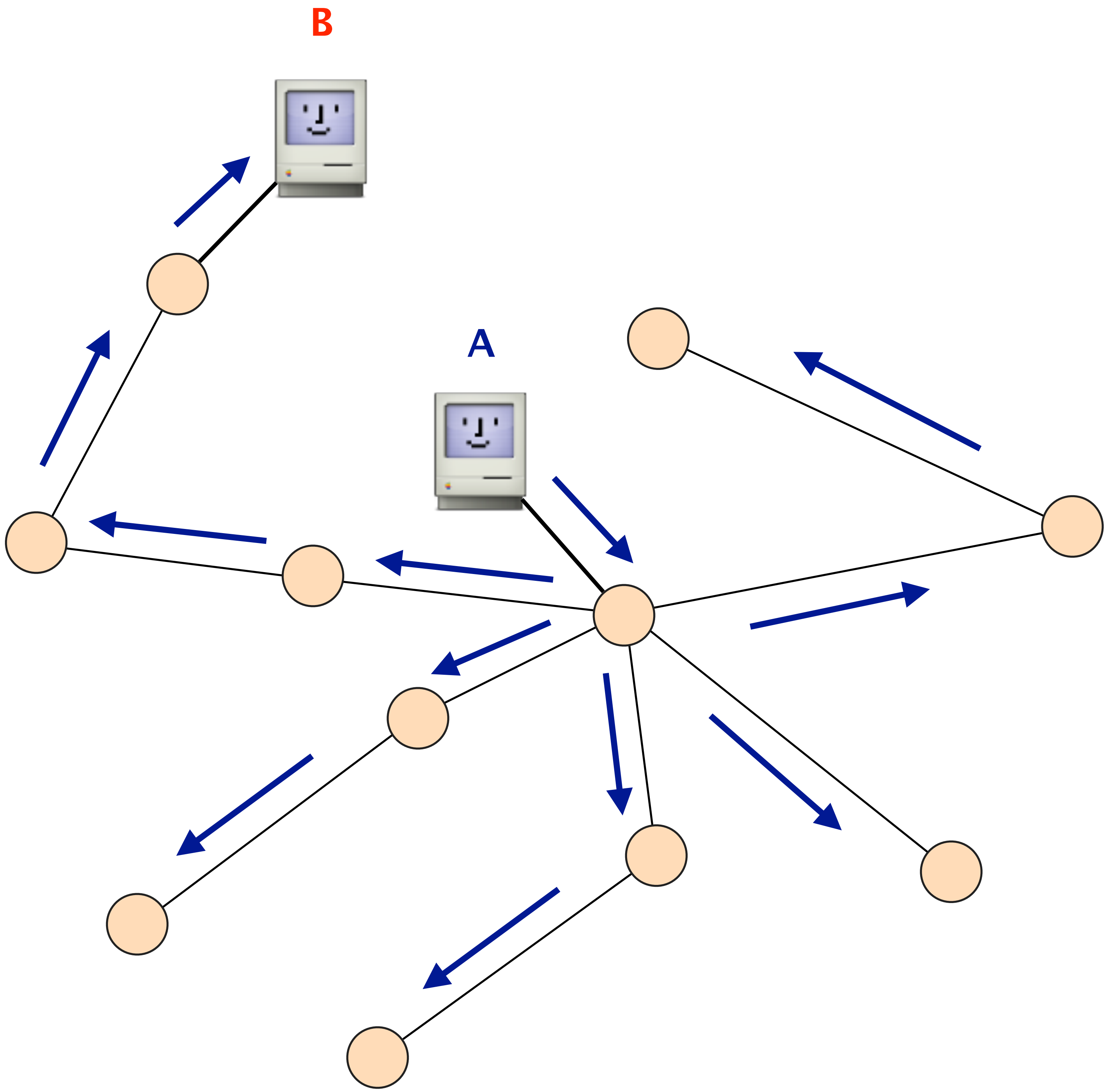
forwarding on it is easy

literally just flood

the packets everywhere

When a packet arrives,

simply **send it on all ports**



While flooding works,

it is quite wasteful

Luckily, nodes can learn how to reach nodes by remembering where packets came from

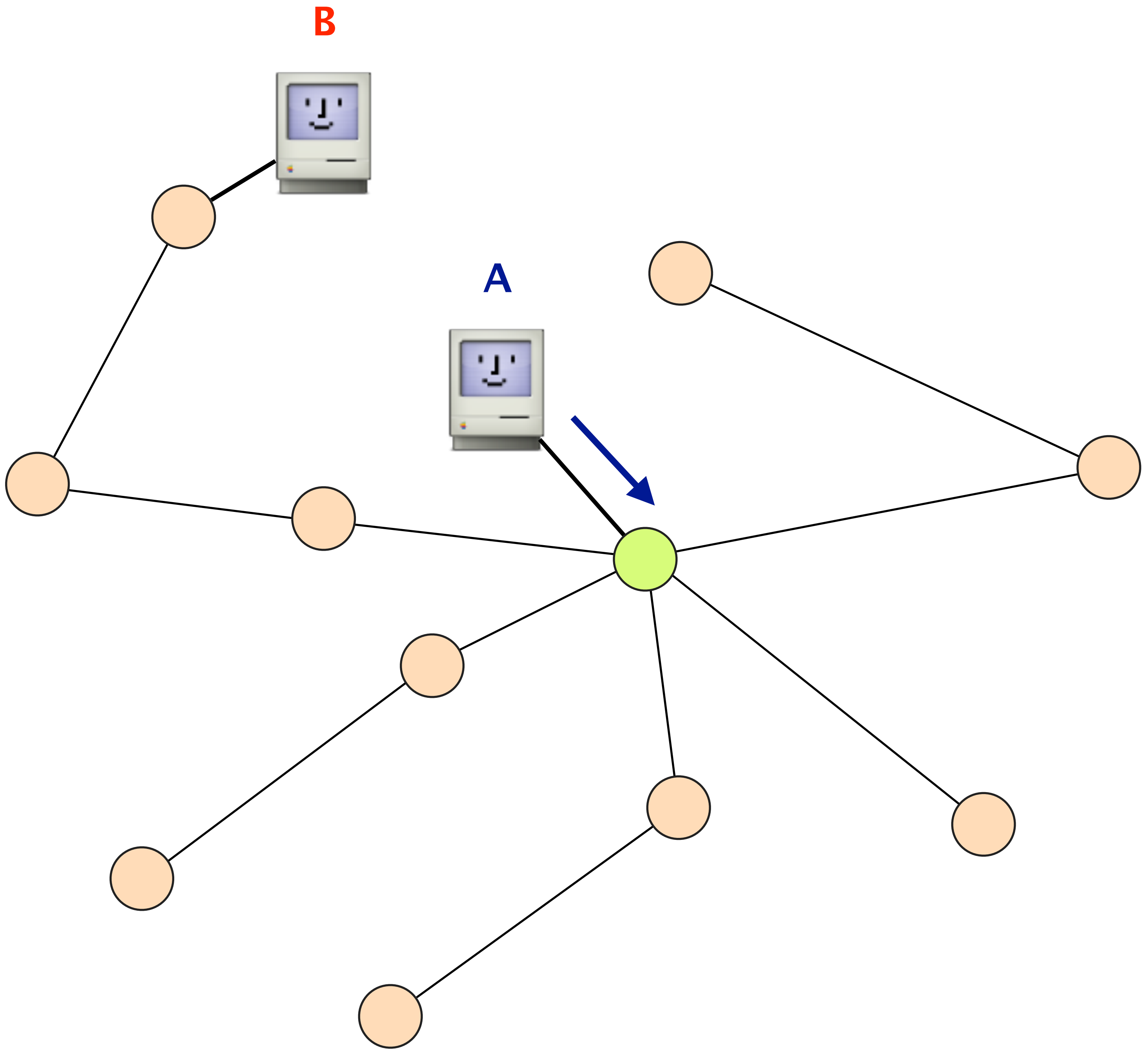
intuition

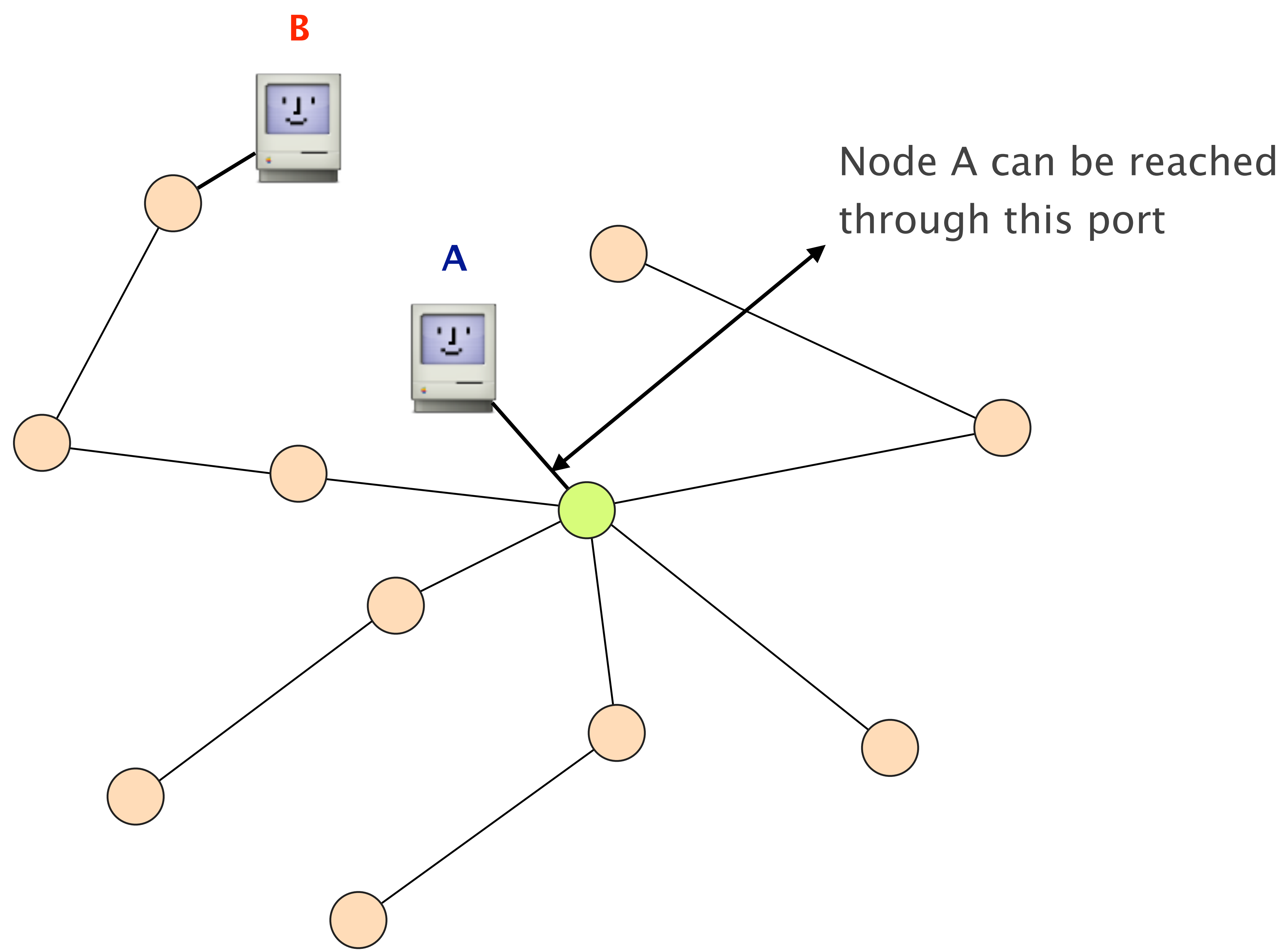
if

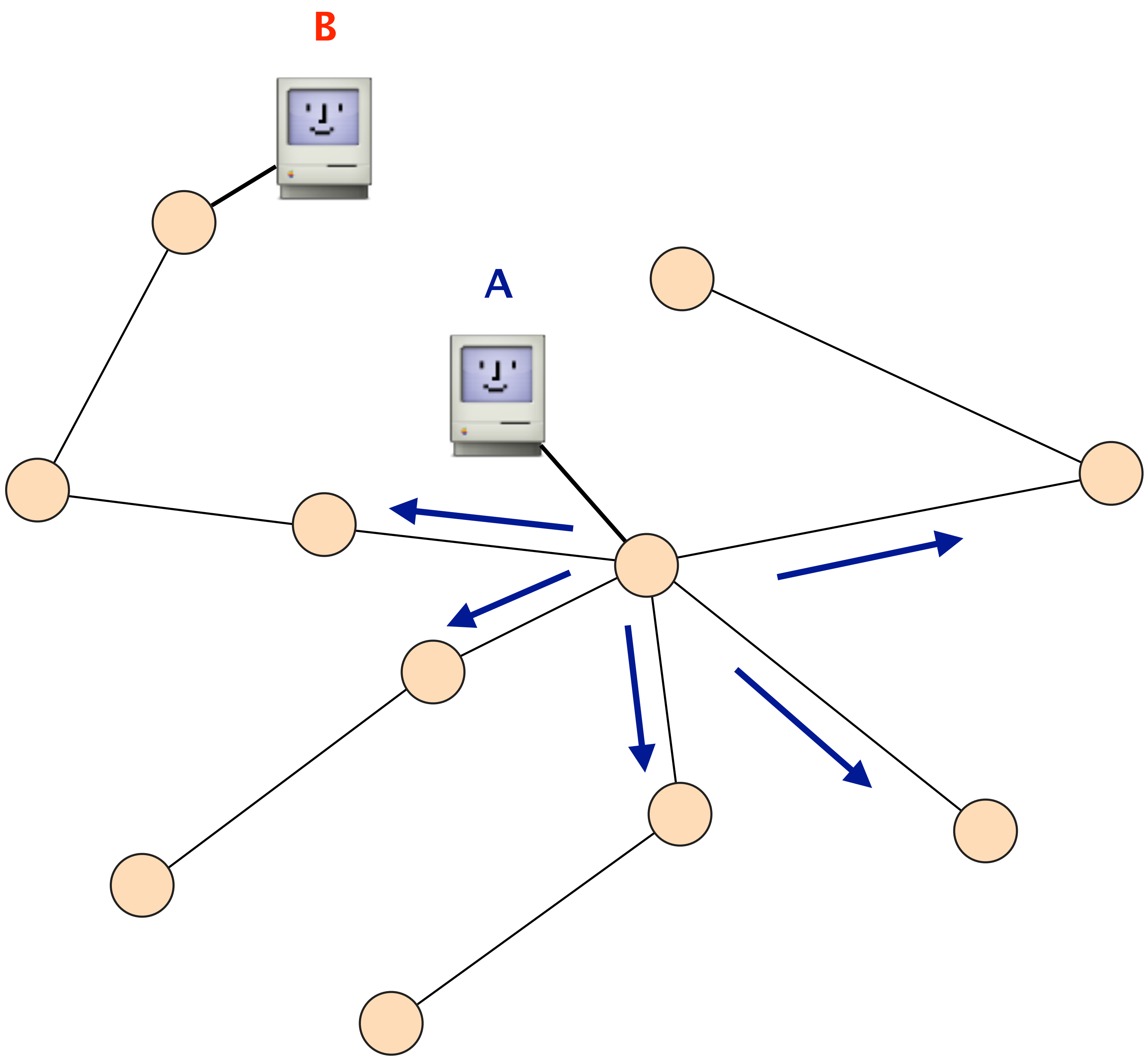
flood packet from node *A*
entered switch *X* on port *4*

then

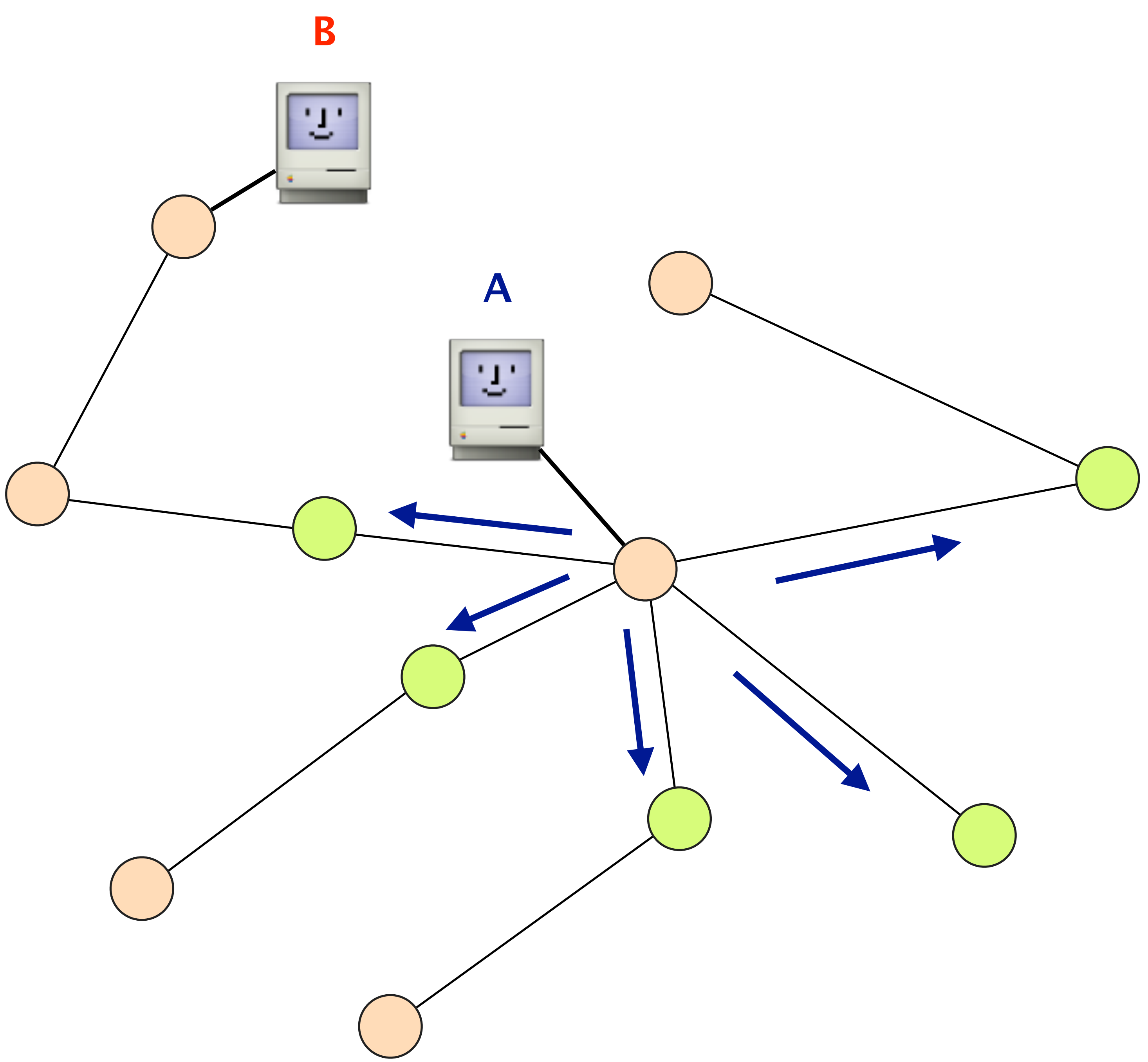
switch *X* can use port *4*
to reach node *A*


B
A

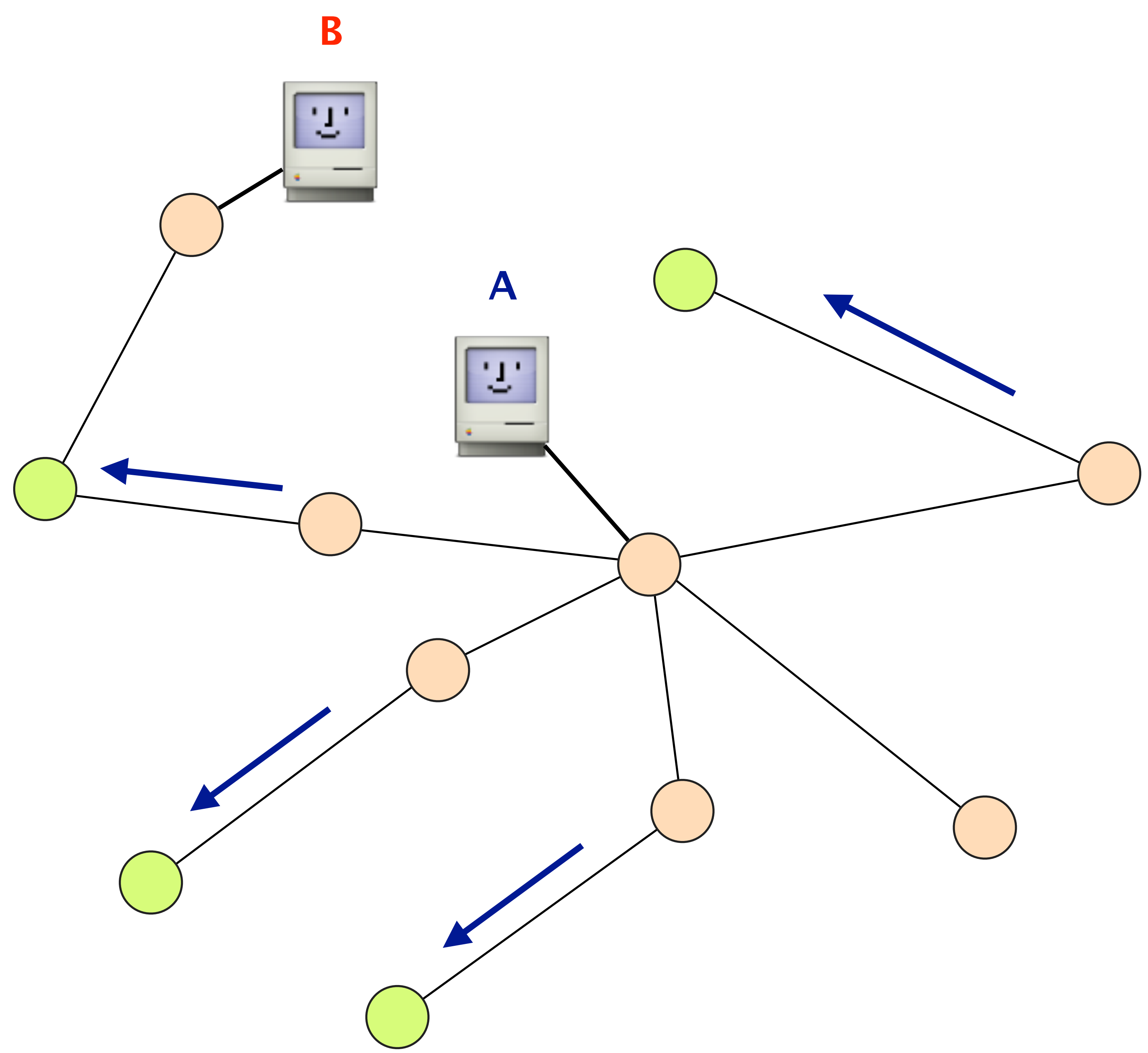

B
A
Node A can be reached
through this port


B
A

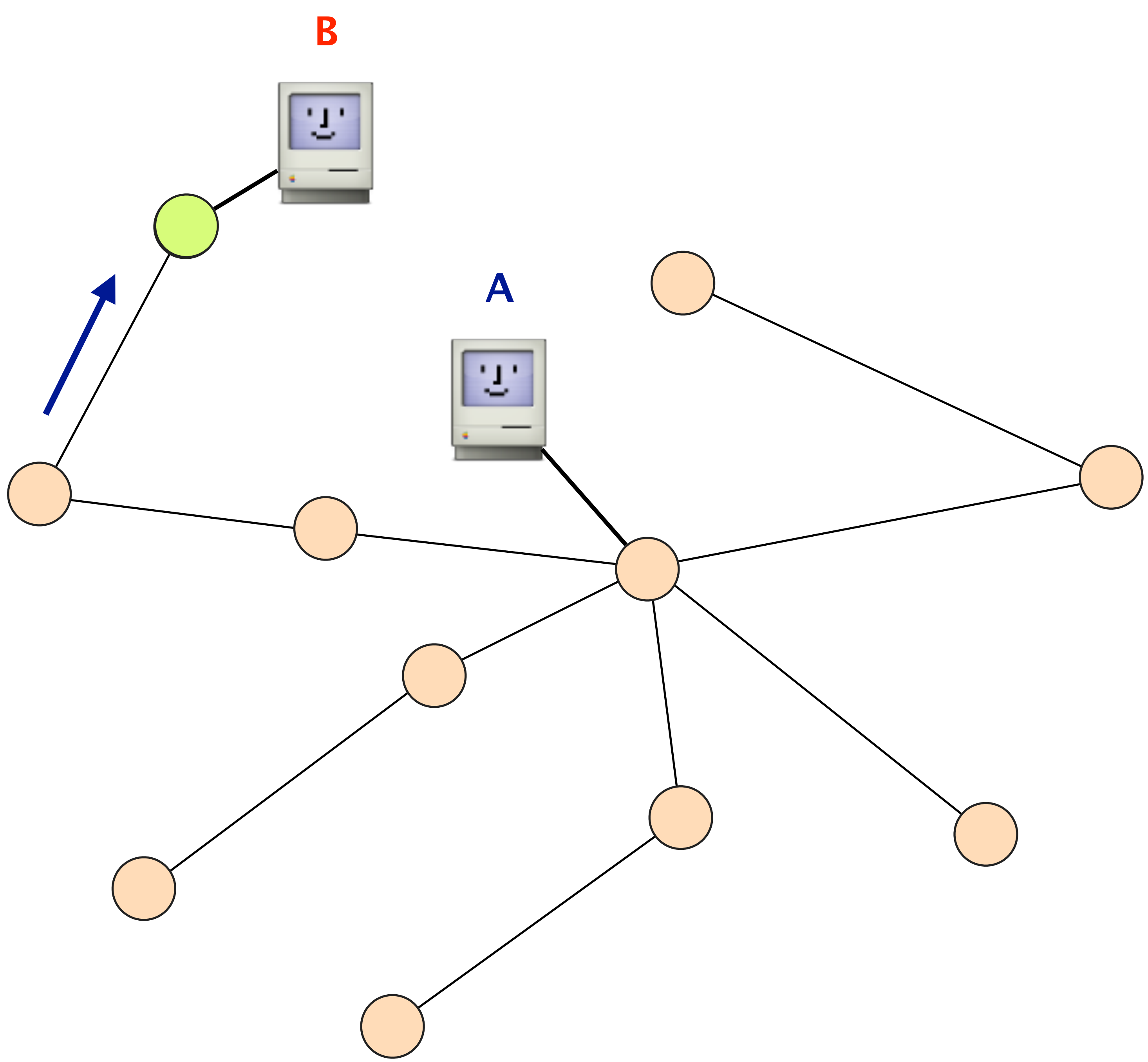
All the green nodes learn how to reach A



All the green nodes learn how to reach A

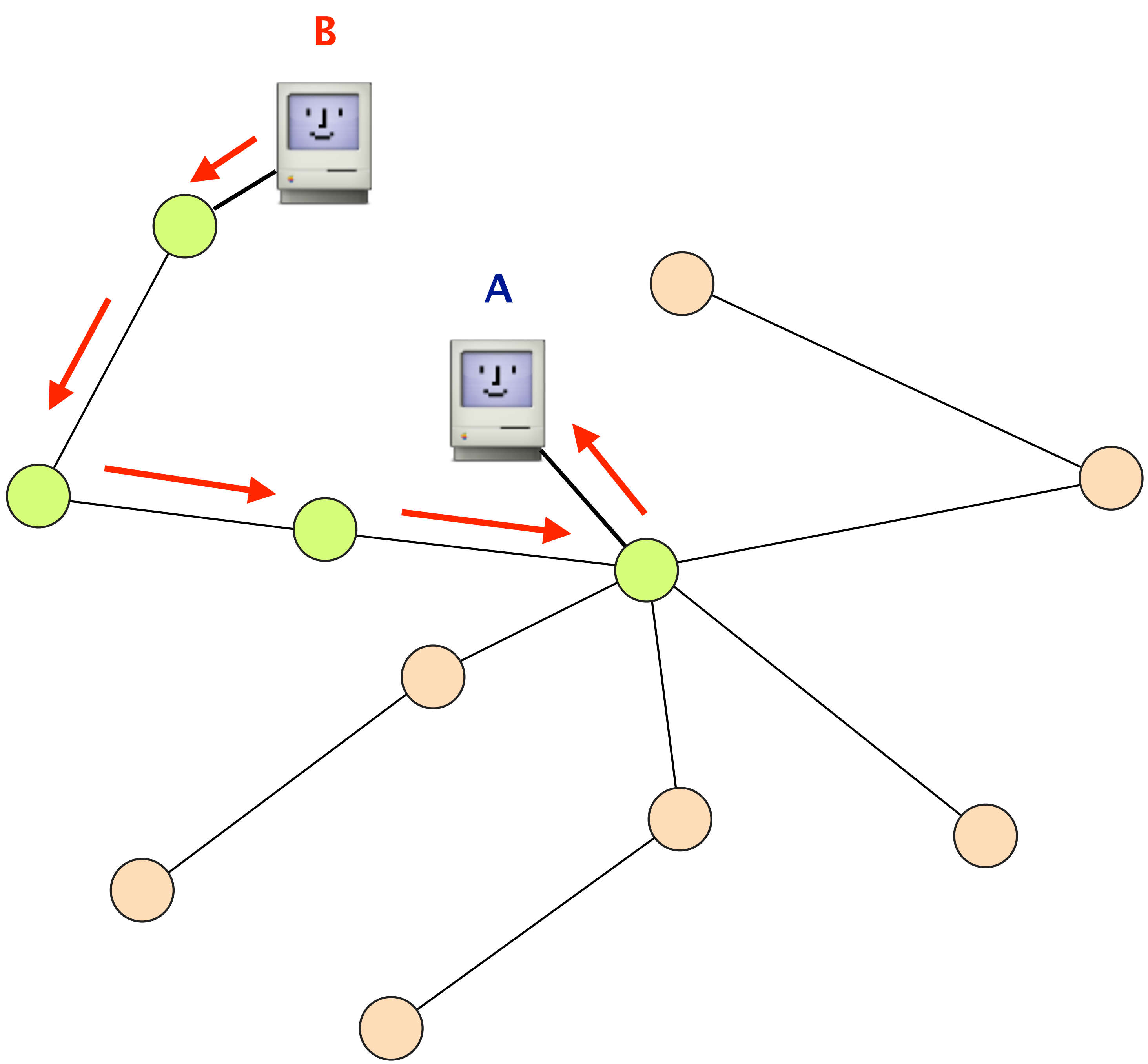


All the nodes in the network know on which port A can be reached

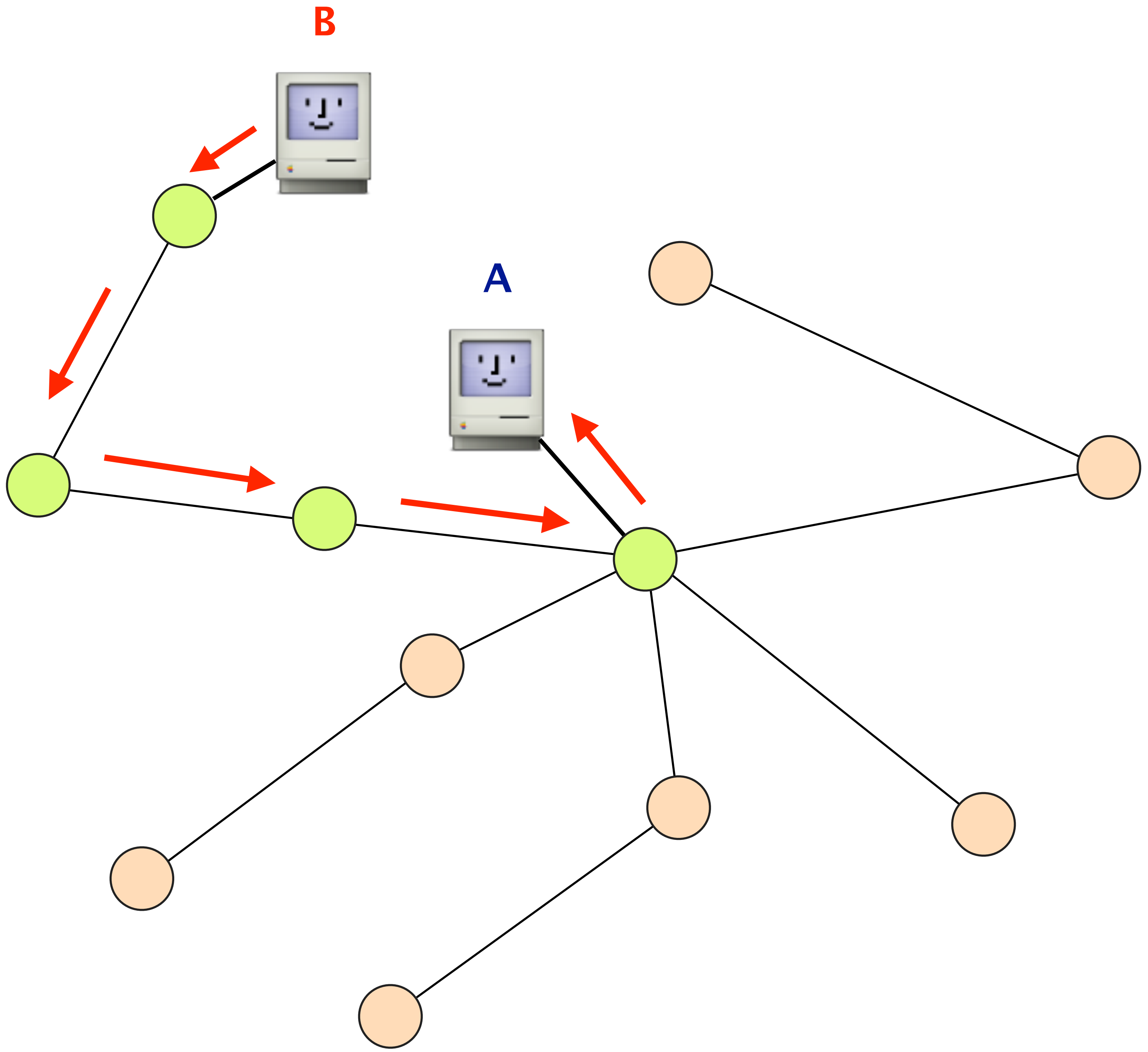


Now B answers back to A

enabling the green nodes to also learn where B is



There is no need for flooding here
as the position of A is already known by everybody



Routing by flooding on a spanning-tree

in a nutshell

Flood first packet to node you're trying to reach

all switches learn where you are

When destination answers, some switches learn where it is

some because packet to you is not flooded anymore

The decision to flood or not is done on each switch

depending on who has communicated before

Spanning-Tree in practice

used in Ethernet

advantages	disadvantages
plug-and-play	mandate a spanning-tree
configuration-free	eliminate many links from the topology
automatically adapts to moving host	slow to react to failures
	host movement

In practice, operators tend to dislike Spanning-Tree…

Essentially,
there are three ways to compute valid routing state

	Use tree-like topologies	Spanning-tree
#2	Rely on a global network view	Link-State SDN
	Rely on distributed computation	Distance-Vector BGP

If each router knows the entire graph,
then it is easy to find paths to any given destination

Once a node u knows the entire topology,
it can compute shortest-paths using **Dijkstra's algorithm**

Initialization

S = {u}

for all nodes v:

if (v is adjacent to u):

D(v) = c(u,v)

else:

D(v) = ∞

Loop

while *not* all nodes in S:

add w with the smallest D(w) to S

update D(v) for all adjacent v not in S:

D(v) = min{D(v), D(w) + c(w,v)}

u is the node running the algorithm

$S = \{u\}$

for all nodes v:

    if (v is adjacent to u):

        $D(v) = c(u,v)$

    else:

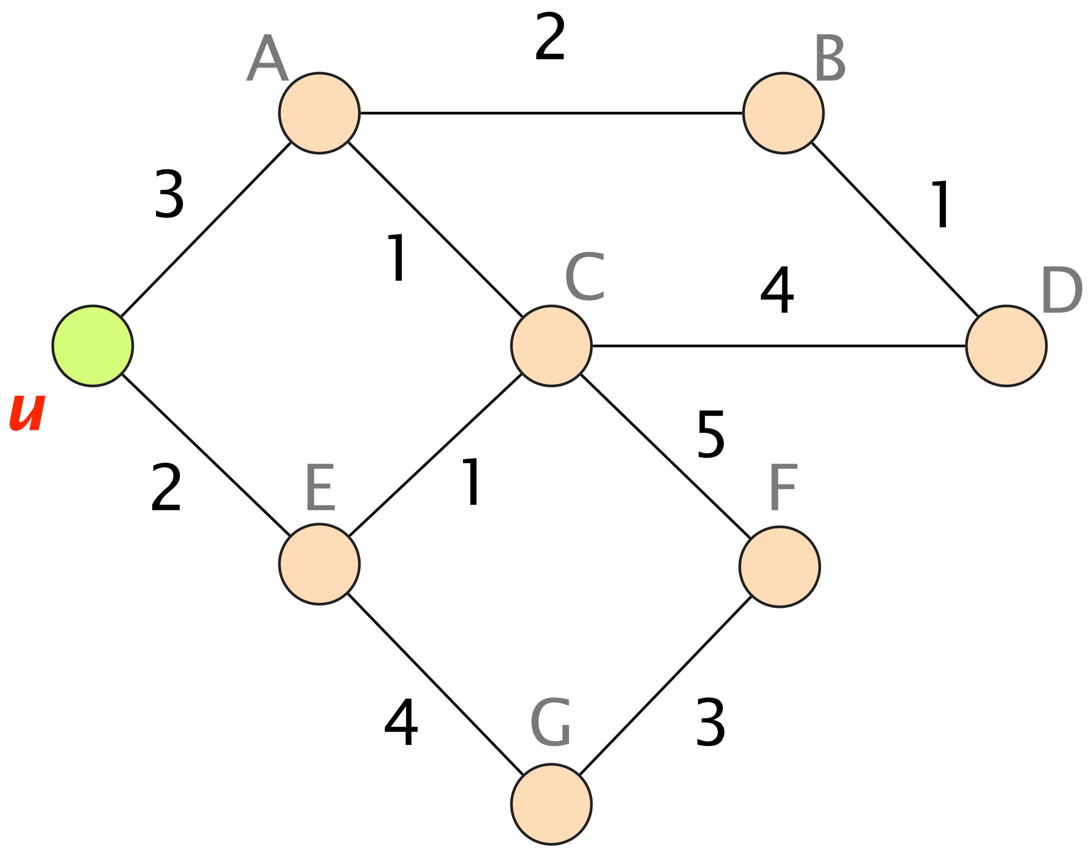
        $D(v) = \infty$

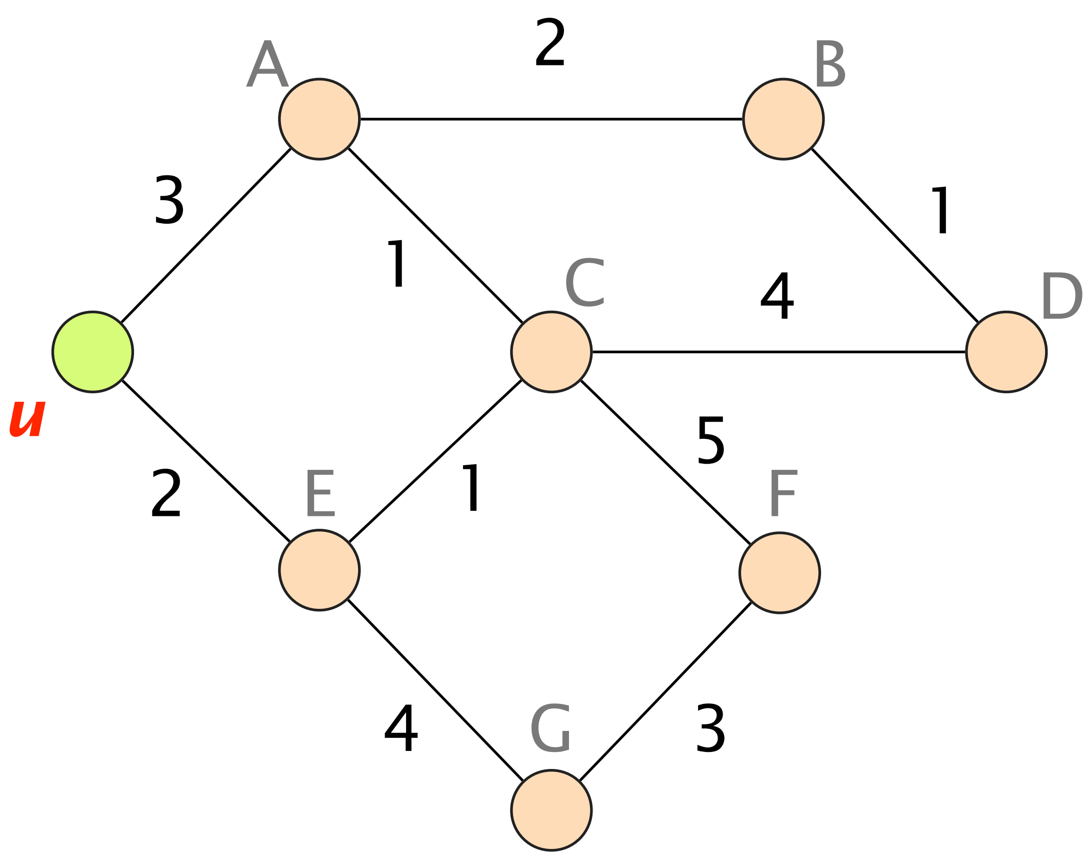
$c(u,v)$ is the weight of the link connecting u and v

$D(v)$ is the smallest distance currently known by u to reach v

Let's compute the shortest-paths

from *u*





Initialization

S = {*u*}

for all nodes *v*:

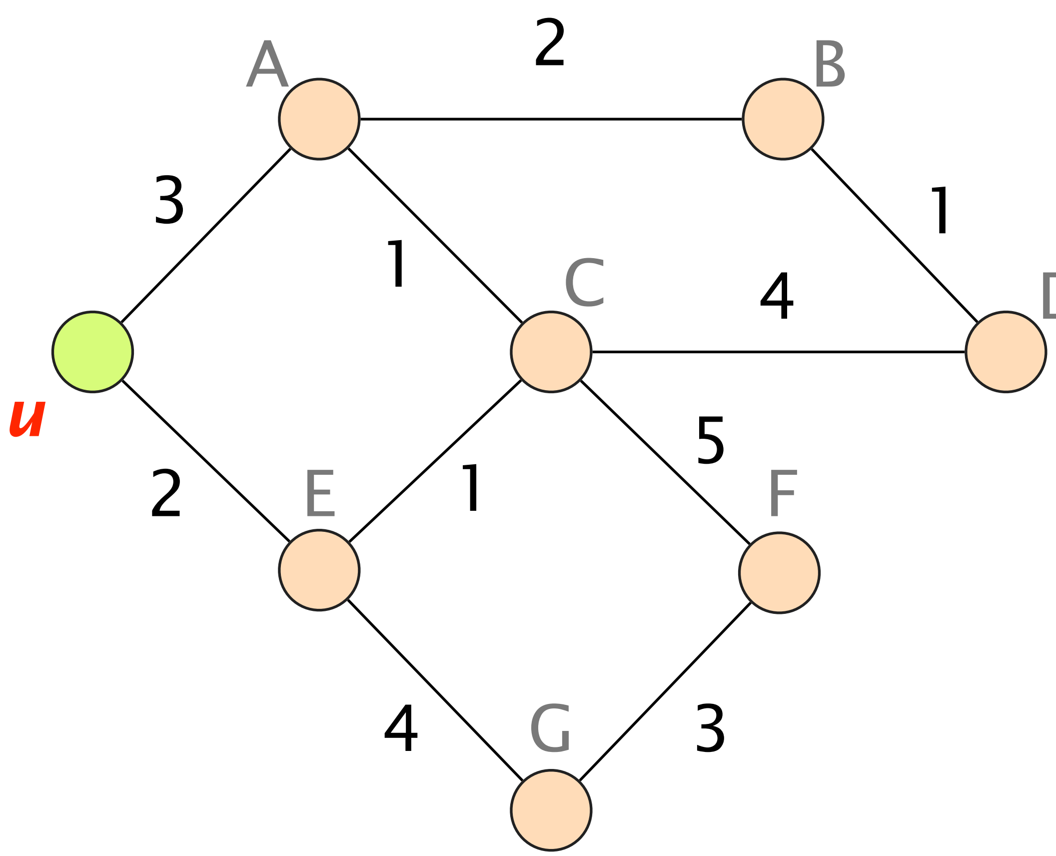
if (*v* is adjacent to *u*):

D(*v*) = c(*u*,*v*)

else:

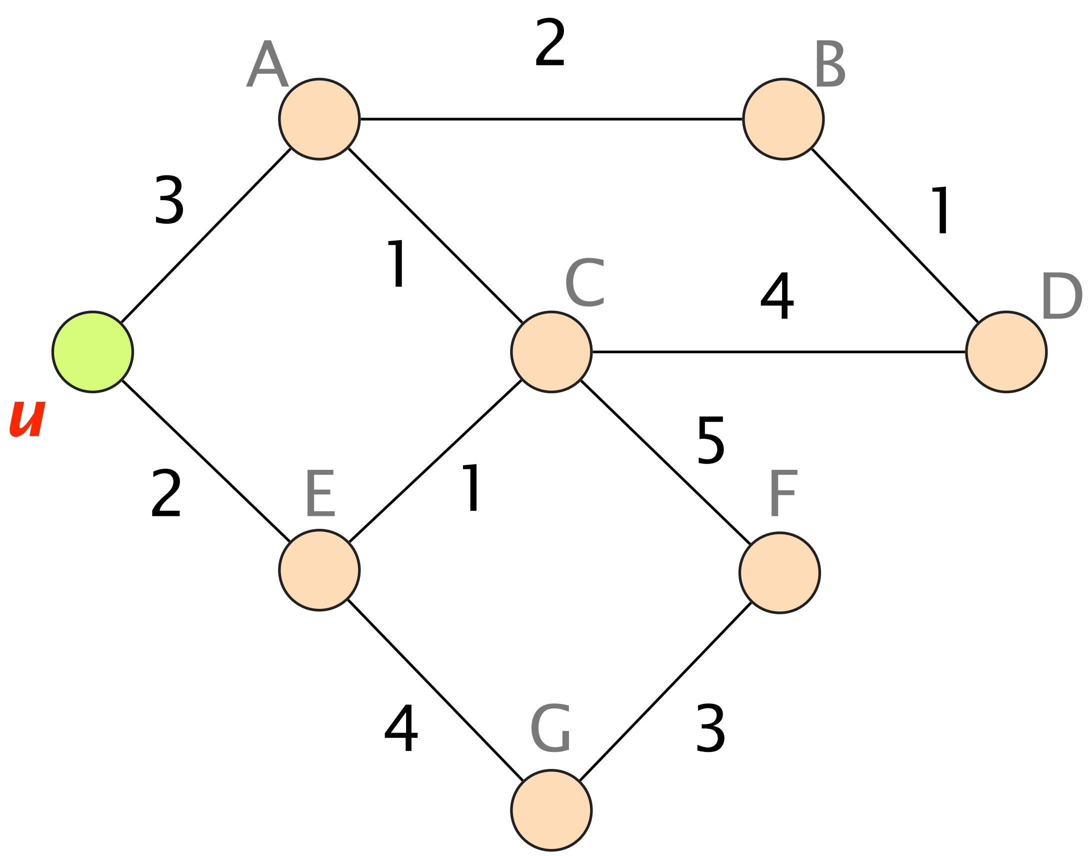
D(*v*) = ∞

D is initialized based on u's weight,
and S only contains u itself



D(.) = S = {u}

A	3
B	∞
C	∞
D	∞
E	2
F	∞
G	∞



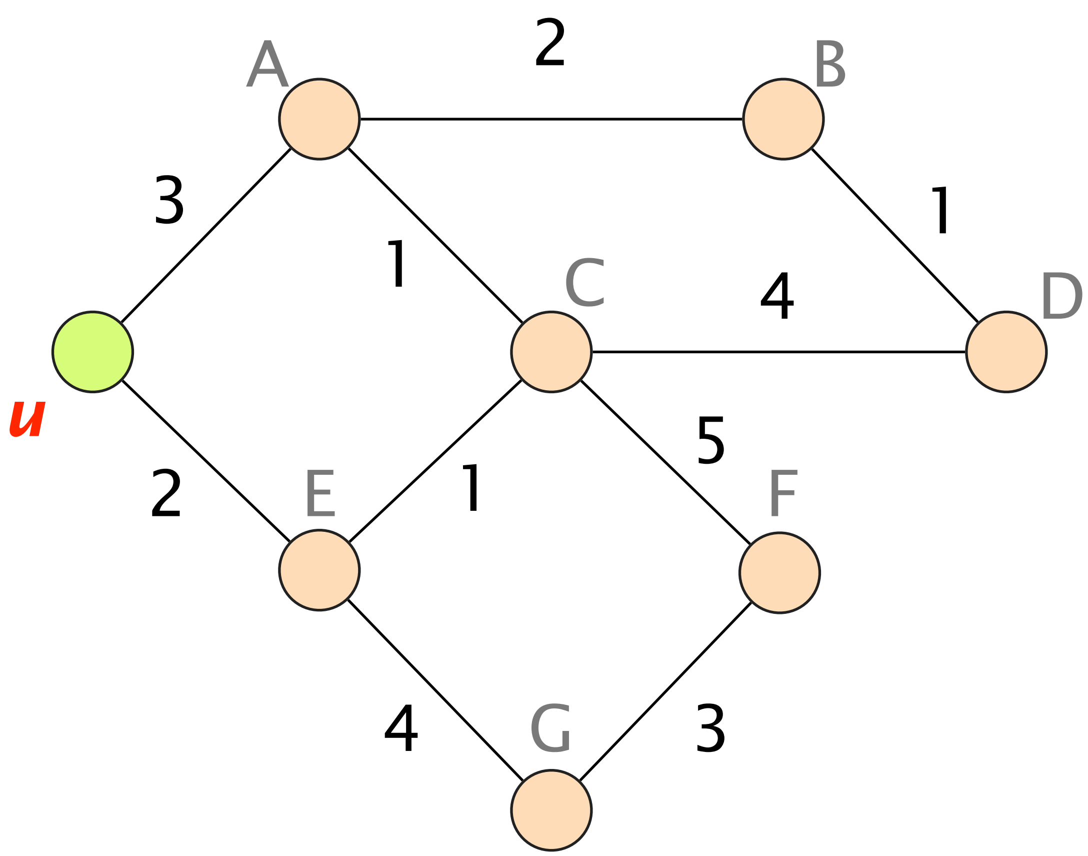
Loop

while *not* all nodes in S:

add *w* with the smallest D(w) to S

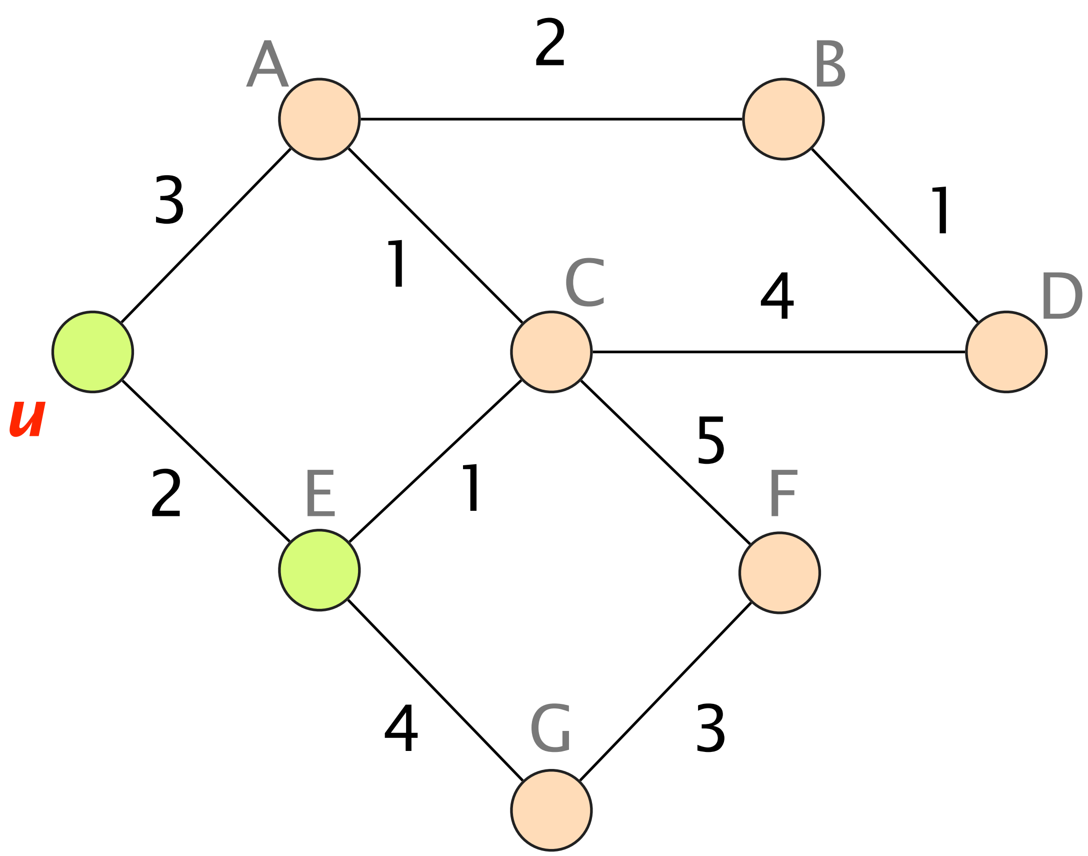
update D(*v*) for all adjacent *v* not in S:

$D(v) = \min\{D(v), D(w) + c(w,v)\}$



$D(.) =$ $S = \{u\}$

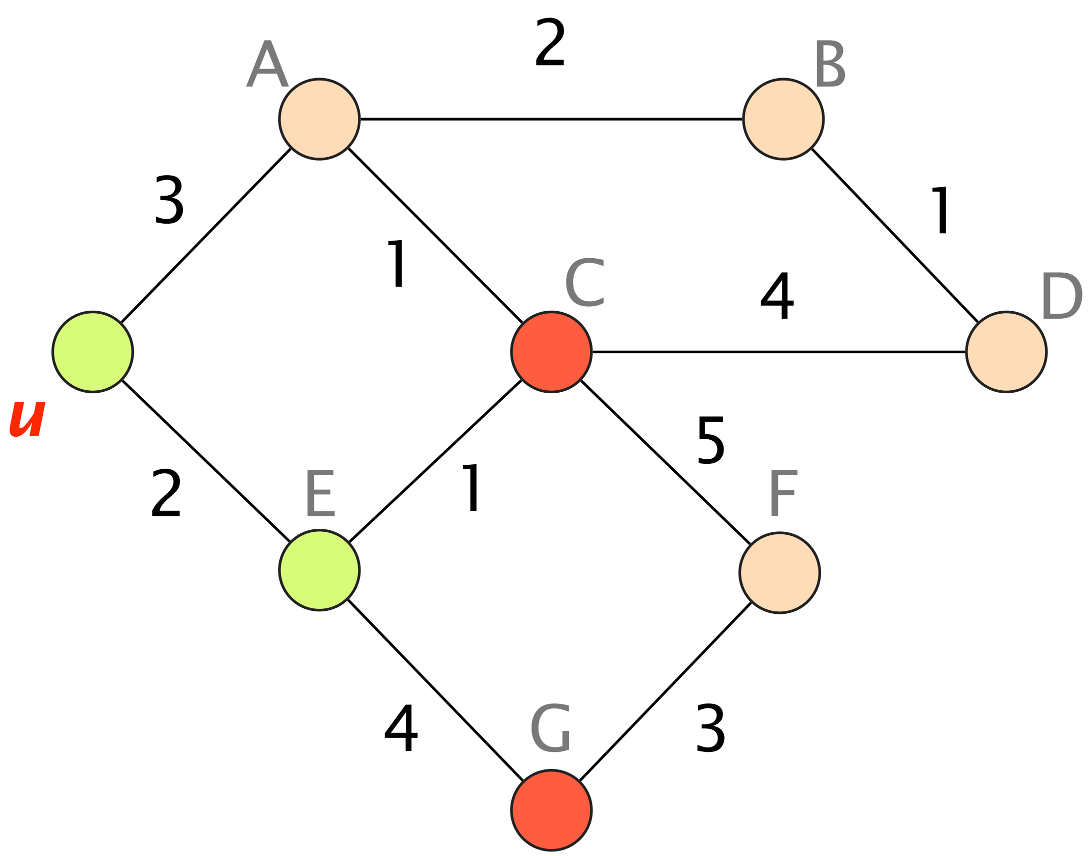
A	3
B	∞
C	∞
D	∞
E	$\boxed{2}$ smallest $D(w)$
F	∞
G	∞



add E to S

D(.) = S = {u, E}

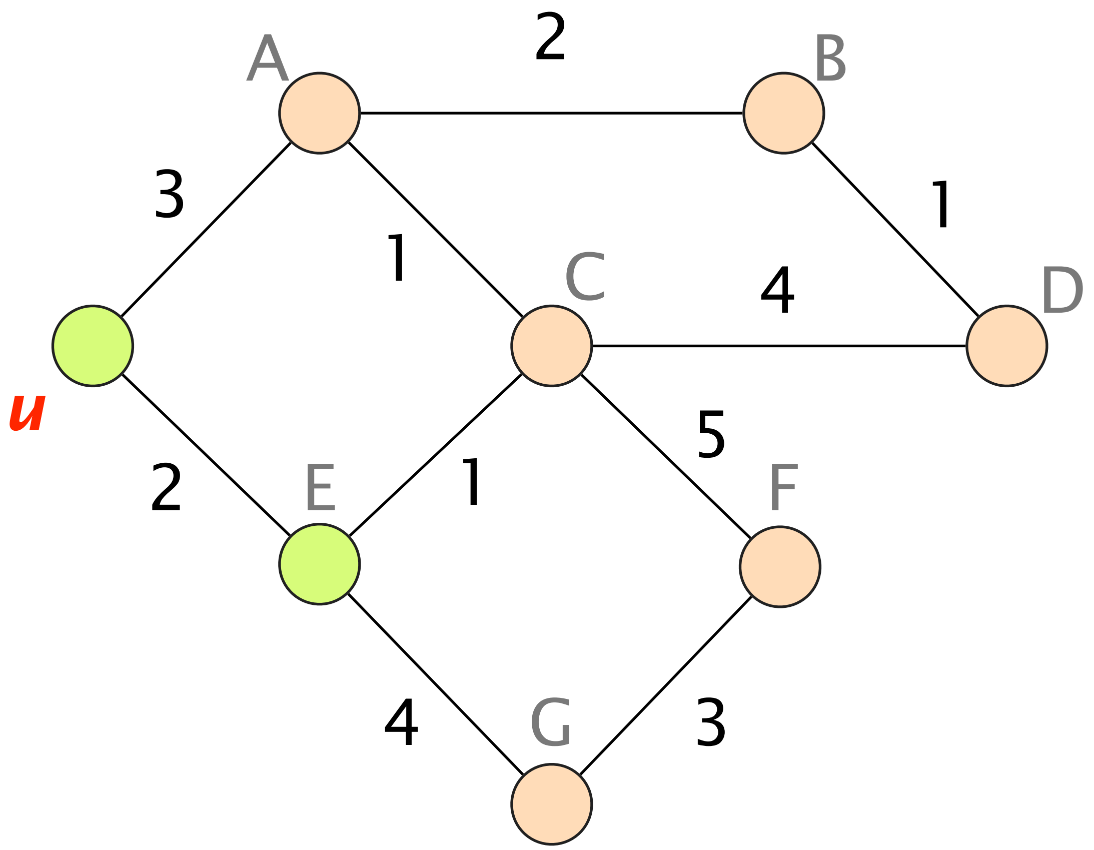
A	3
B	∞
C	∞
D	∞
E	2
F	∞
G	∞



D(.) =   S = {u, E}

A	3	
B	∞	
C	3	$D(v) = \min\{\infty, 2 + 1\}$
D	∞	
E	2	
F	∞	
G	6	$D(v) = \min\{\infty, 2 + 4\}$

Now, do it by yourself

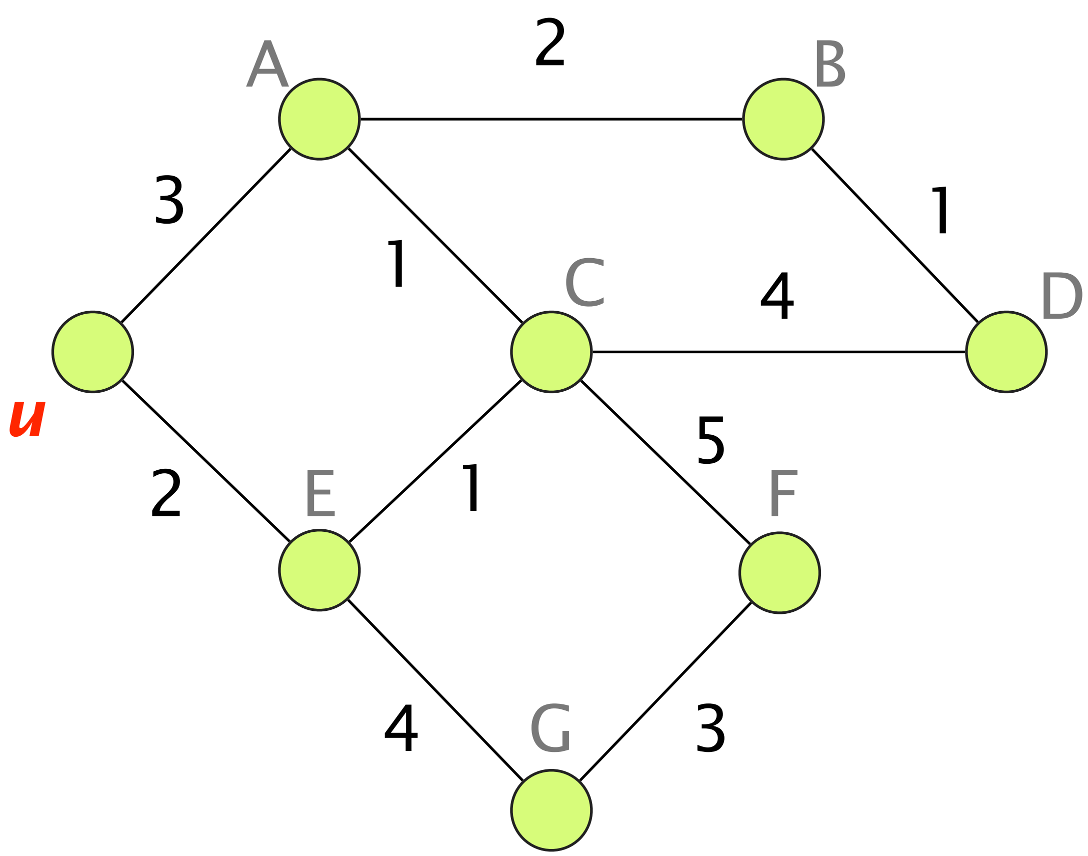


D(.) =

S = {u, E}

A	3
B	∞
C	3
D	∞
E	2
F	∞
G	6

Here is the final state



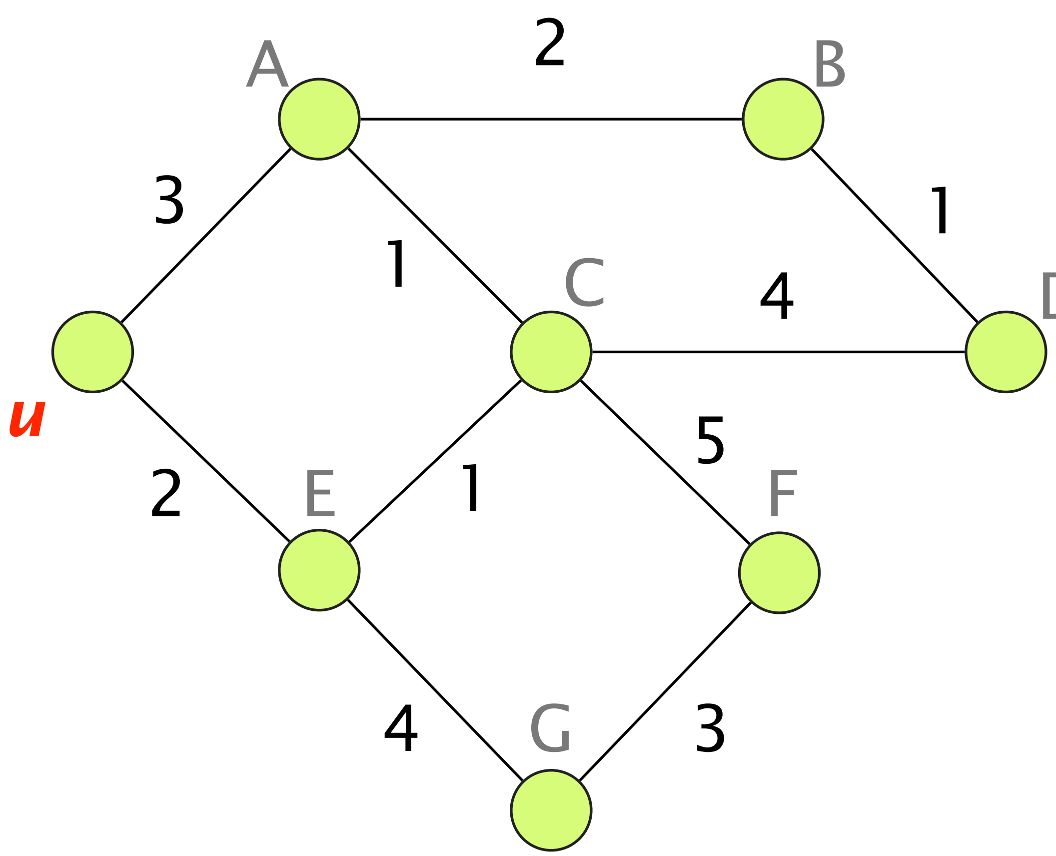
D(.) =

A	3
B	5
C	3
D	6
E	2
F	8
G	6

S = {u, A, B, C, D, E, F,G}

From the shortest-paths,

u can directly compute its forwarding table



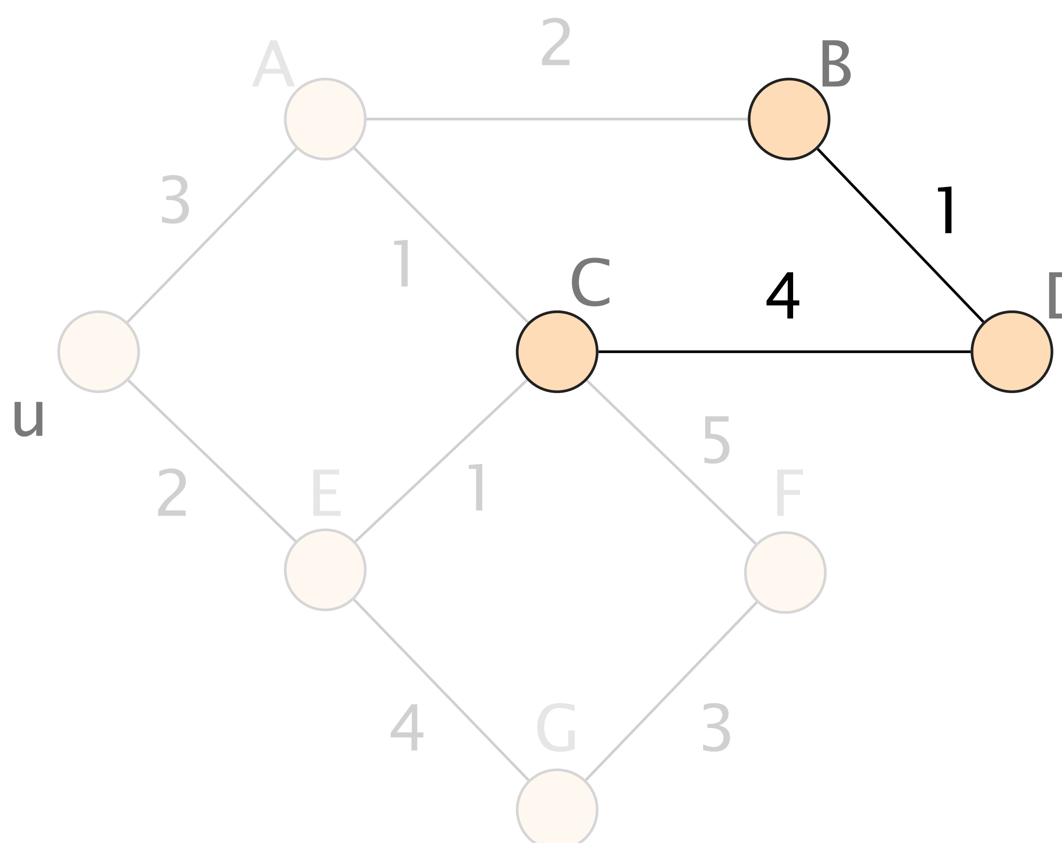
Forwarding table

destination	*next-hop*
A	A
B	A
C	E
D	A
E	E
F	E
G	E

To build this global view

routers essentially solve a jigsaw puzzle

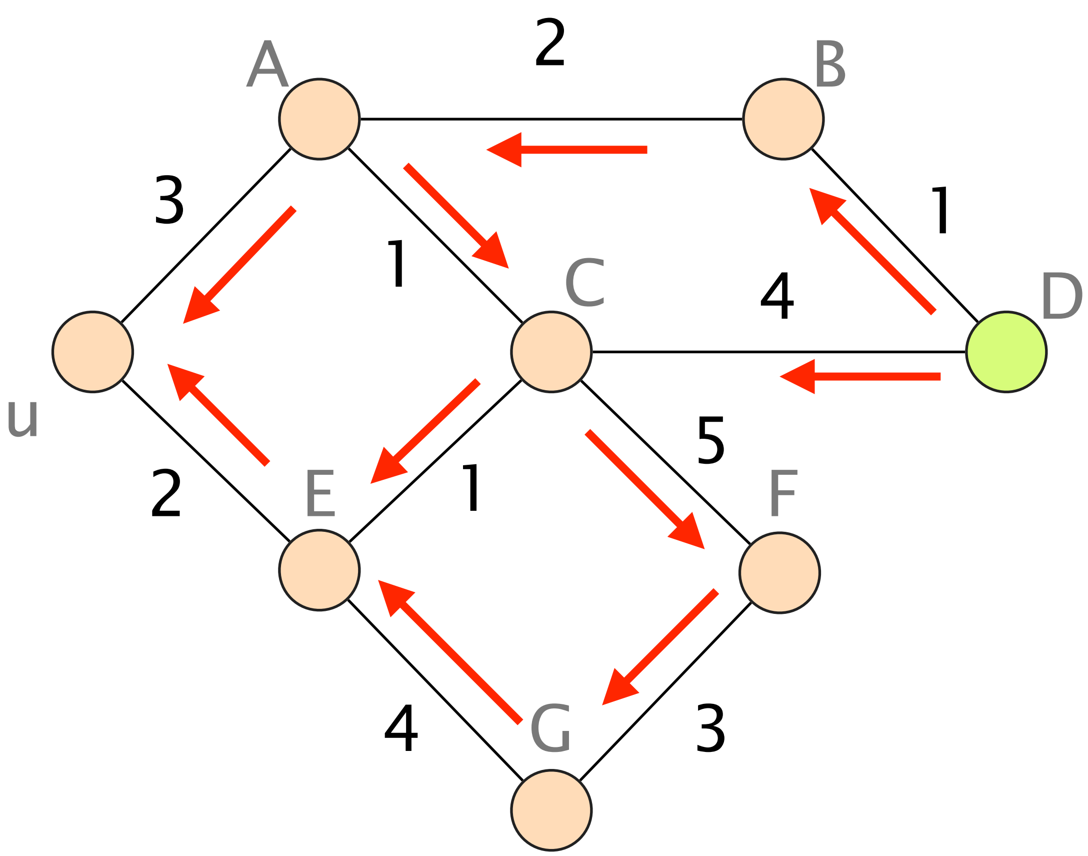
Initially,
routers only know their ID and their neighbors



D only knows,
it is connected to B and C

along with the weights to reach them
(by configuration)

Each routers builds a message (known as Link-State) and floods it (reliably) in the entire network

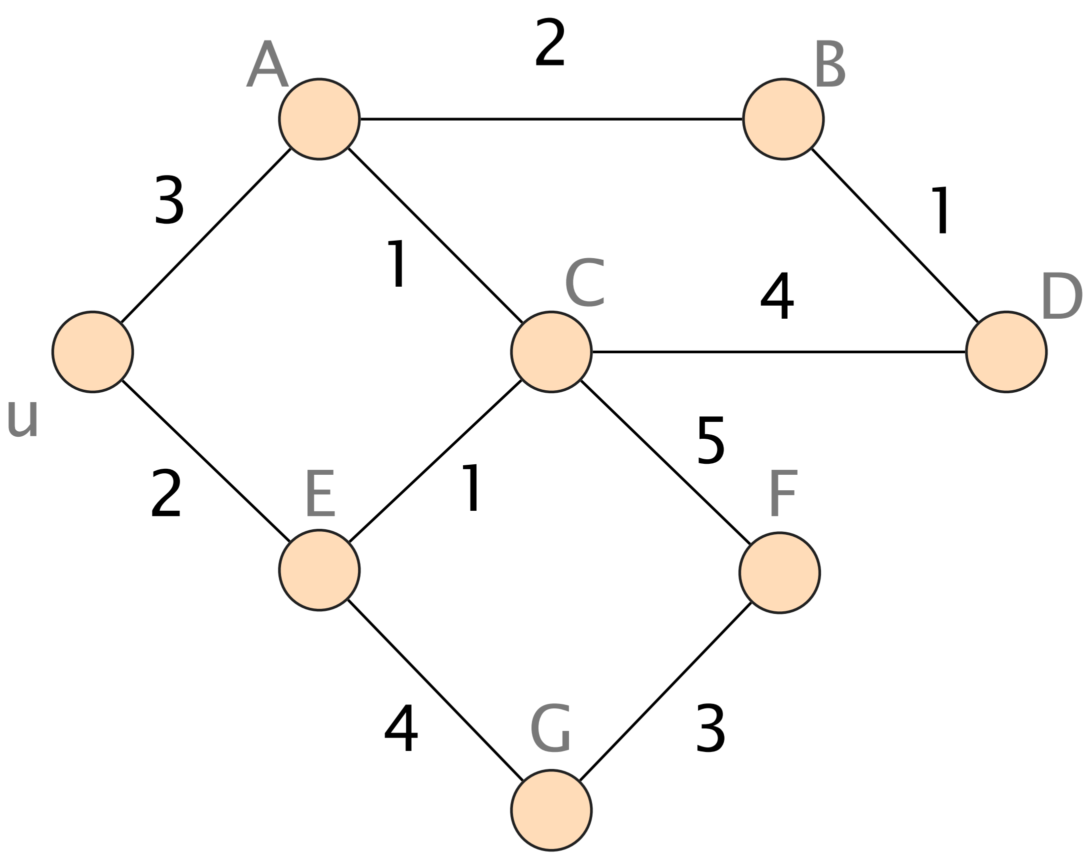


D's Advertisement

edge (D,B); cost: 1
edge (D,C); cost: 4

At the end of the flooding process,
everybody share the exact same view of the network

required for correctness
see exercise



We’ll see in few weeks how OSPF implements all this in real networks (and is used within ETH’s)

Essentially,
there are three ways to compute valid routing state

	Use tree-like topologies	Spanning-tree
	Rely on a global network view	Link-State SDN
#3	Rely on distributed computation	Distance-Vector BGP

Instead of locally compute paths based on the graph, paths can be computed in a distributed fashion

Let $d_x(y)$ be the cost of the least-cost path known by x to reach y

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known by x to reach y

until convergence

Each node bundles these distances
into one message (called a vector)
that it repeatedly sends to all its neighbors

Let $d_x(y)$ be the cost of the least-cost path known by x to reach y

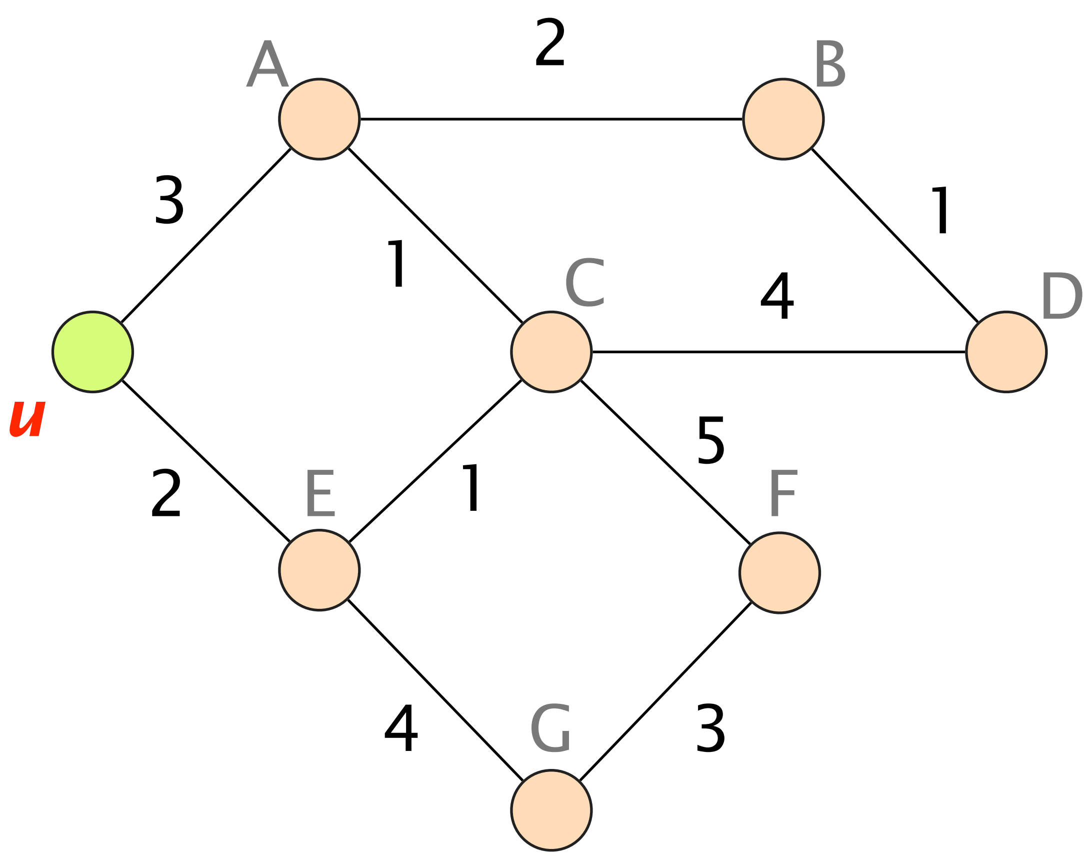
Each node bundles these distances into one message (called a vector) that it repeatedly sends to all its neighbors

until convergence

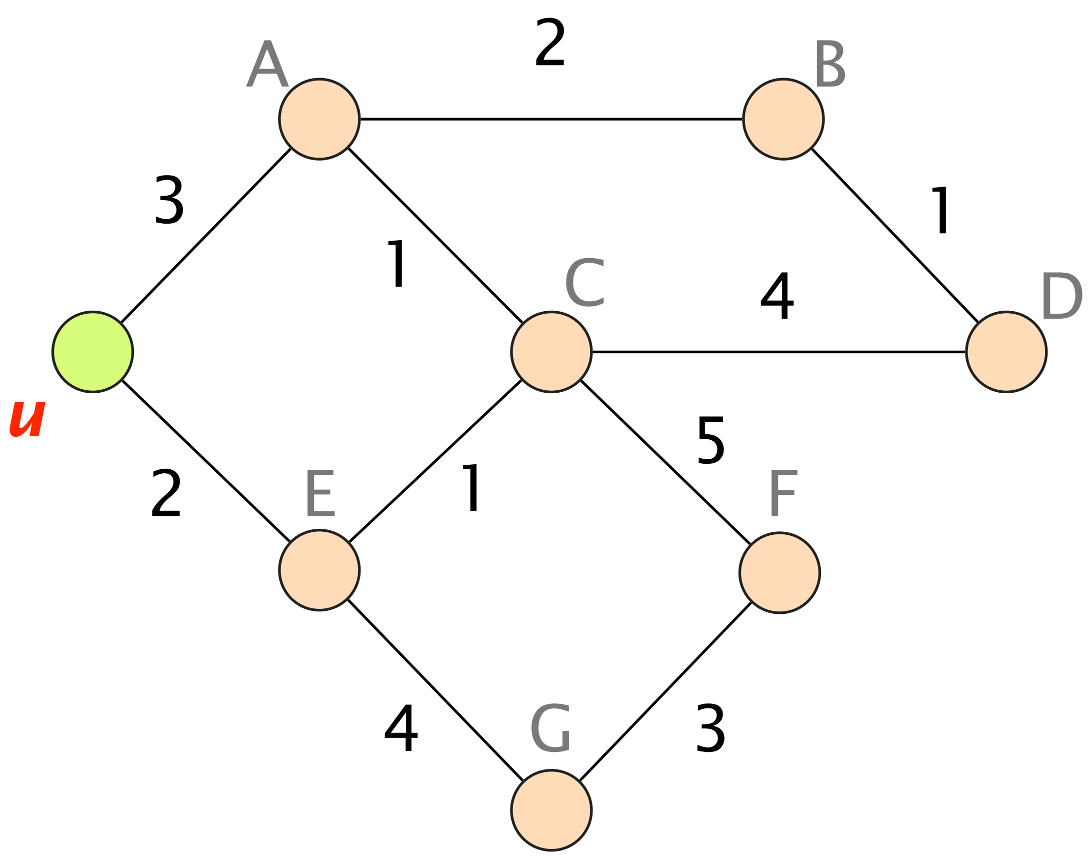
Each node updates its distances based on neighbors' vectors:

$d_x(y) = \min\{\ c(x,v) + d_v(y)\ \}$ over all neighbors v

Let's compute the shortest-path from *u* to D



The values computed by a node *u*
depends on what it learns from its neighbors (A and E)

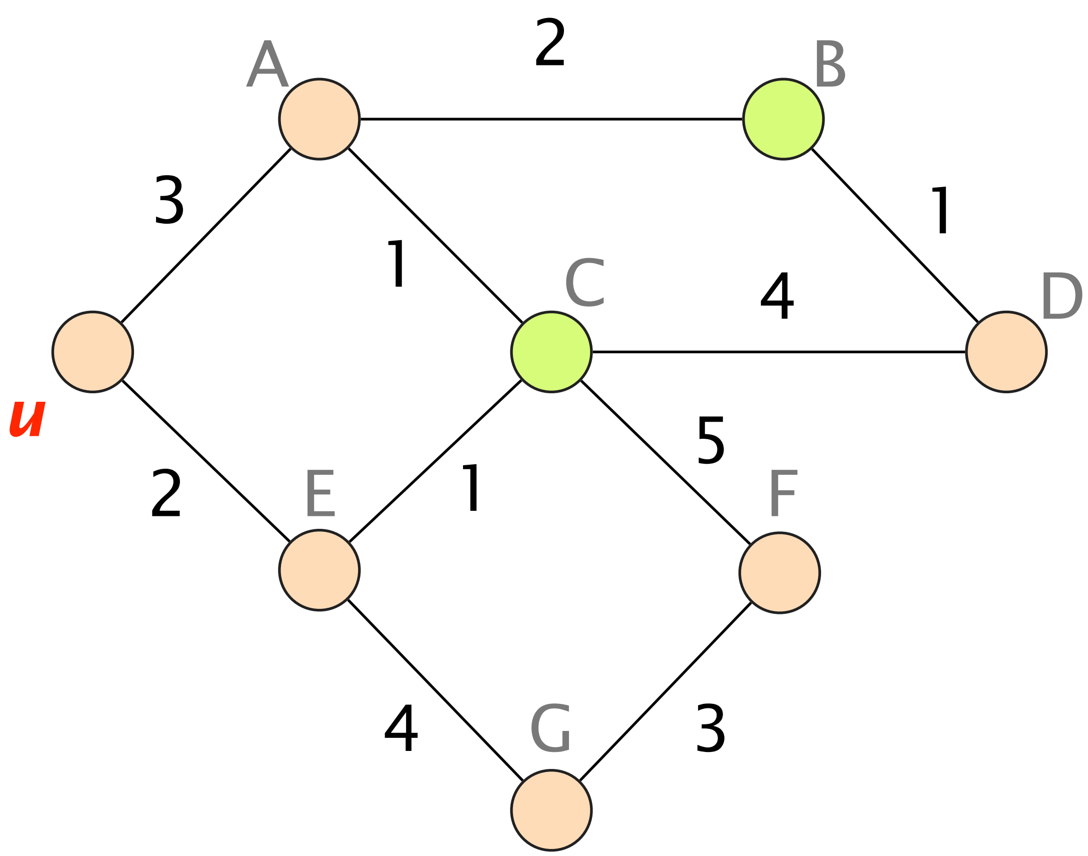


$d_x(y) = \min\{\ c(x,v) + d_v(y)\ \}$

over all neighbors *v*

$d_u(D) = \min\{\ c(u,A) + d_A(D),$
$c(u,E) + d_E(D)\ \}$

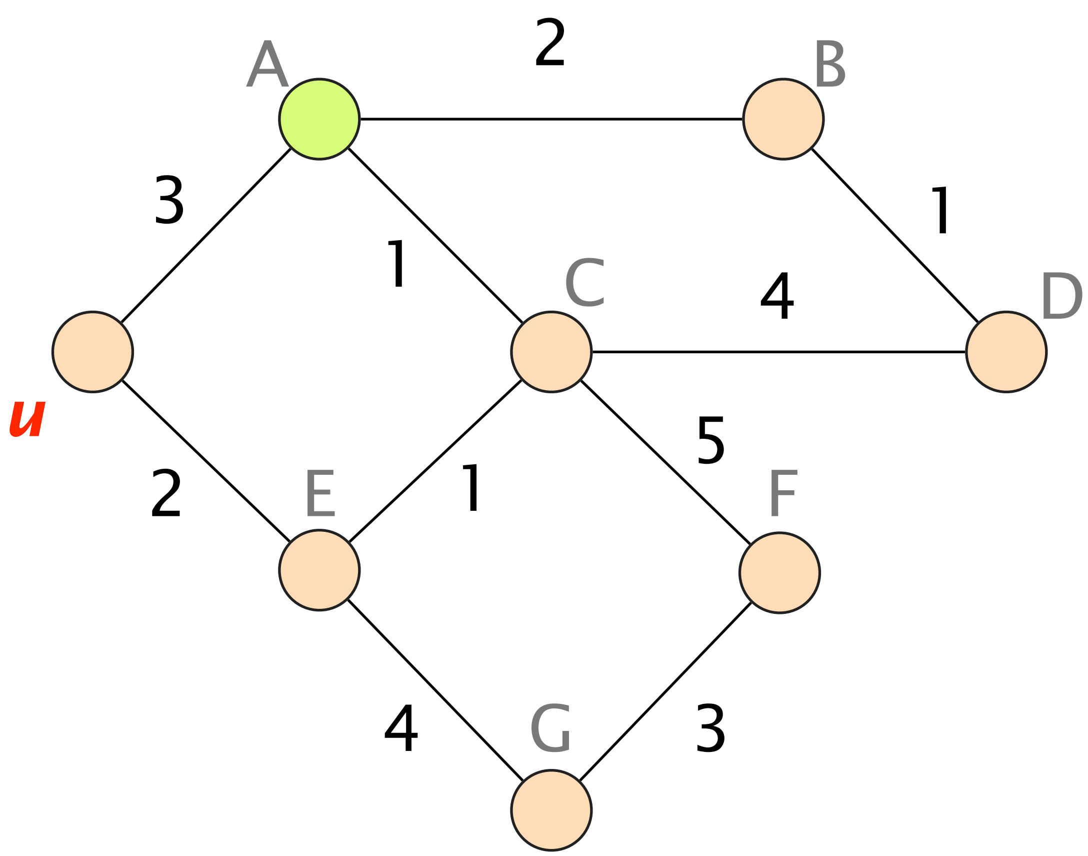
To unfold the recursion,
let's start with the direct neighbor of D



$d_{B}(D) = 1$

$d_{C}(D) = 4$

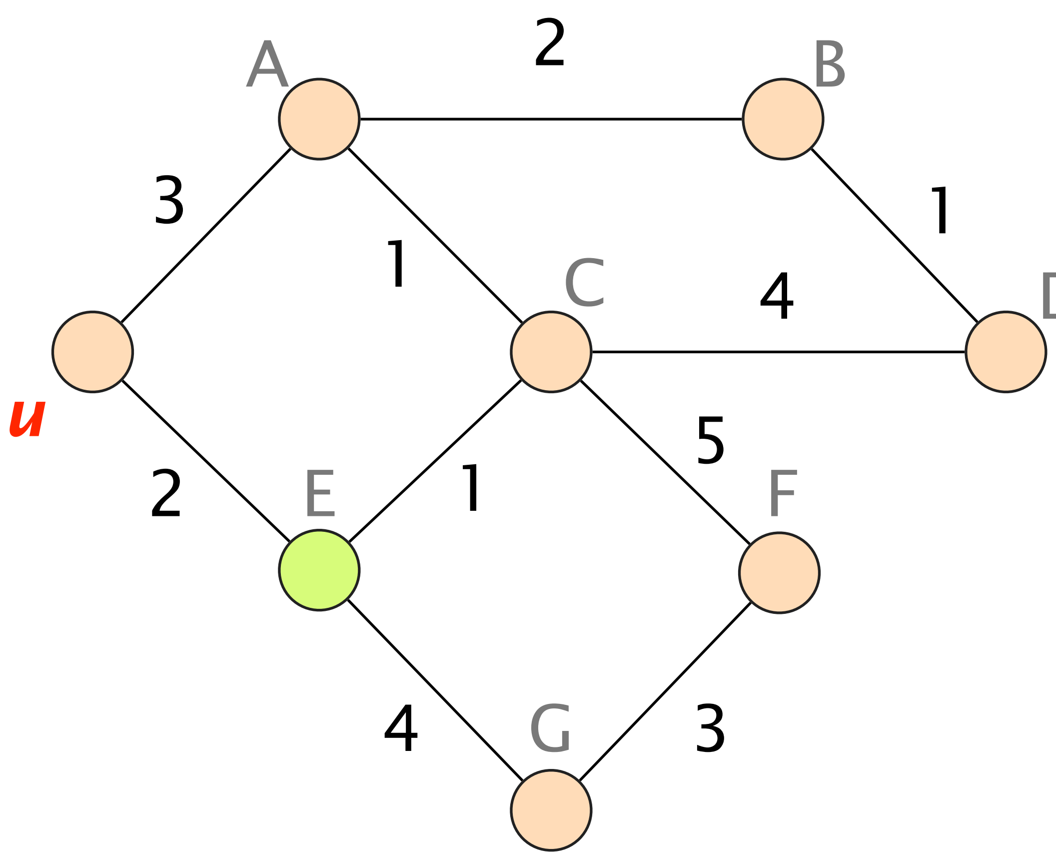
B and C announce their vector to their neighbors, enabling A to compute its shortest-path



$$d_A(D) = \min\{\, 2 + \overbrace{\boxed{d_B(D)}}^{1},\; 1 + \underbrace{\boxed{d_C(D)}}_{4} \,\}$$

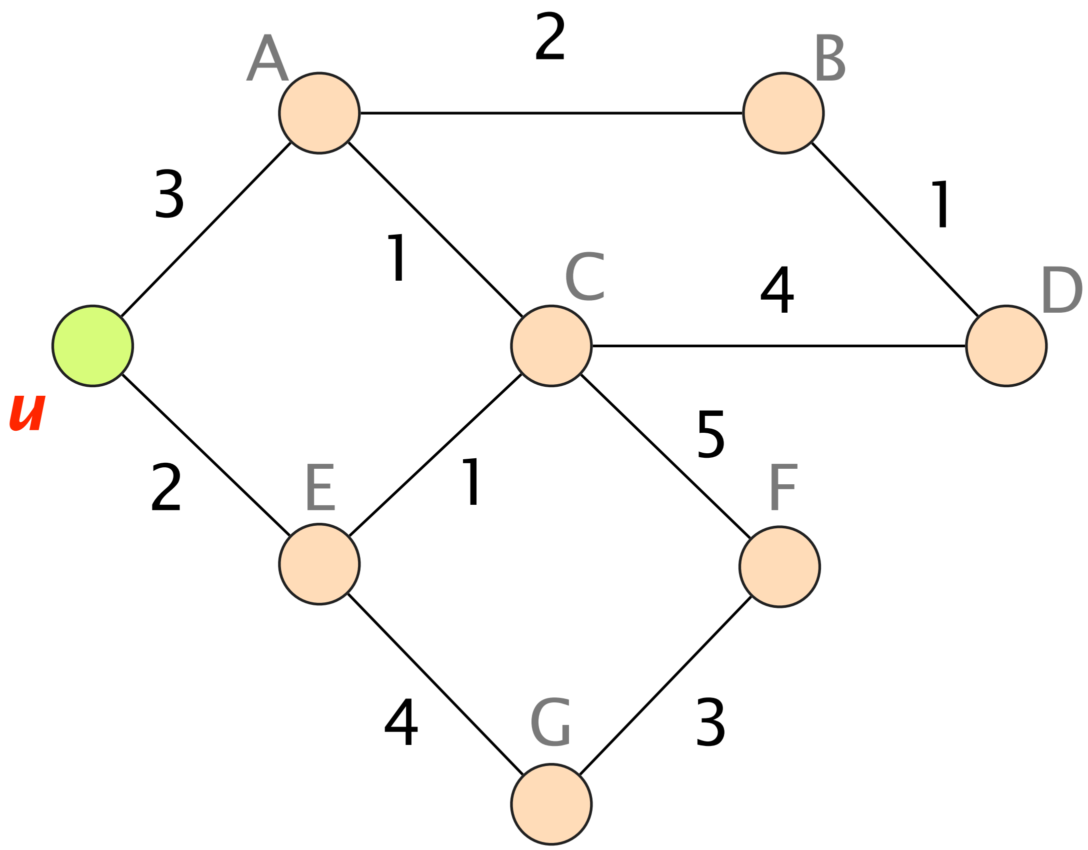
$$= 3$$

As soon as a distance vector changes, each node propagates it to its neighbor



$$
\begin{aligned}
d_E(D) = \min \{ & 1 + d_C(D), \\
& 4 + d_G(D), \\
& 2 + d_u(D)\} \\
= 5 &
\end{aligned}
$$

Eventually, the process converges
to the shortest-path distance to each destination



$$d_u(D) = \min \{ 3 + d_A(D), \; 2 + d_E(D) \}$$

$$= 6$$

As before, *u* can directly infer its forwarding table by directing the traffic to the best neighbor

the one which advertised the smallest cost

In few weeks, we’ll learn how BGP uses distributed computation to forward packets in the Internet

Next week on

Communication Networks

Reliable transport!

Communication Networks

Spring 2017

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March, 6 2017