Computer Networks and Internet Technology

2021W703033 VO Rechnernetze und Internettechnik
Winter Semester 2021/22

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With materials and inspiration from Scott Shenker, Jennifer Rexford, Phil Levis, Adrian Perrig and Laurent Vanbever

Todays Schedule

- Recap last week
  - Layers
  - Network characterization

- Part 2: Core concepts
  - Routing
    - 3 variants
  - Reliable Delivery
    - Loss, delay, corruption, reordering

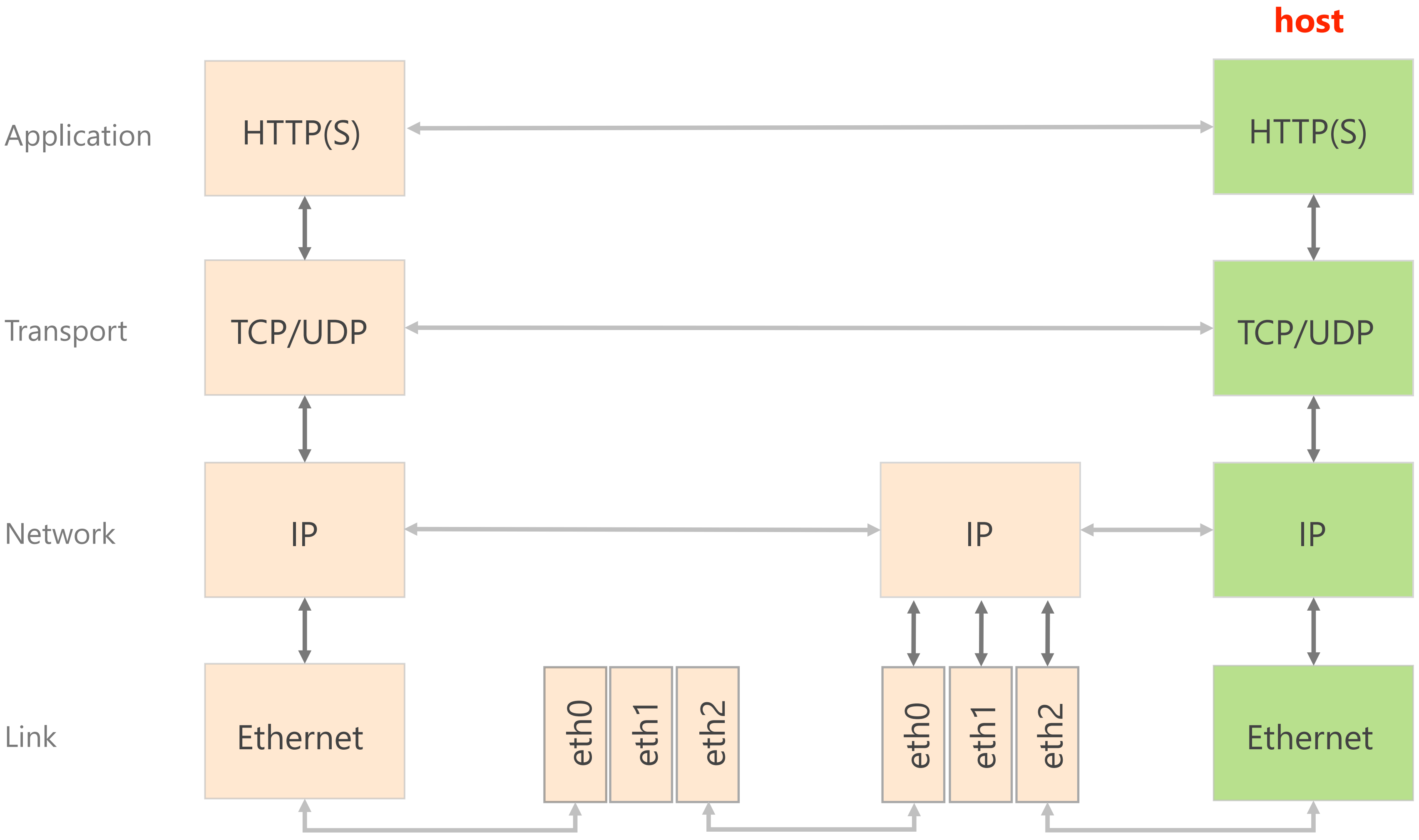
Communication Networks and Internet Technology

Recap of last weeks lecture

Each layer provides a service to the layer above

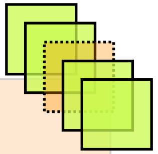
	layer	service provided:
L5	Application	network access
L4	Transport	end-to-end delivery (reliable or not)
L3	Network	global best-effort delivery
L2	Link	local best-effort delivery
L1	Physical	physical transfer of bits

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



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

delay



loss

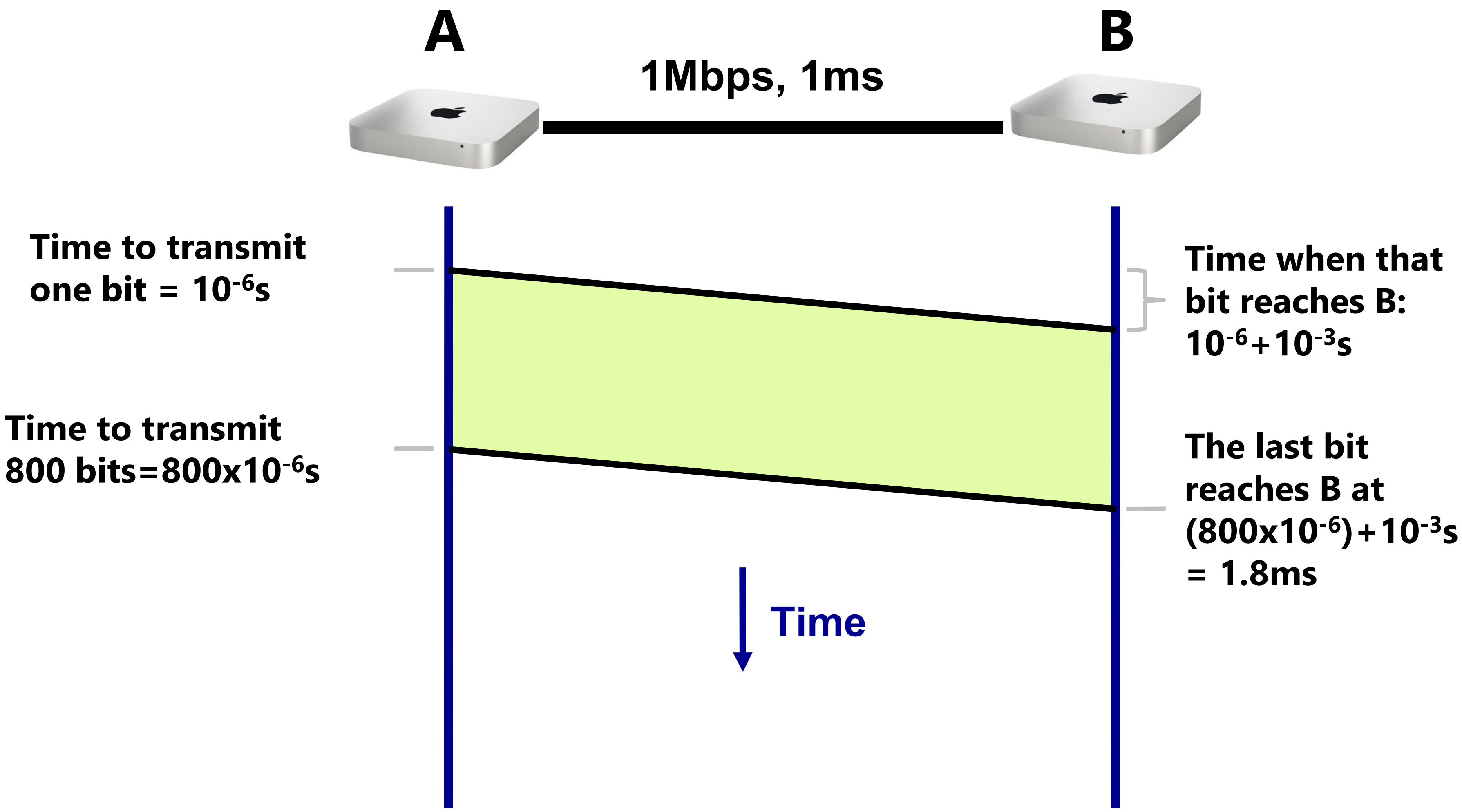
throughput

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

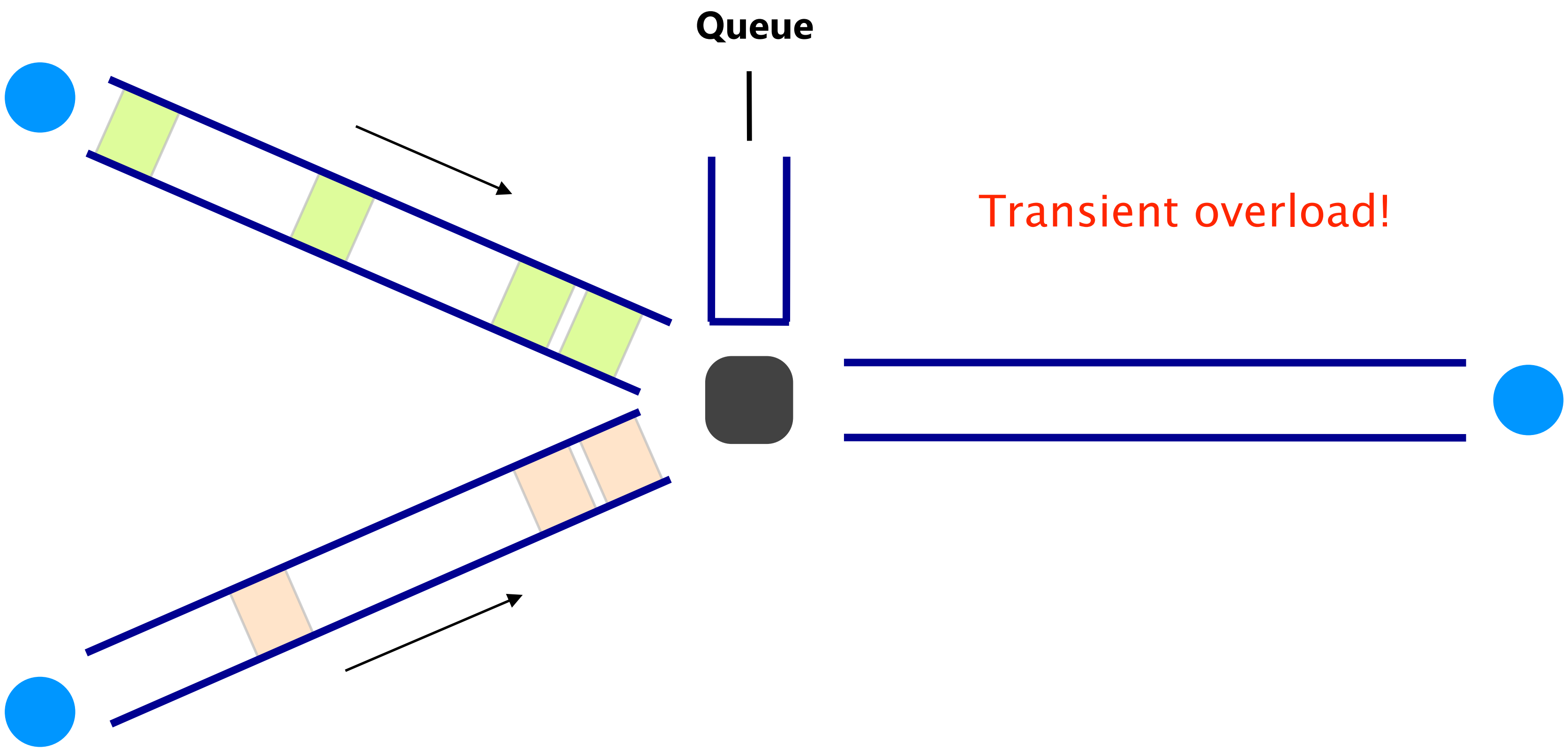
What fraction of packets sent to a destination are dropped?

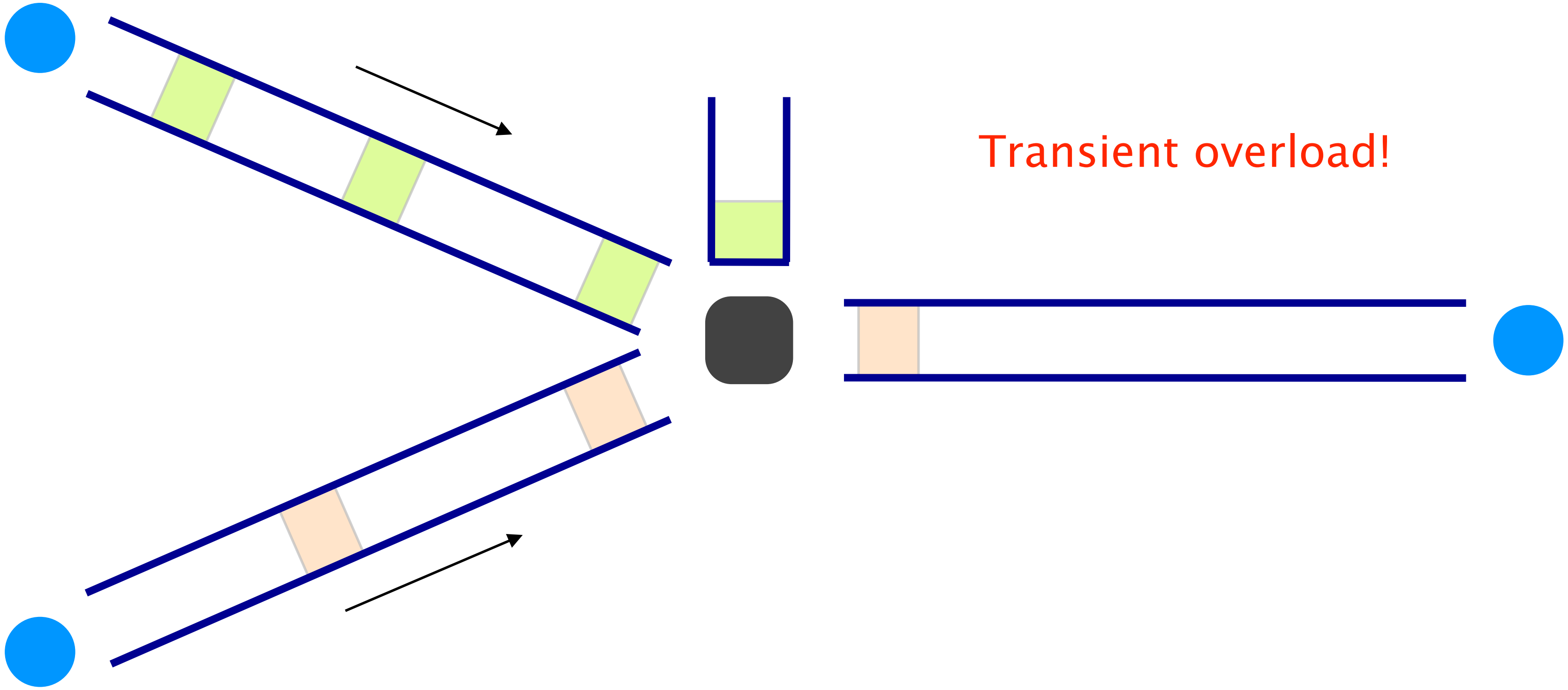
At what rate is the destination receiving data from the source?

How long does it take to exchange 100 Bytes packet?

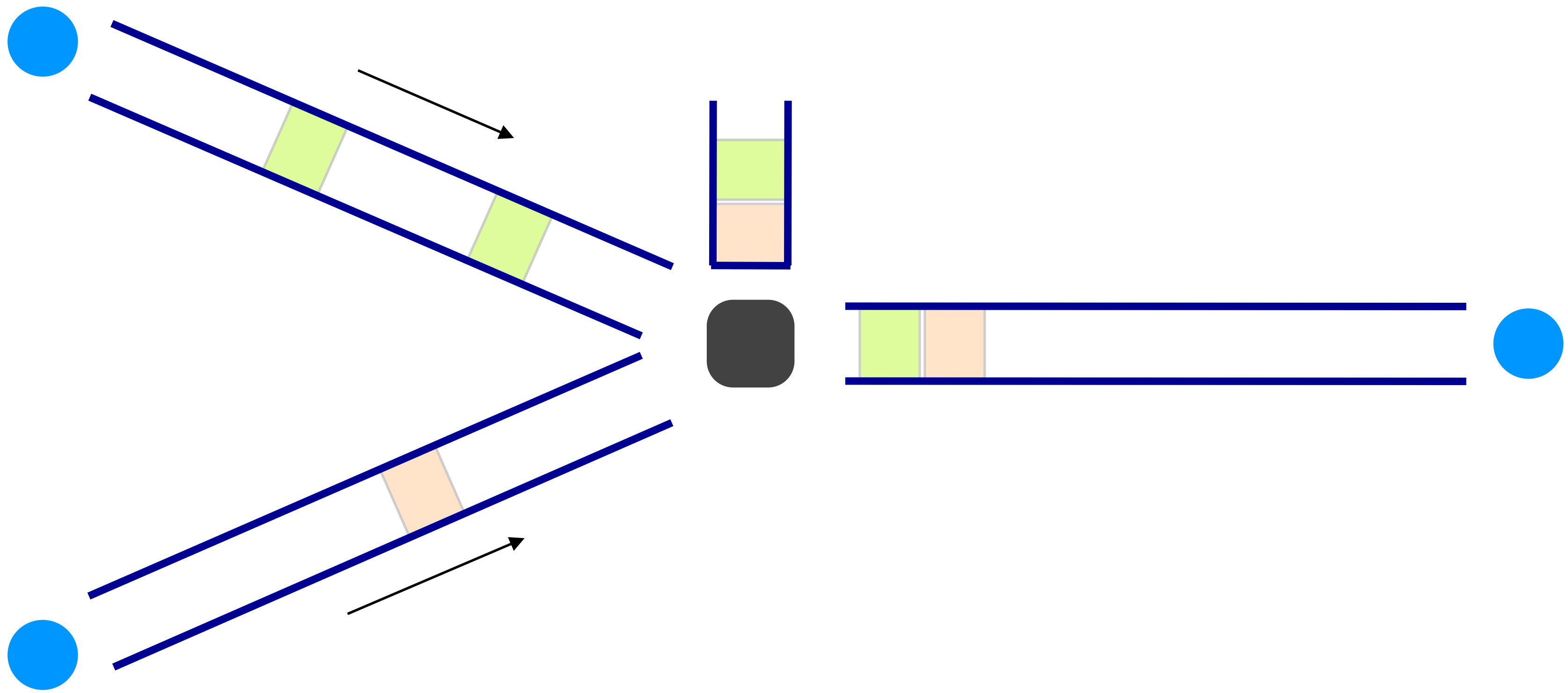


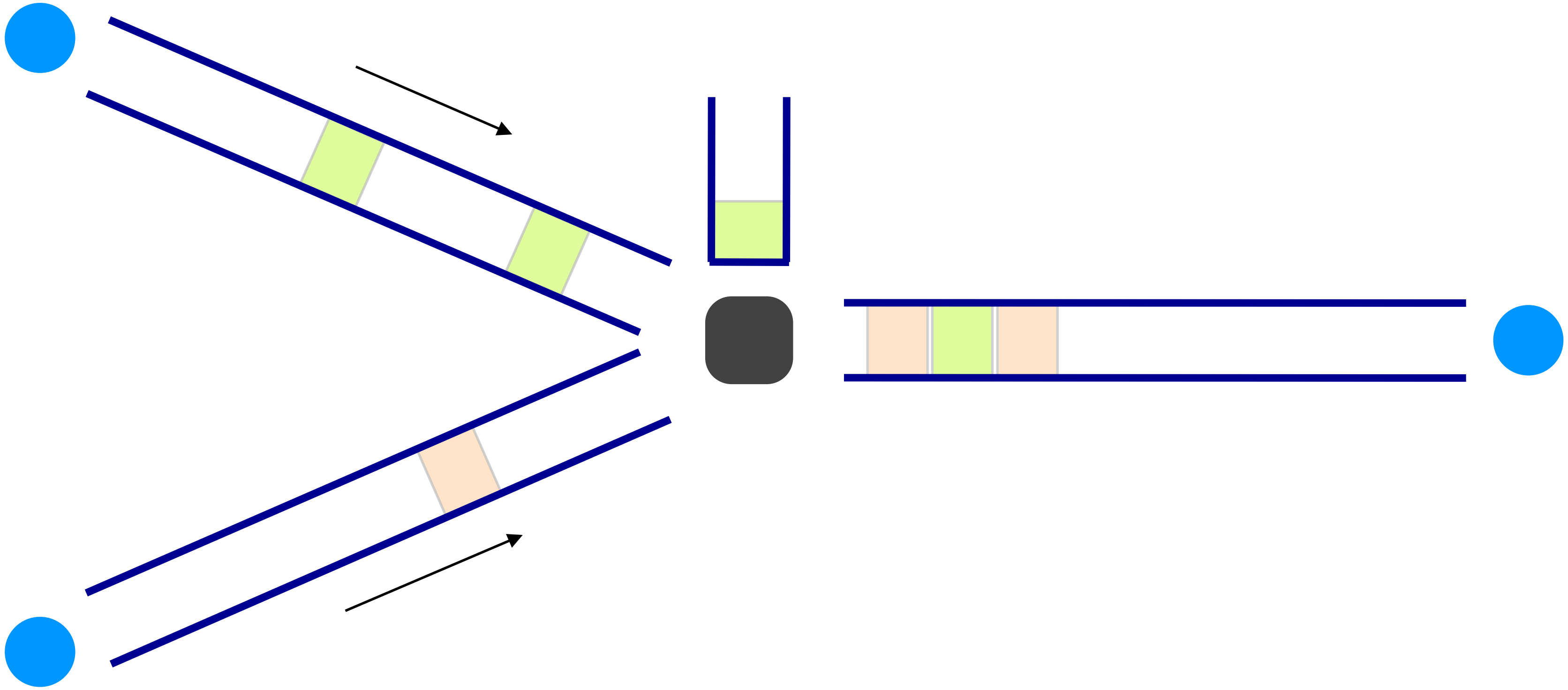
Queuing delay depends on the traffic pattern

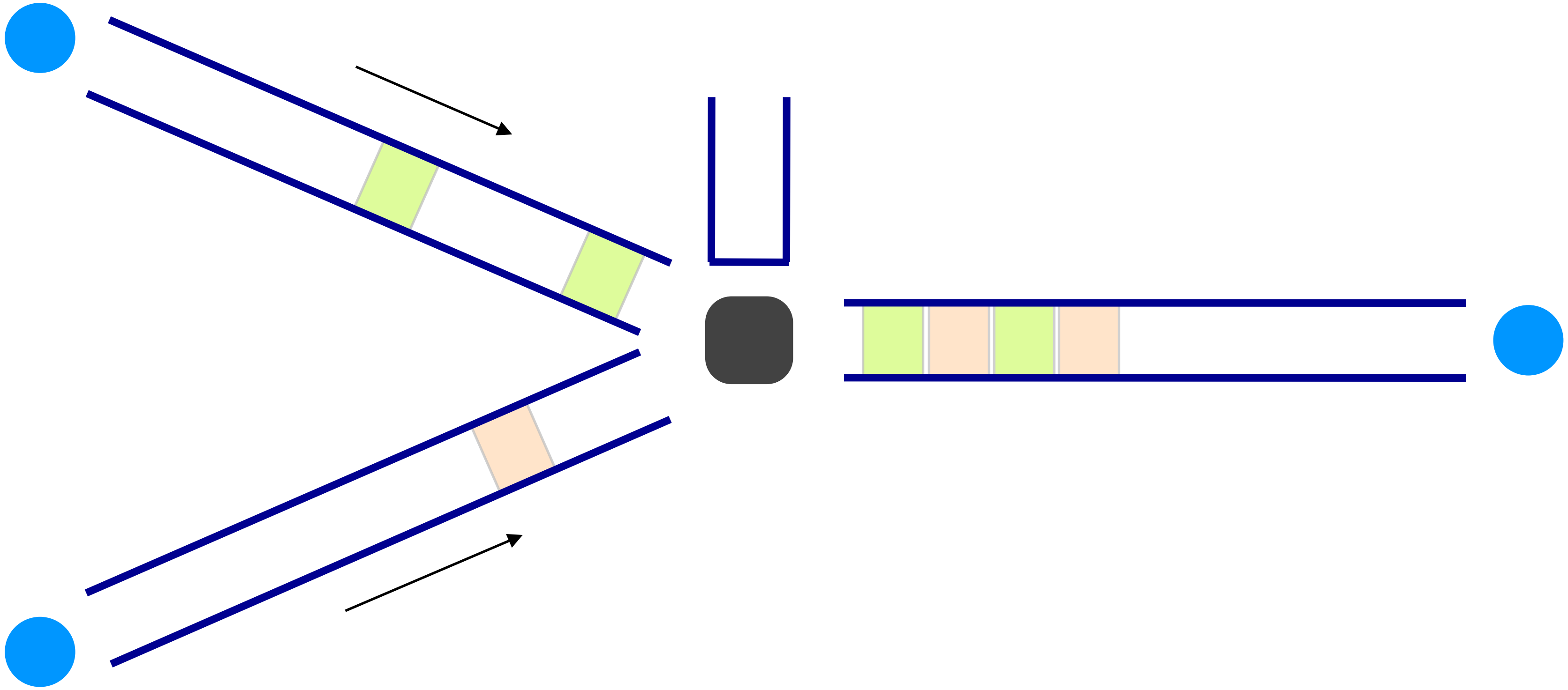




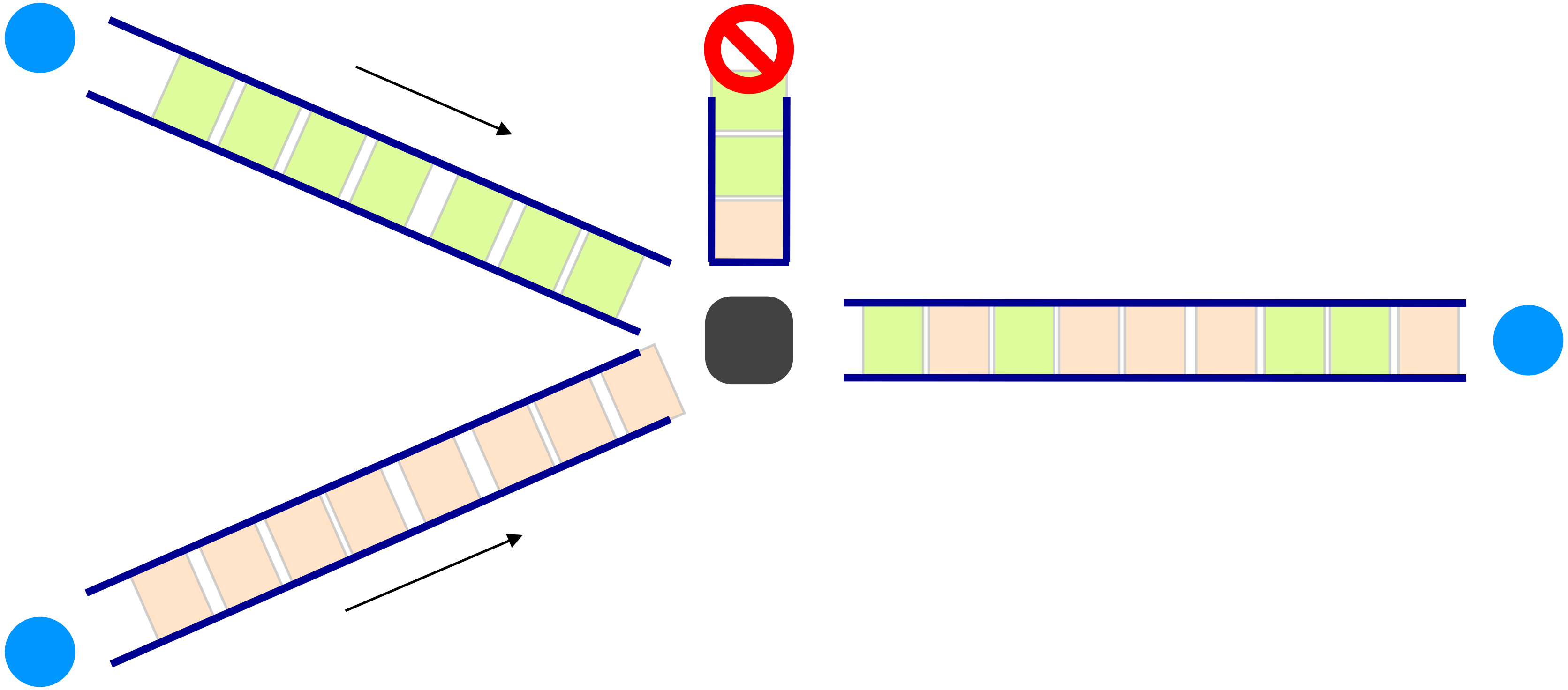
Transient overload!



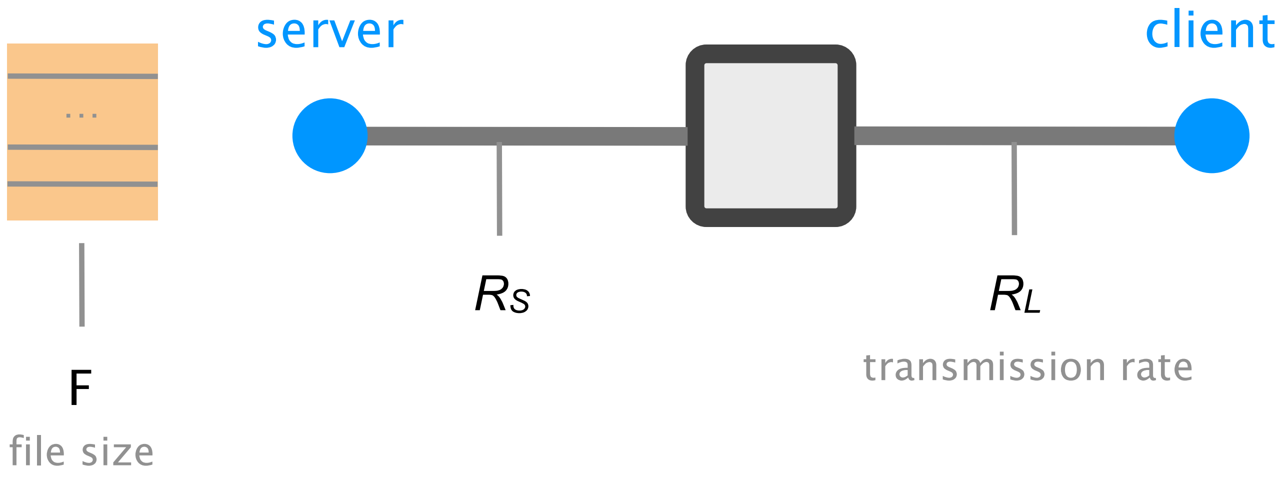




If the queue is persistently overloaded,
it will eventually drop packets (loss)



To compute throughput, one has to consider the bottleneck link



Average throughput $\min(R_S, R_L)$

= transmission rate of the bottleneck link

Communication Networks and Internet Technology

This weeks lecture

Communication Networks and Internet Technology

Part 2: Concepts

routing

reliable delivery

Communication Networks and Internet Technology

Part 2: Concepts

routing

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

reliable delivery

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

routing

reliable delivery

How do you guide packets from a source to destination?

Think of IP packets as envelopes

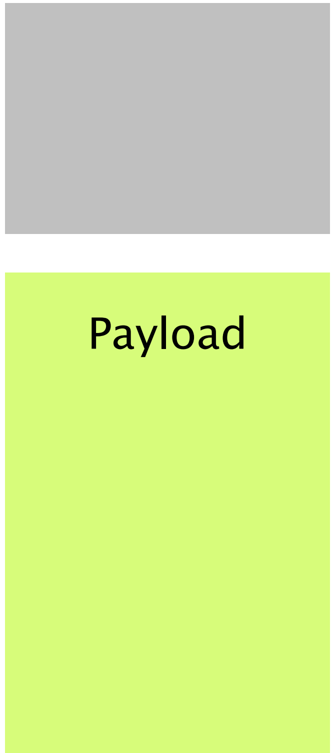
Packet

Like an envelope,

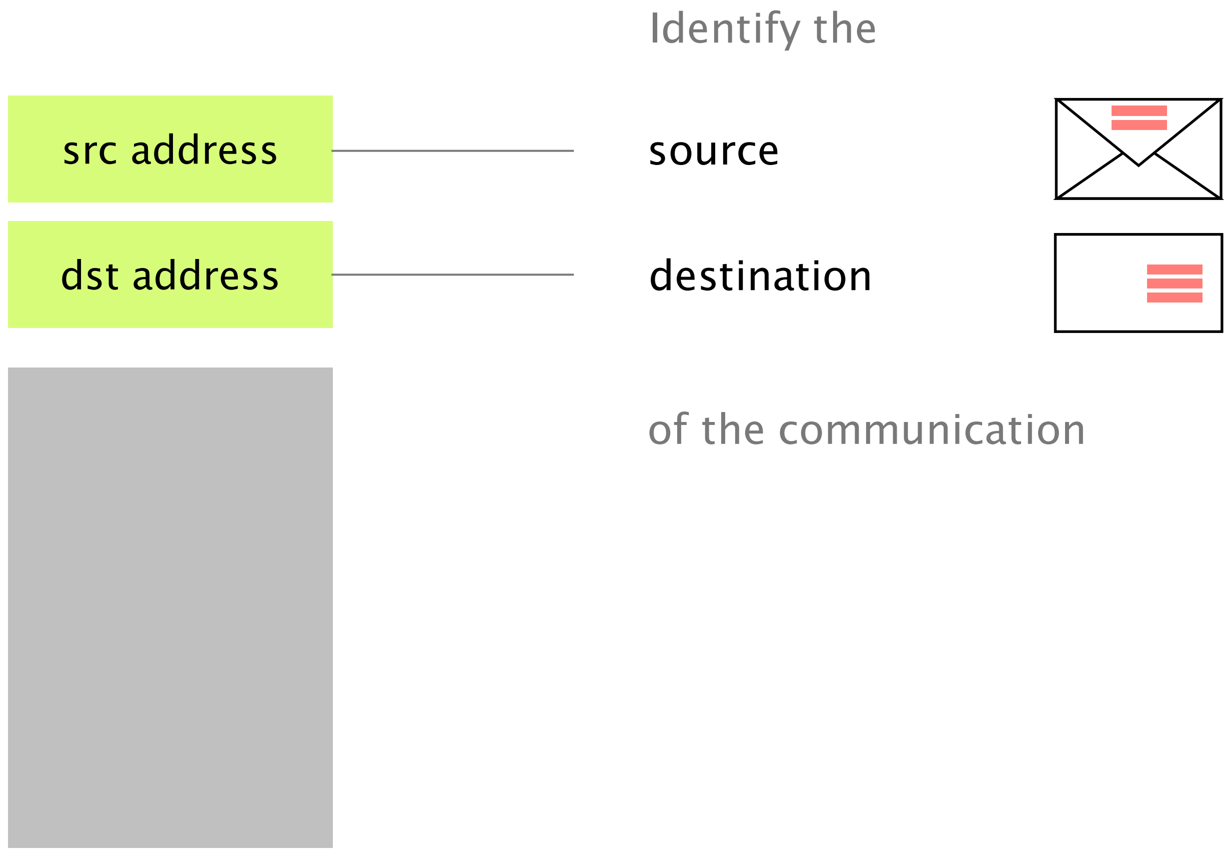
packets have a header

Like an envelope,

packets have a payload

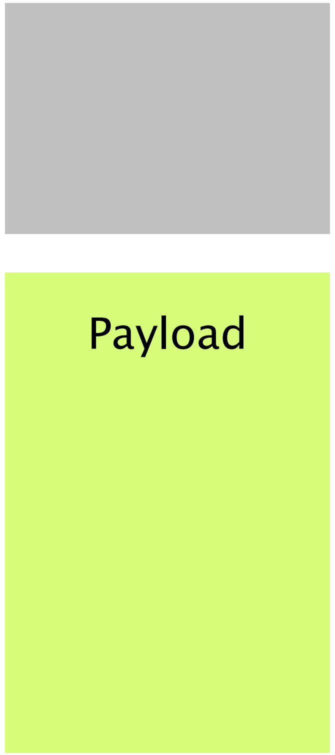


The **header** contains the **metadata** needed **to forward** the packet

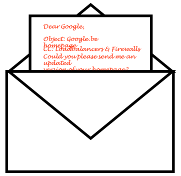


The payload contains

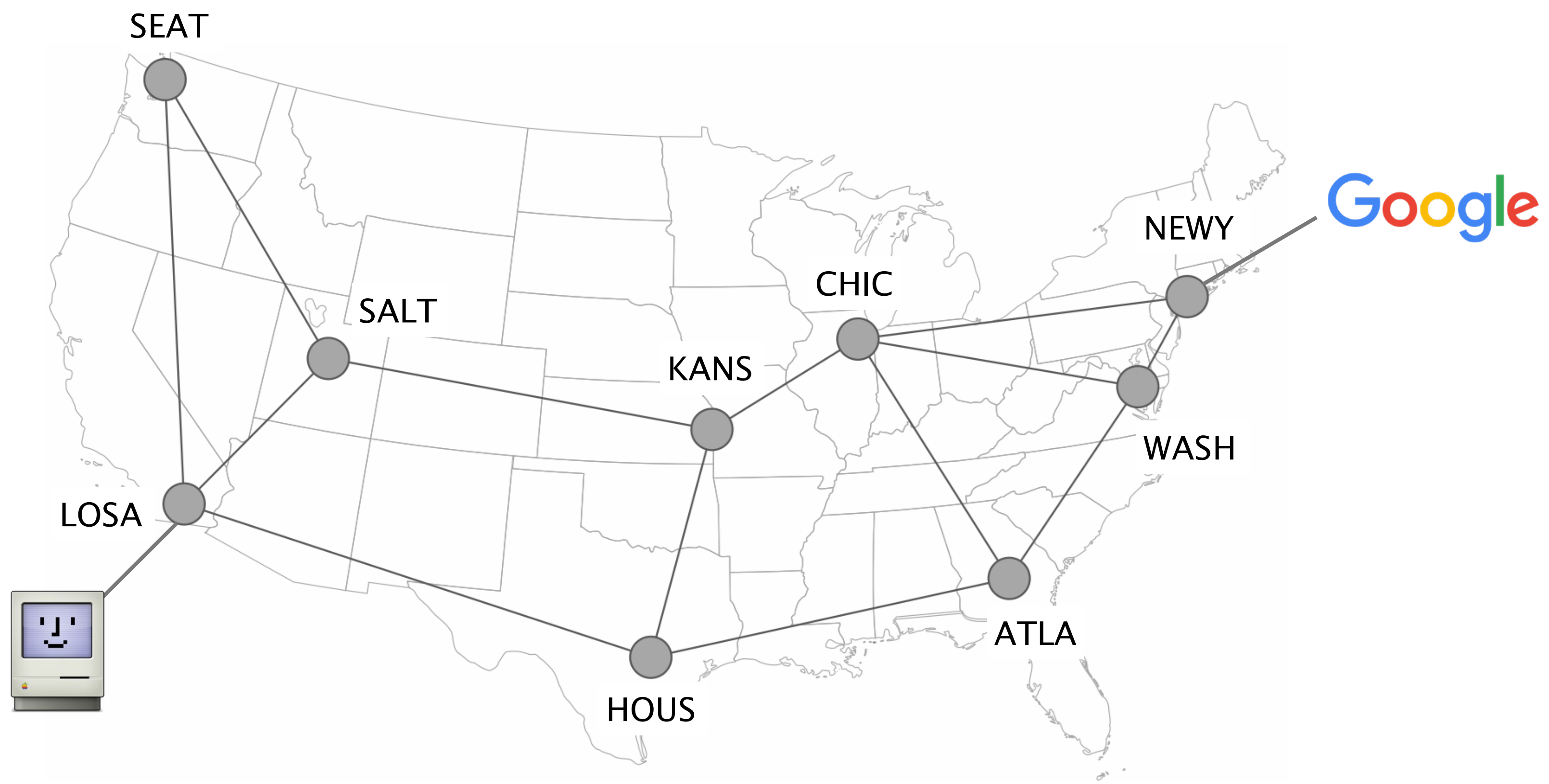
the data to be delivered

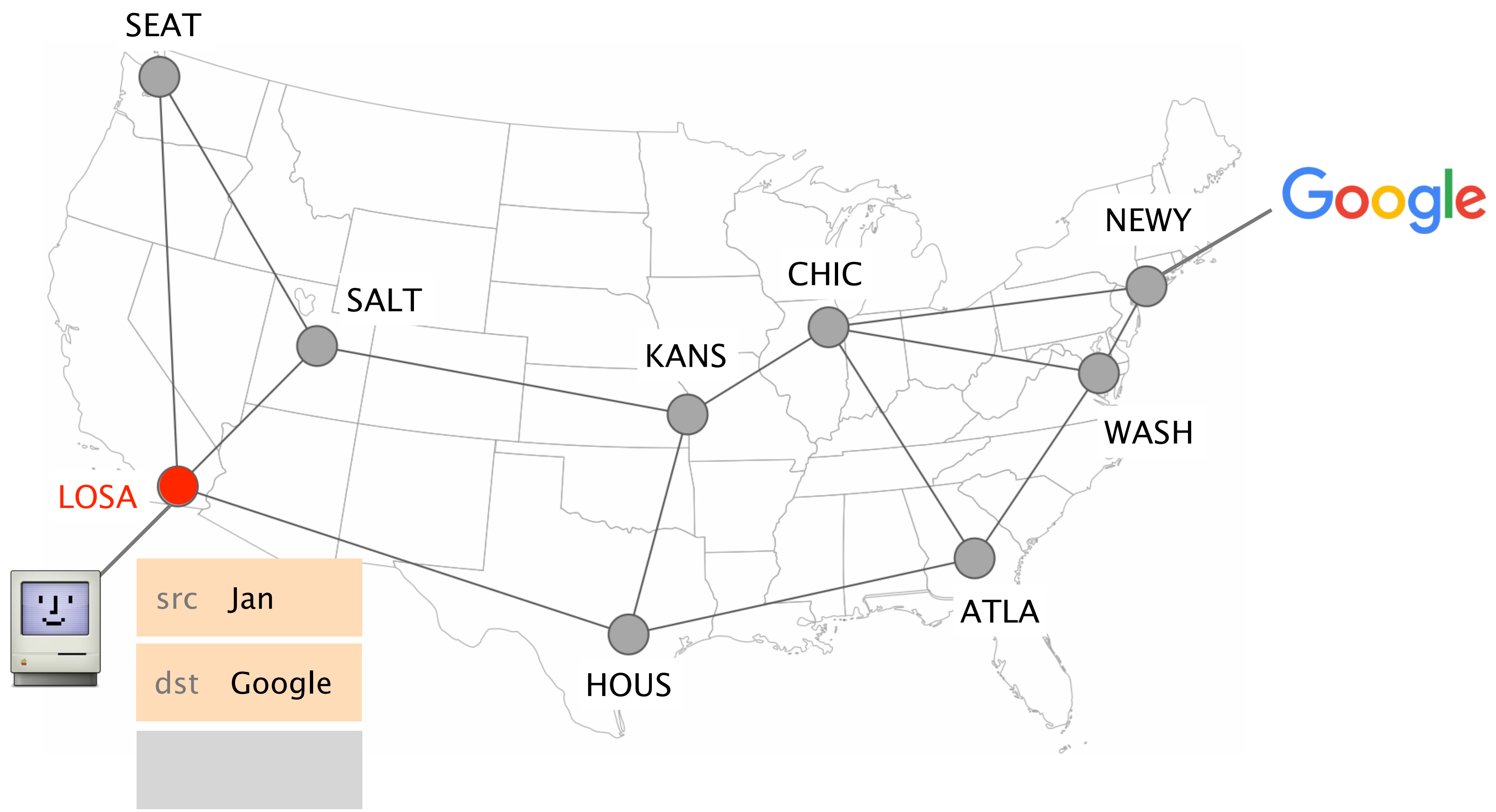


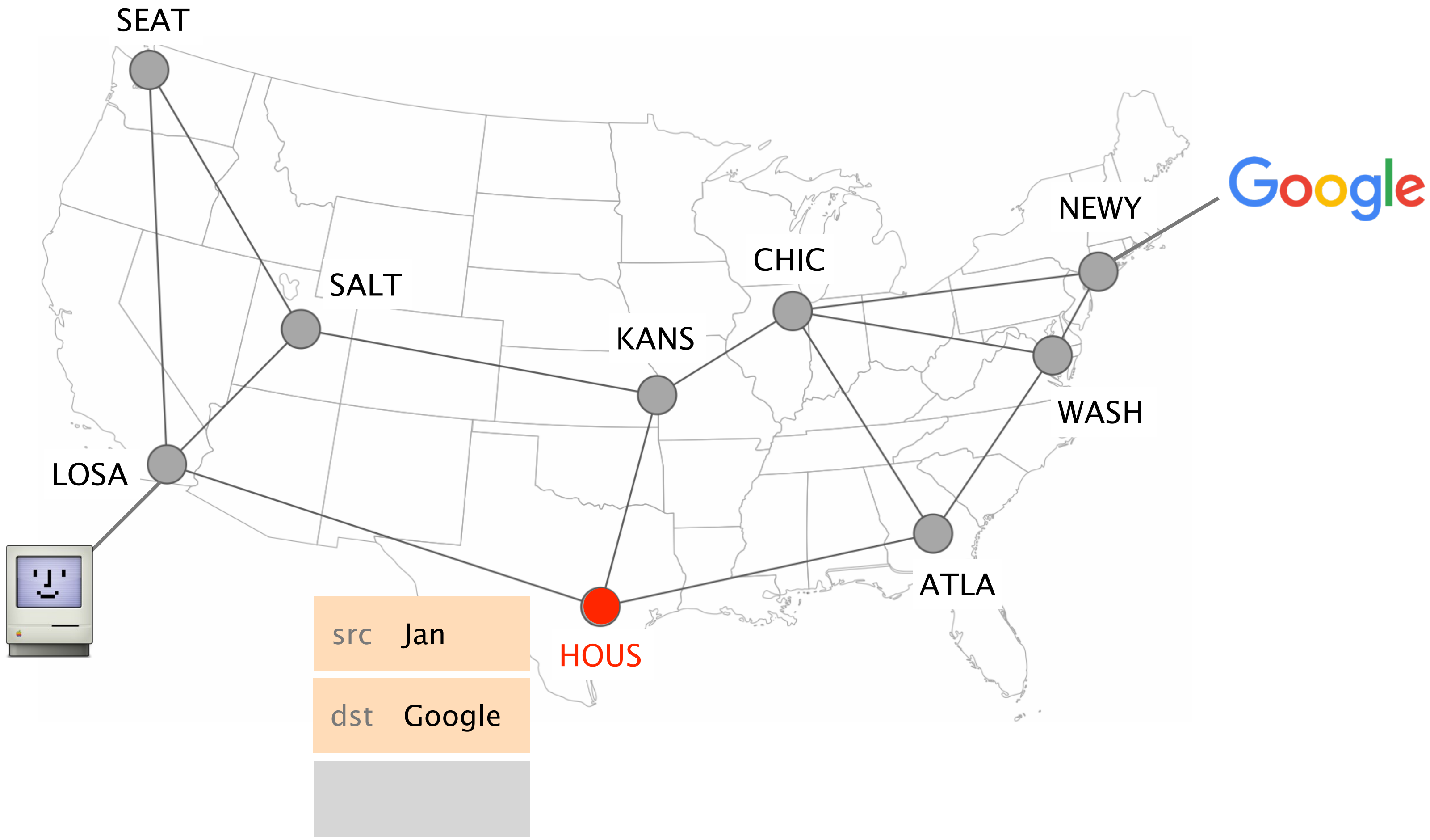

```html
<html><head>
<meta http-equiv="content-type" content="text/html; charset=UTF-8">
<title>Google</title>
</head><body>
  <img alt="Google" height=110 src="images/logo.gif" width=276>
  <form action="/search" name=f>
   <input name=hl type=hidden value=en>
   <input name=q size=55 title="Google 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
LOSA
KANS
CHIC
NEWY
WASH
ATLA
HOUS
Google
src Jan
dst Google


SEAT
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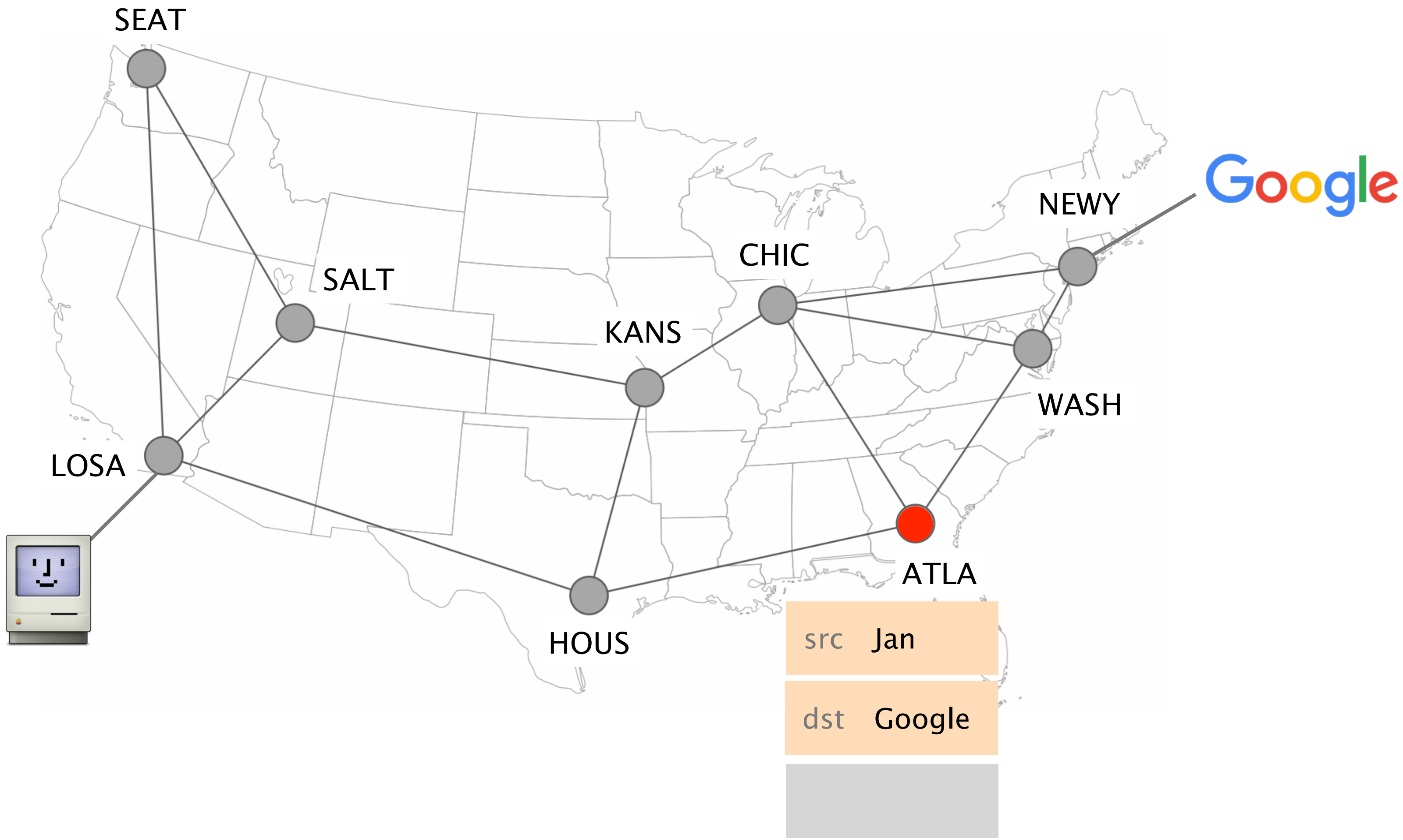
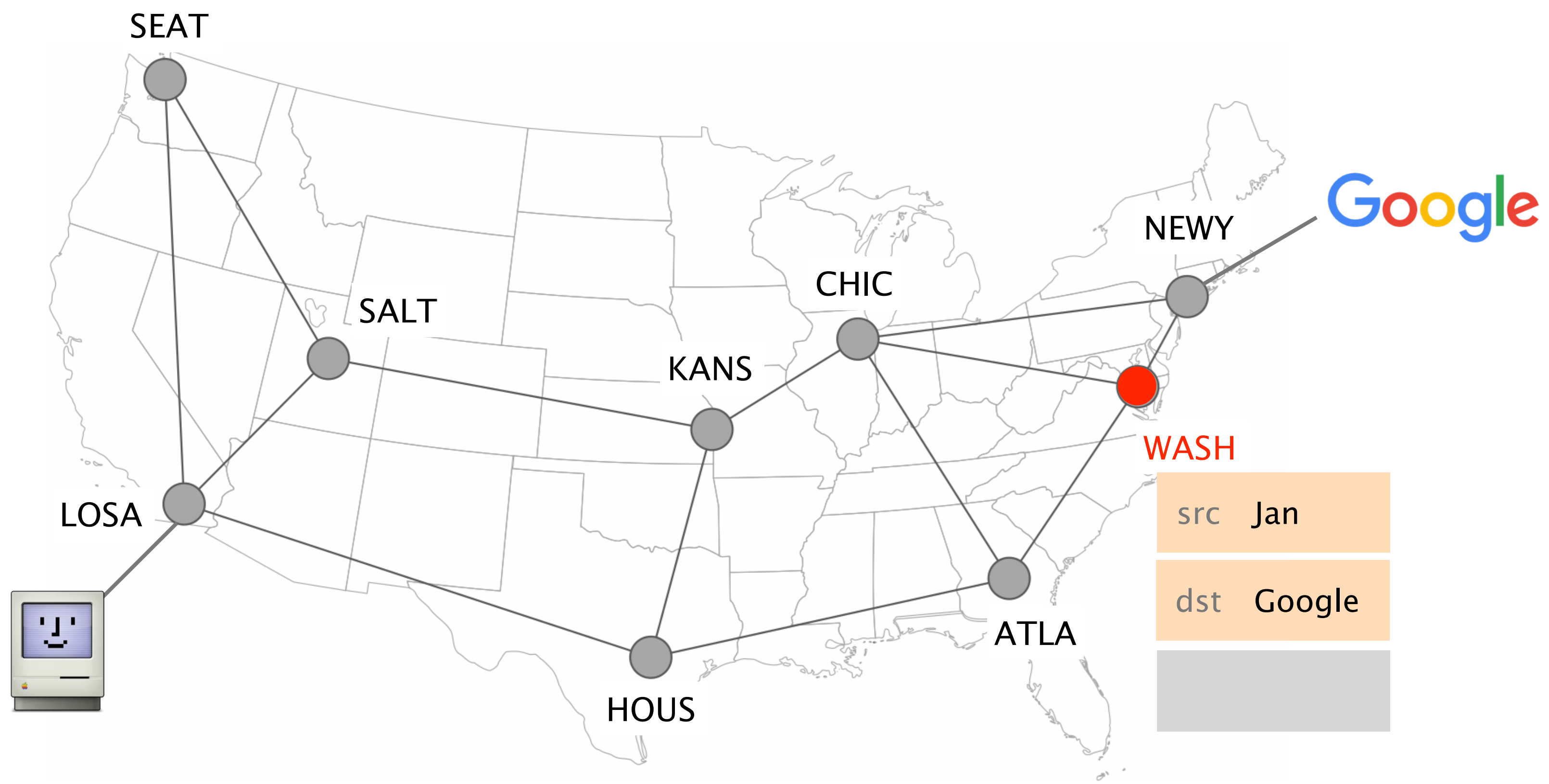
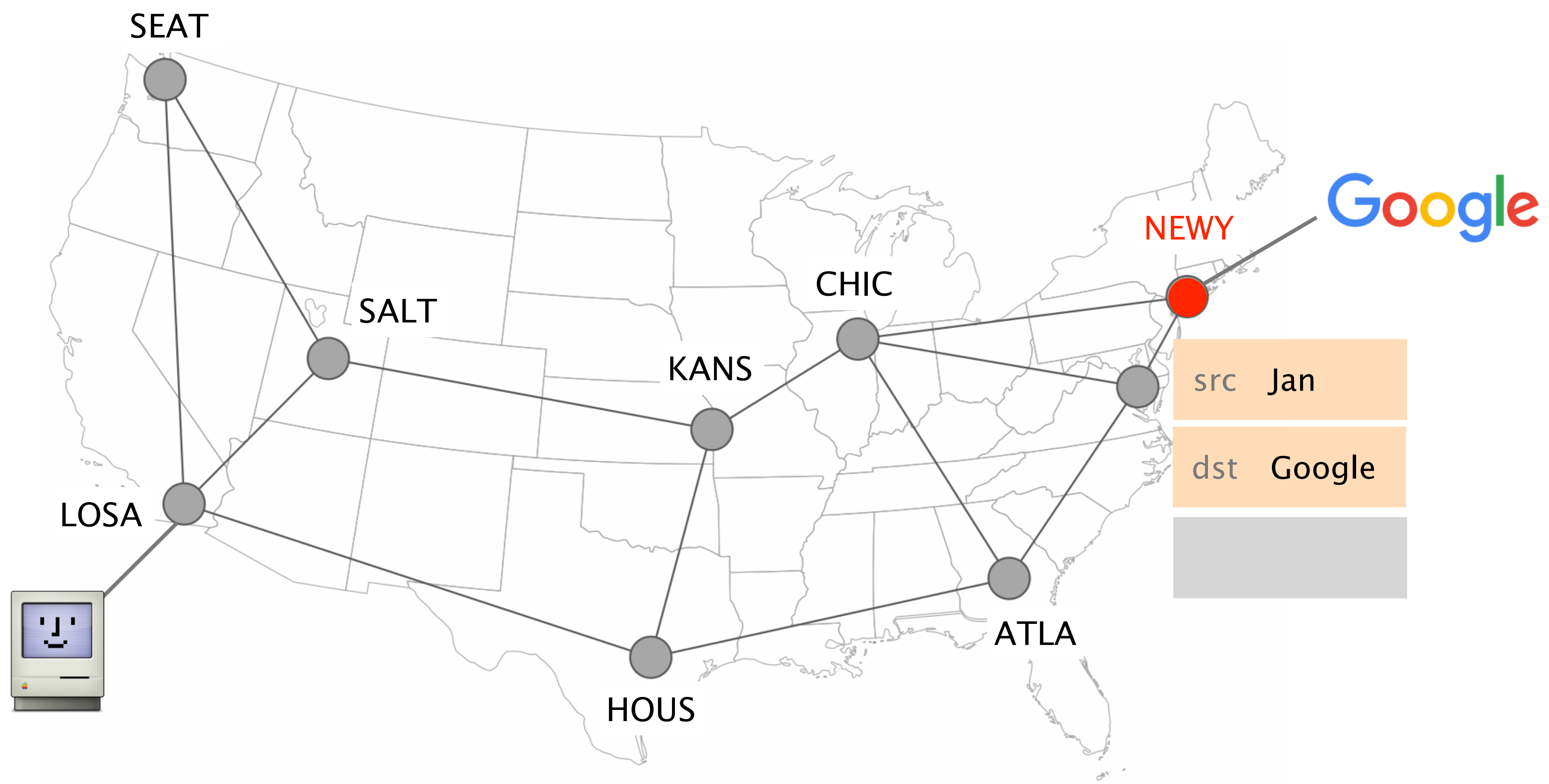

SEAT
SALT
KANS
CHIC
NEWY
Google
WASH
LOSA
ATLA
HOUS
src Jan
dst Google


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


SEAT
SALT
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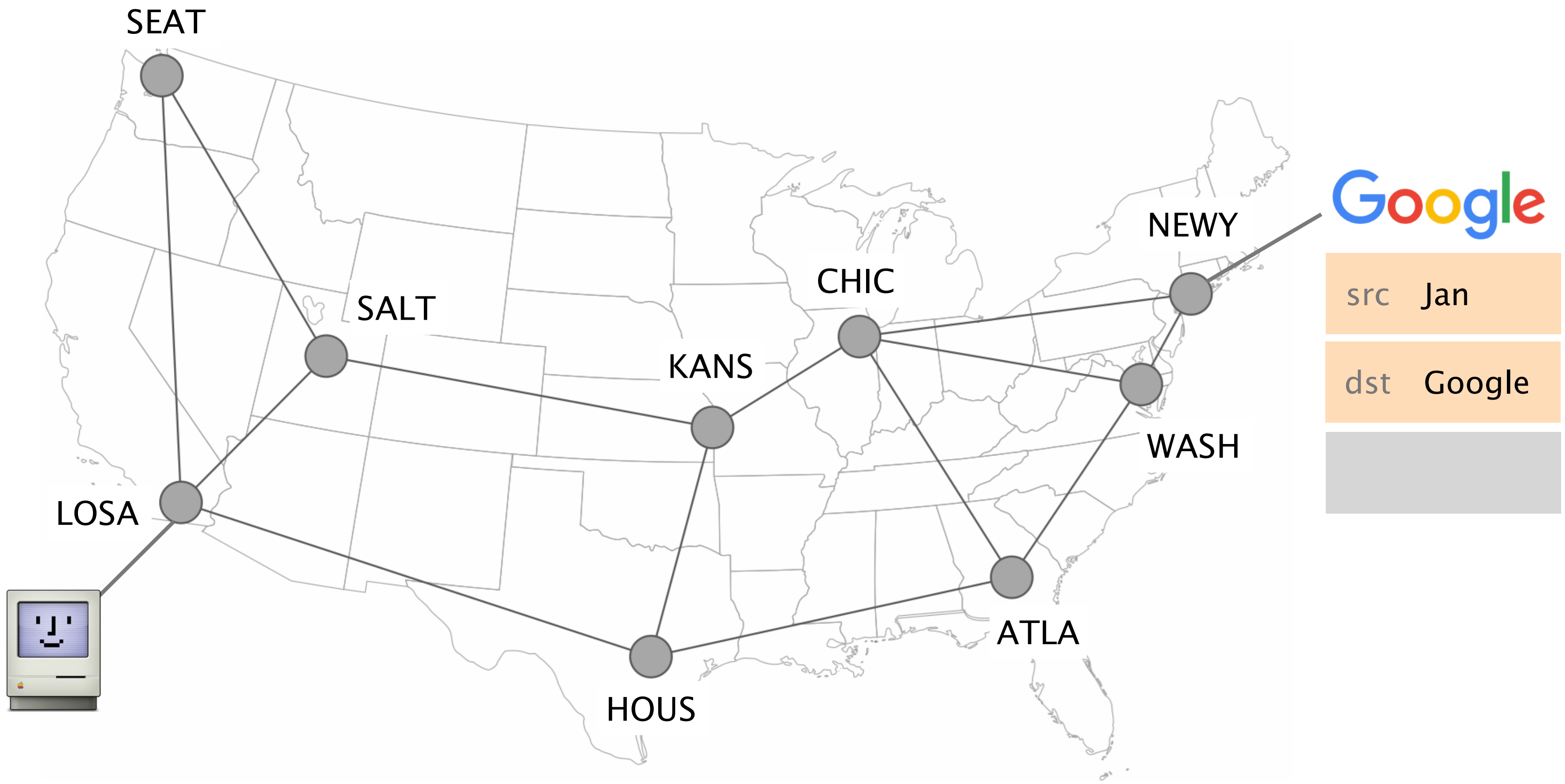
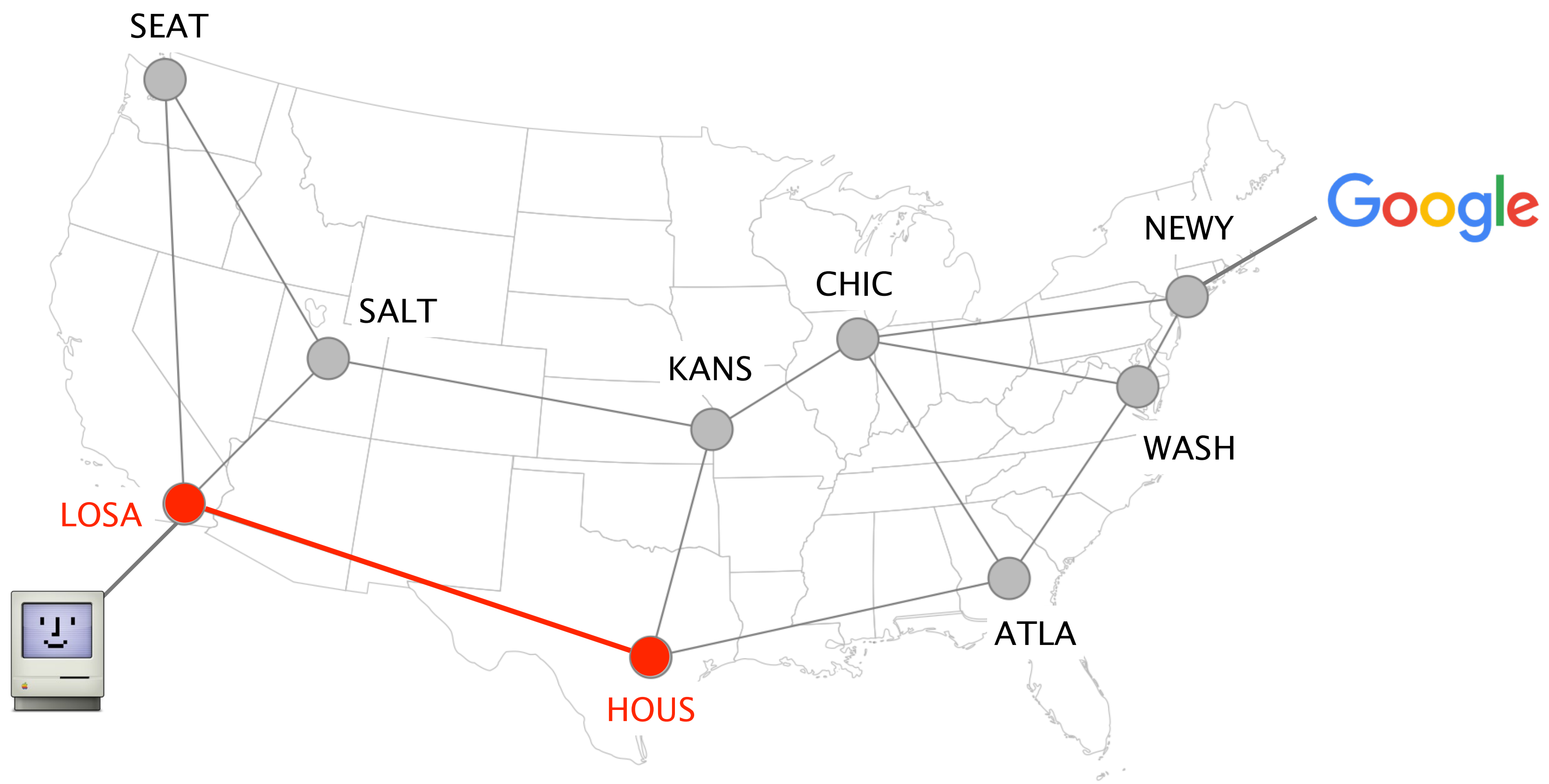
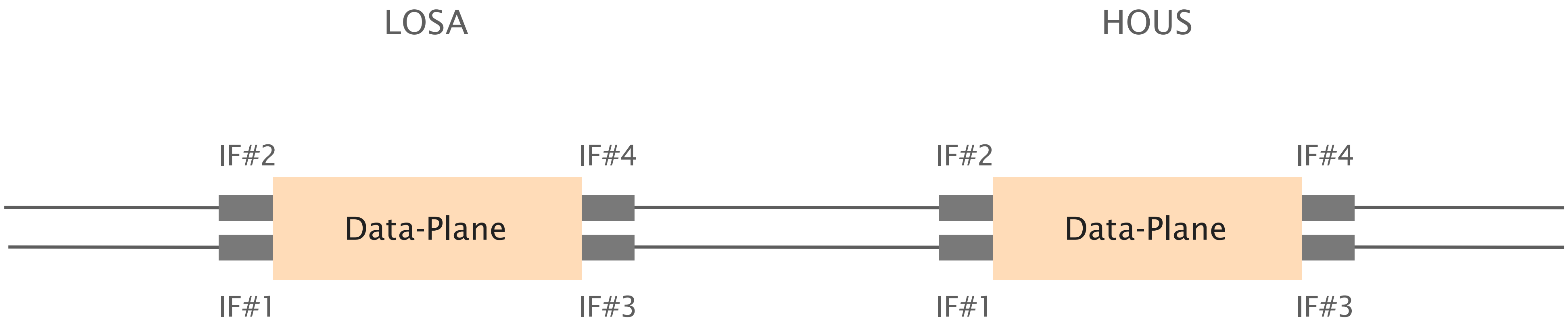
src Jan
dst Google

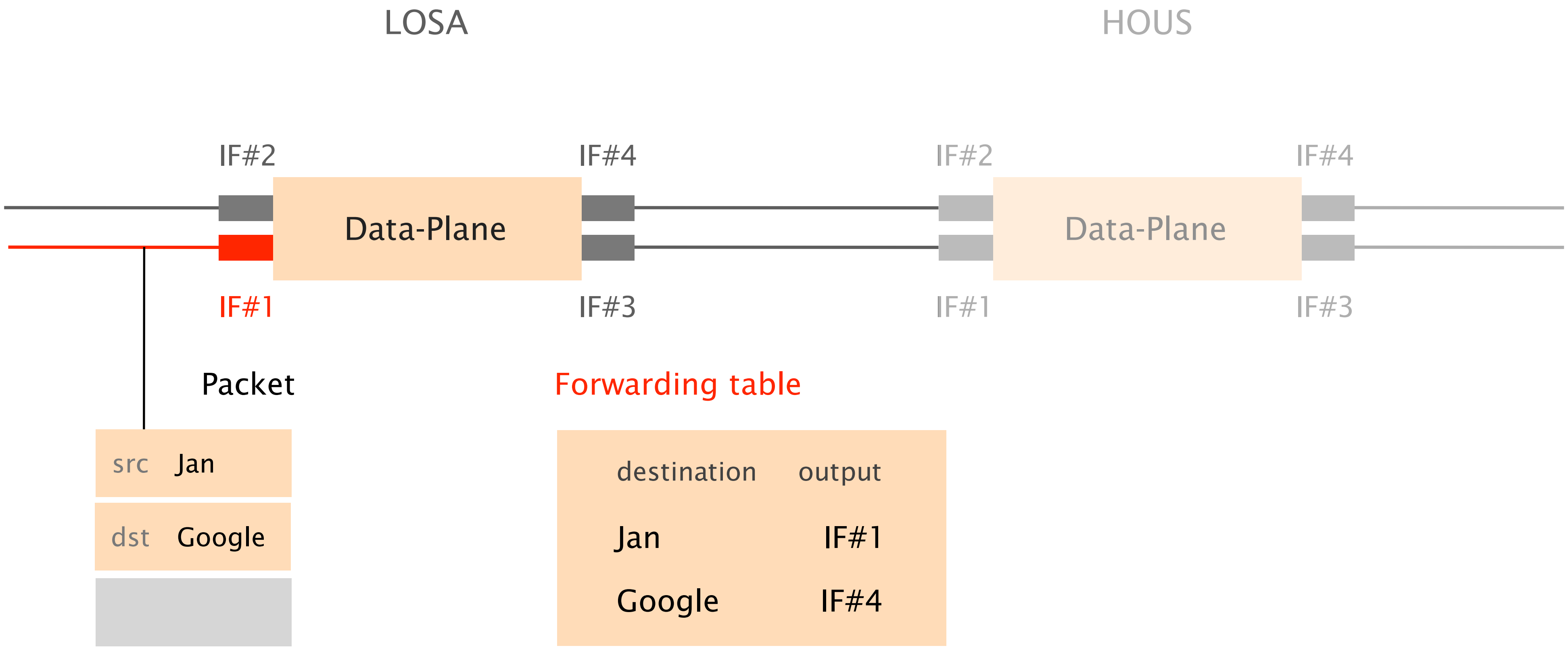

SEAT
SALT
KANS
CHIC
NEWY
WASH
LOSA
HOUS
ATLA
src Jan
dst Google

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

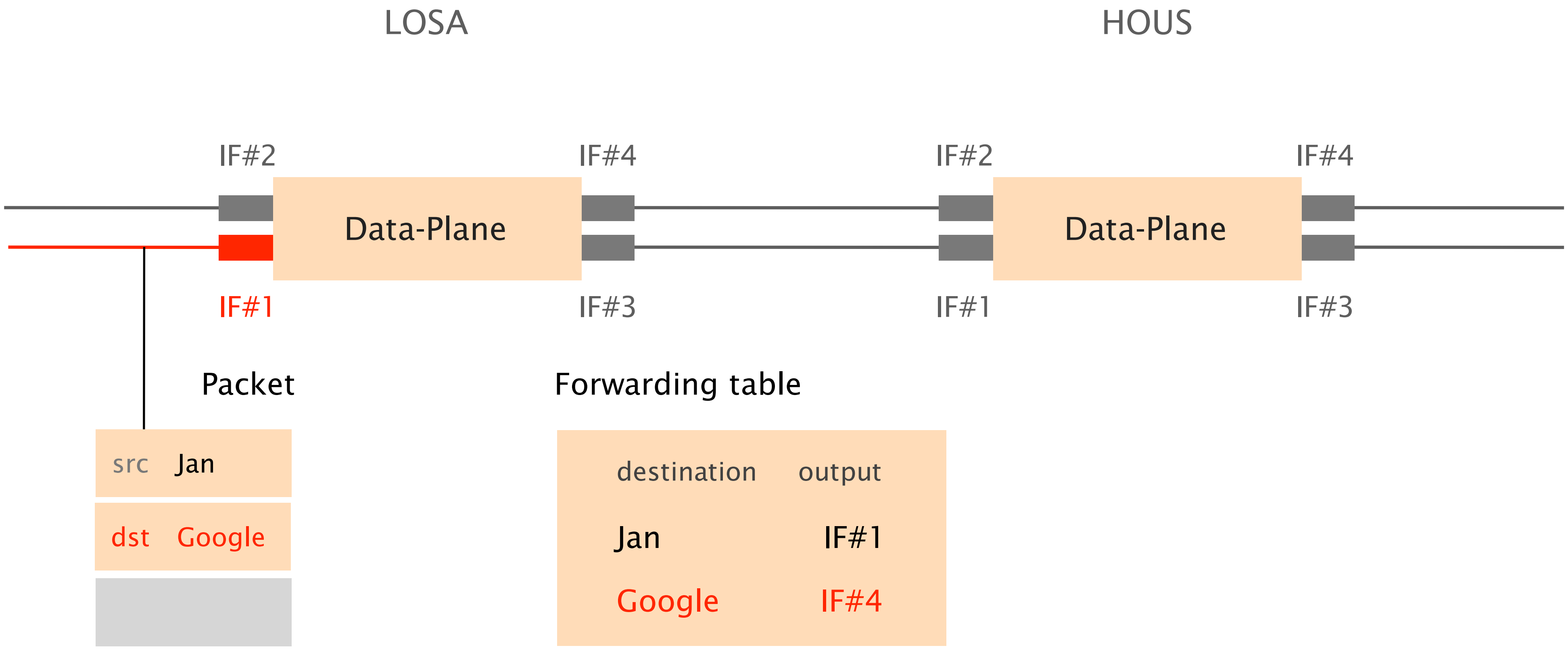



LOSA
HOUS
IF#2
IF#4
IF#2
IF#4
Data-Plane
Data-Plane
IF#1
IF#3
IF#1
IF#3

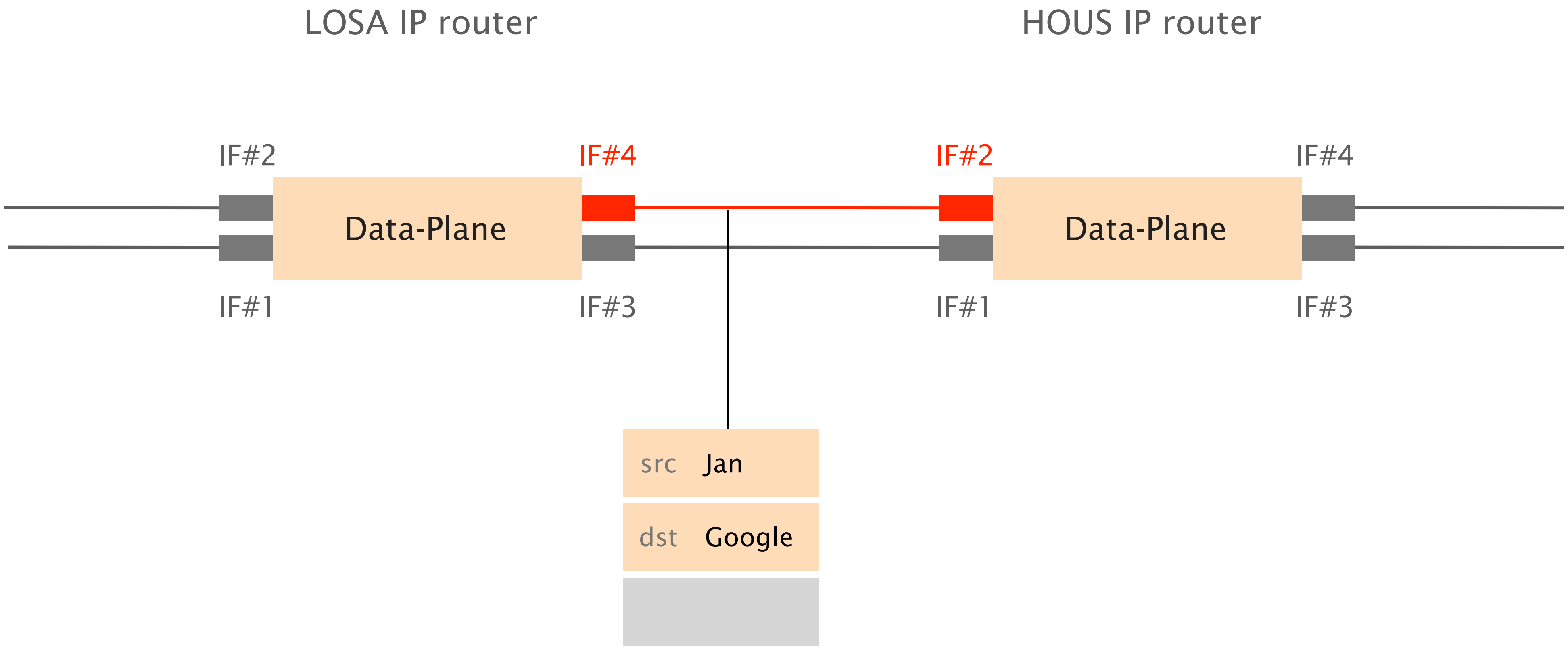
Upon packet reception, routers locally look up their **forwarding table** to know where to send it next



Here, the packet should be directed to IF#4

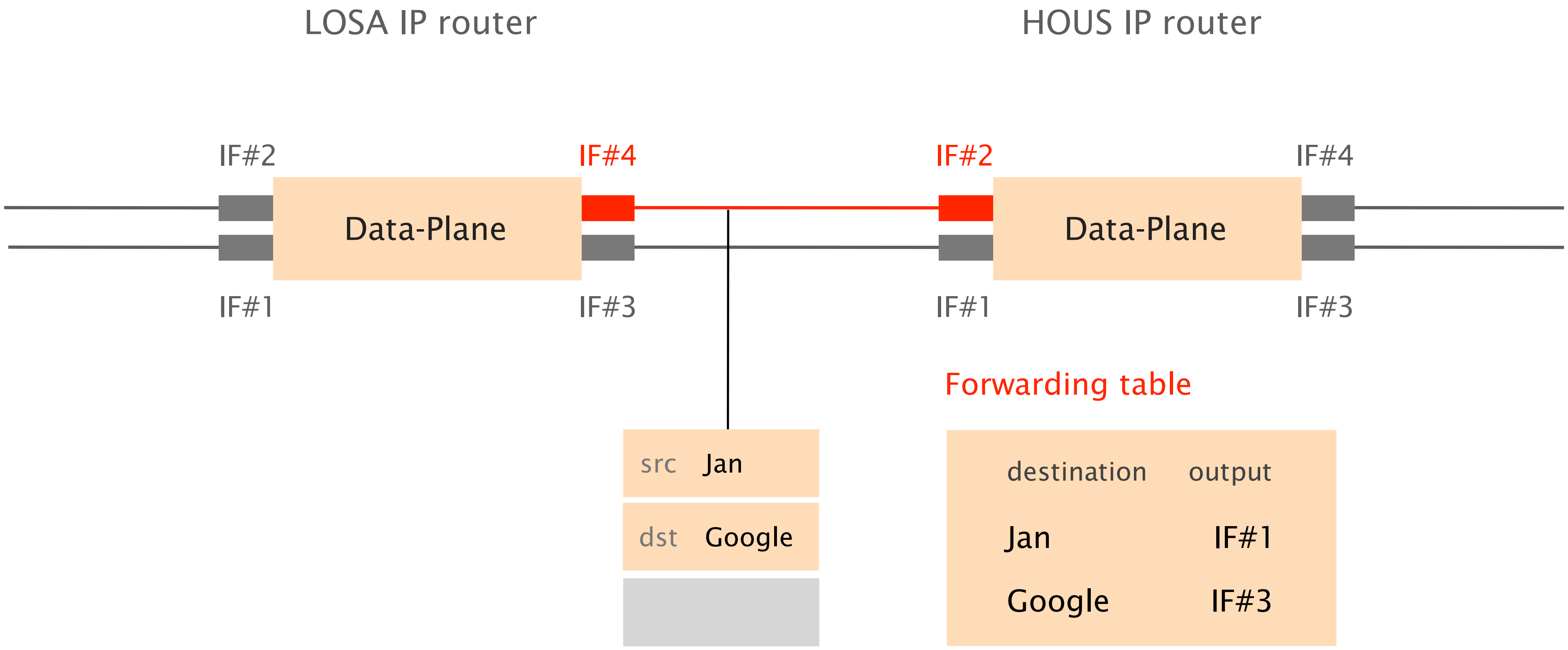


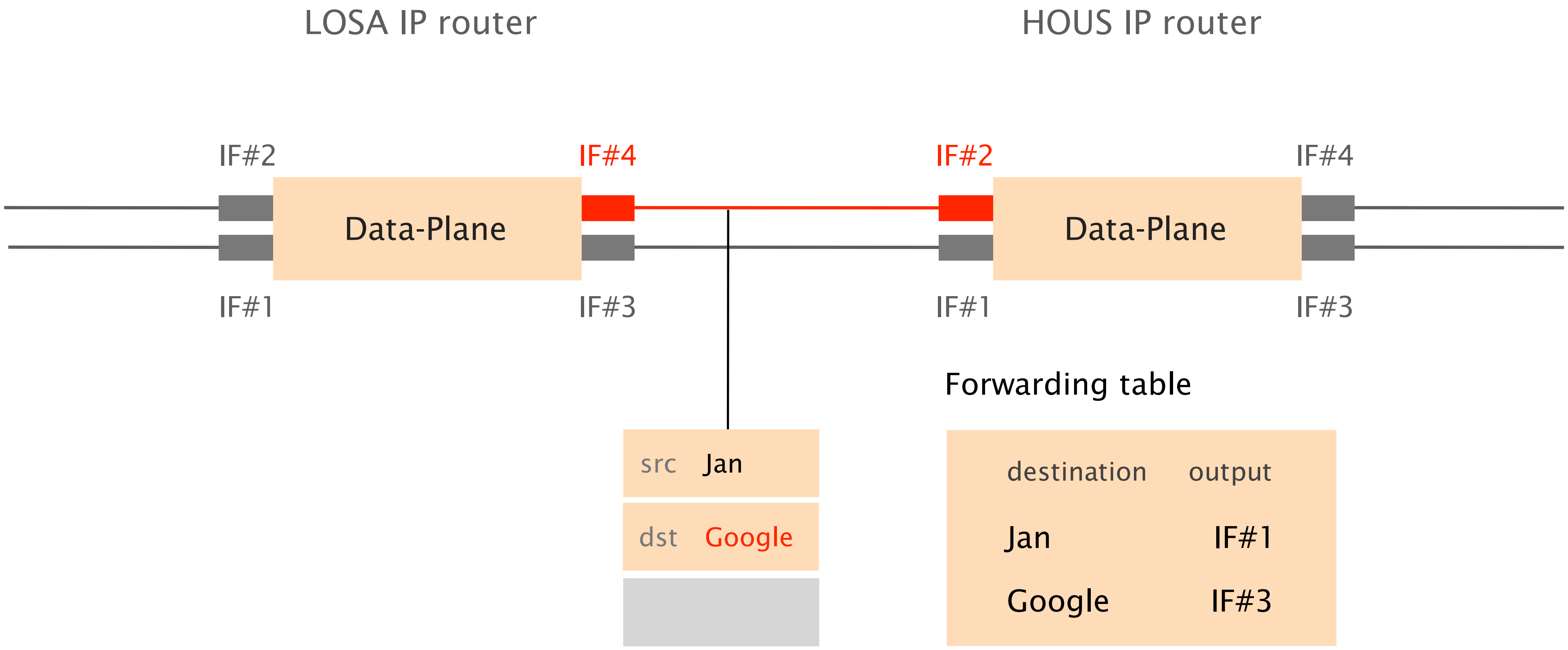
destination	output
Jan	IF#1
Google	IF#4



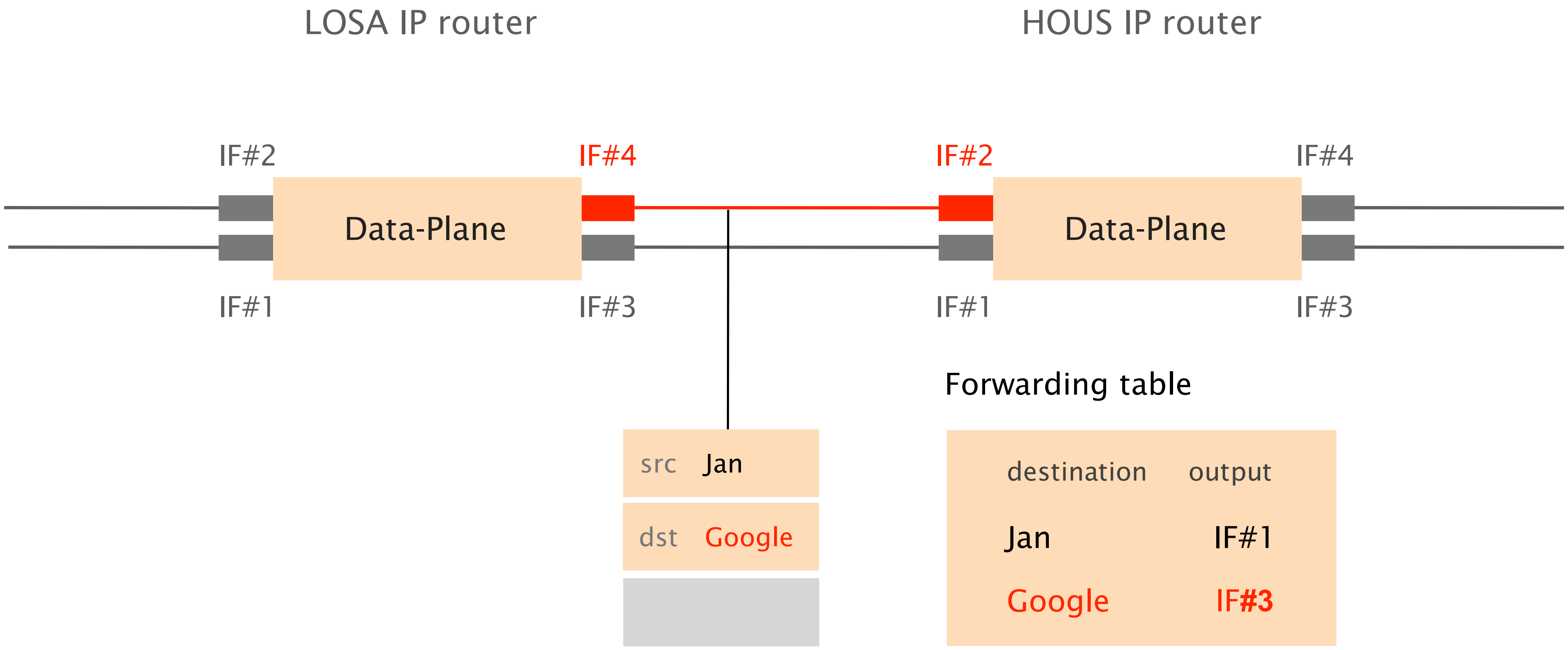
LOSA IP router
HOUS IP router
IF#2
IF#4
IF#2
IF#4
Data-Plane
Data-Plane
IF#1
IF#3
IF#1
IF#3
src Jan
dst Google

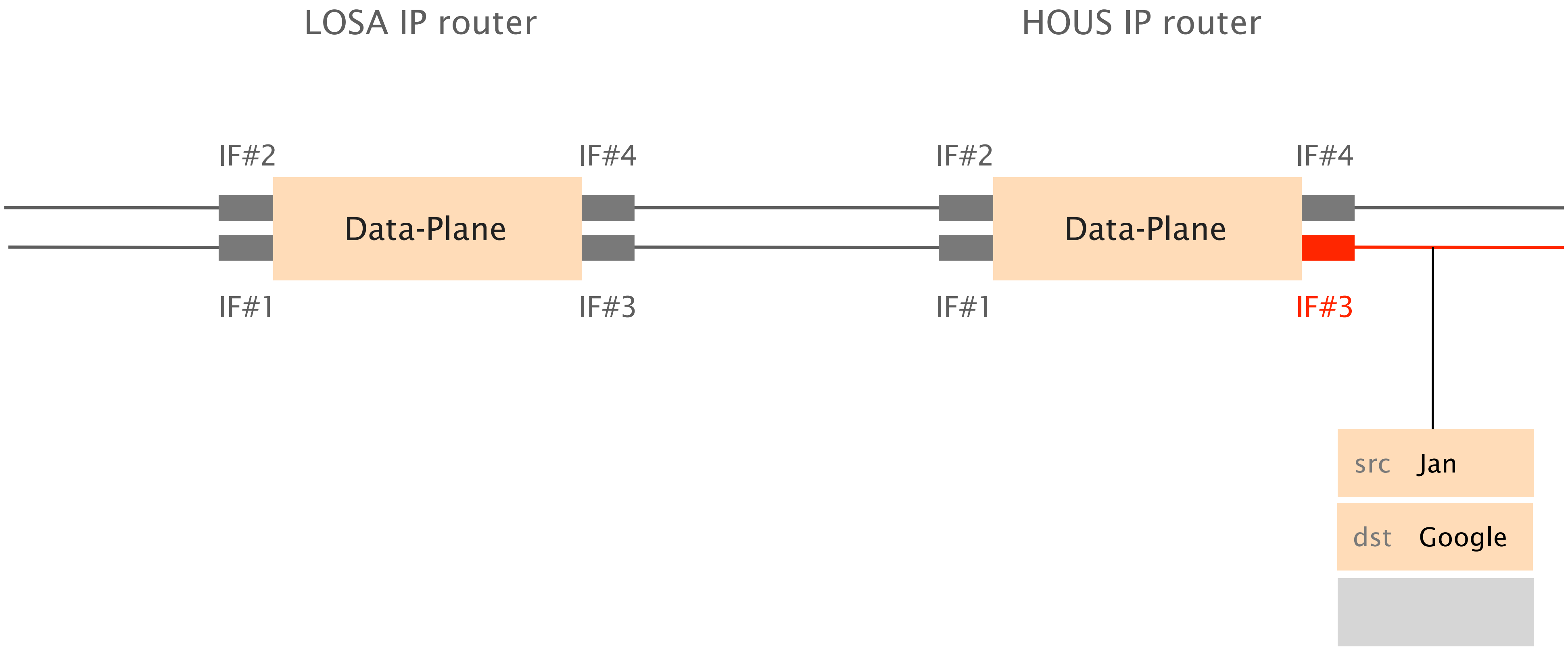
Forwarding is repeated at each router,
until the destination is reached



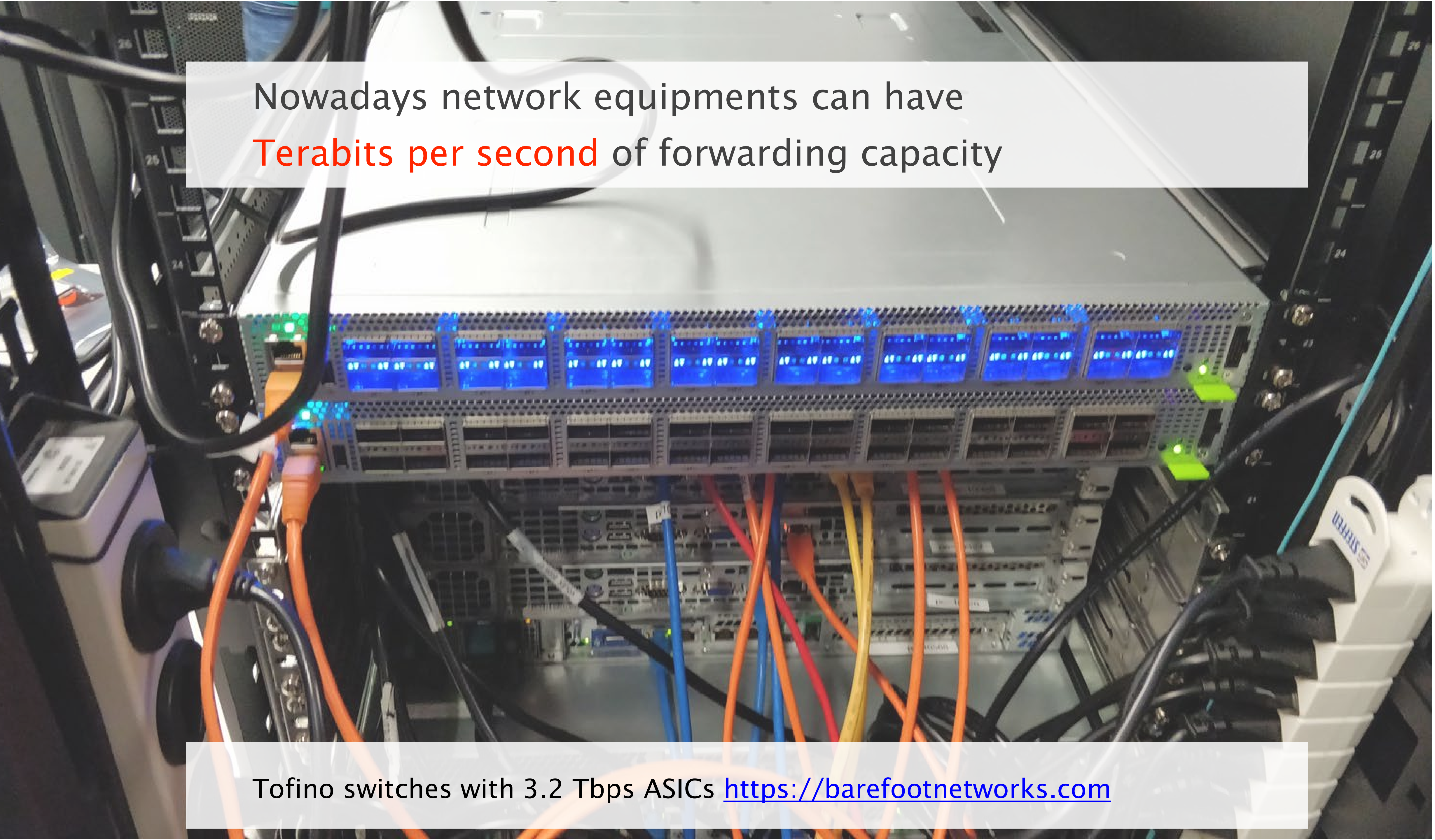


LOSA IP router
HOUS IP router
IF#2
IF#4
Data-Plane
IF#1
IF#3
IF#2
IF#4
Data-Plane
IF#1
IF#3
src Jan
dst Google
Forwarding table
destination output
Jan IF#1
Google IF#3


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 Jan
dst Google
destination output
Jan 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 Jan
dst Google

Nowadays network equipments can have
Terabits per second of forwarding capacity

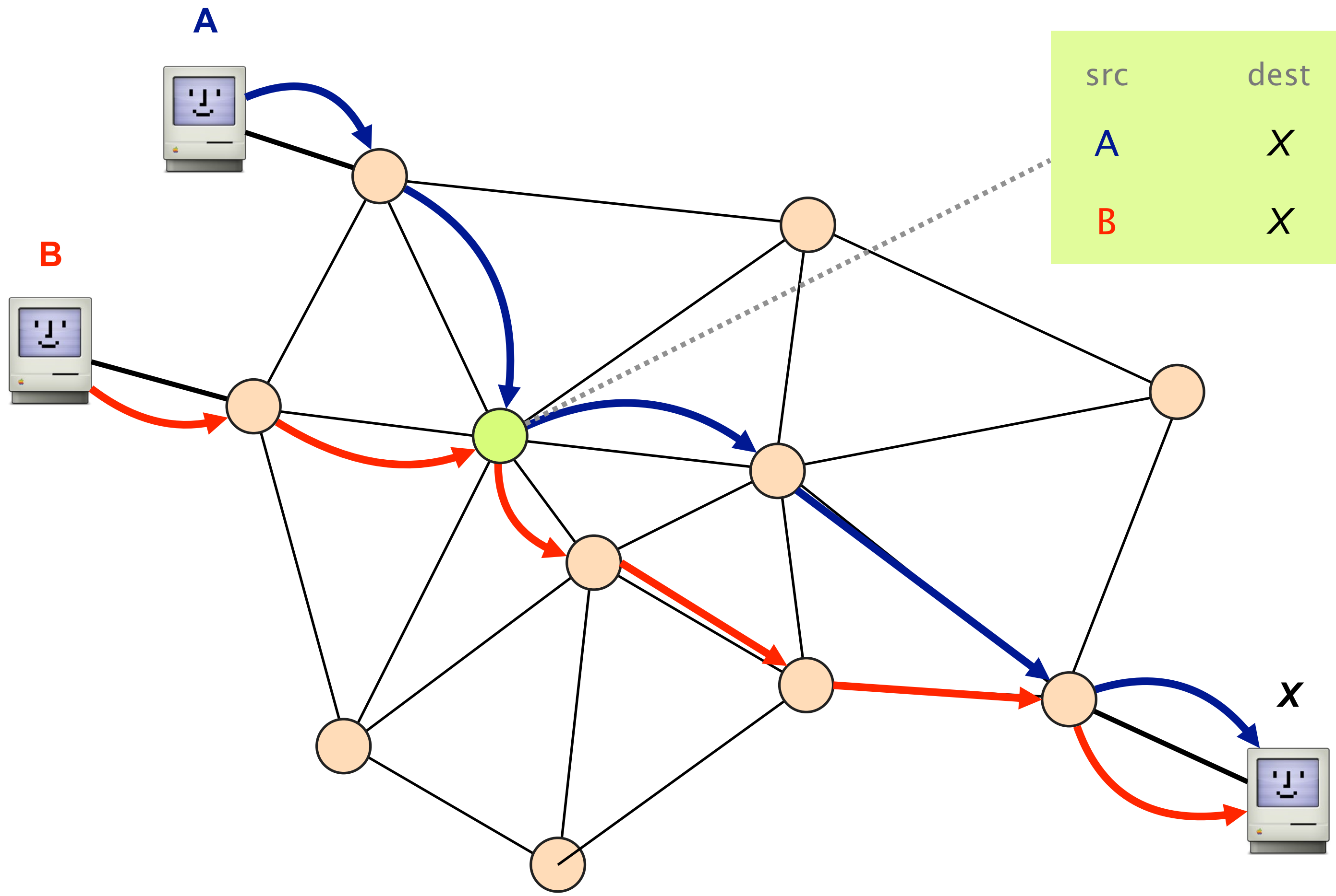


Tofino switches with 3.2 Tbps ASICs https://barefootnetworks.com

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
	+any other header	

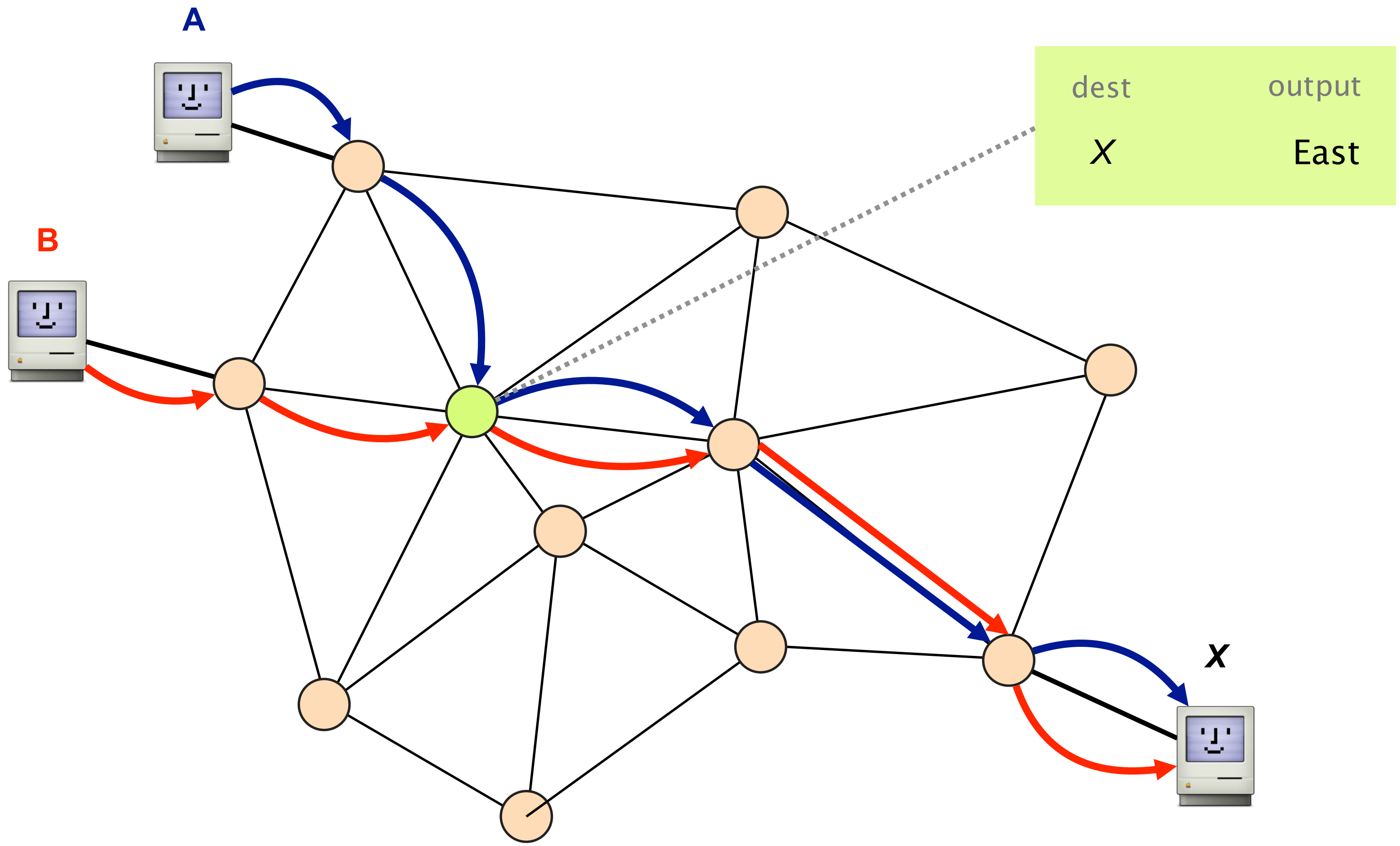
With source- & destination-based routing, paths from different sources can differ



src	dest	output
A	X	East
B	X	South-East

With **destination-based routing**,

paths from different source coincide once they overlap



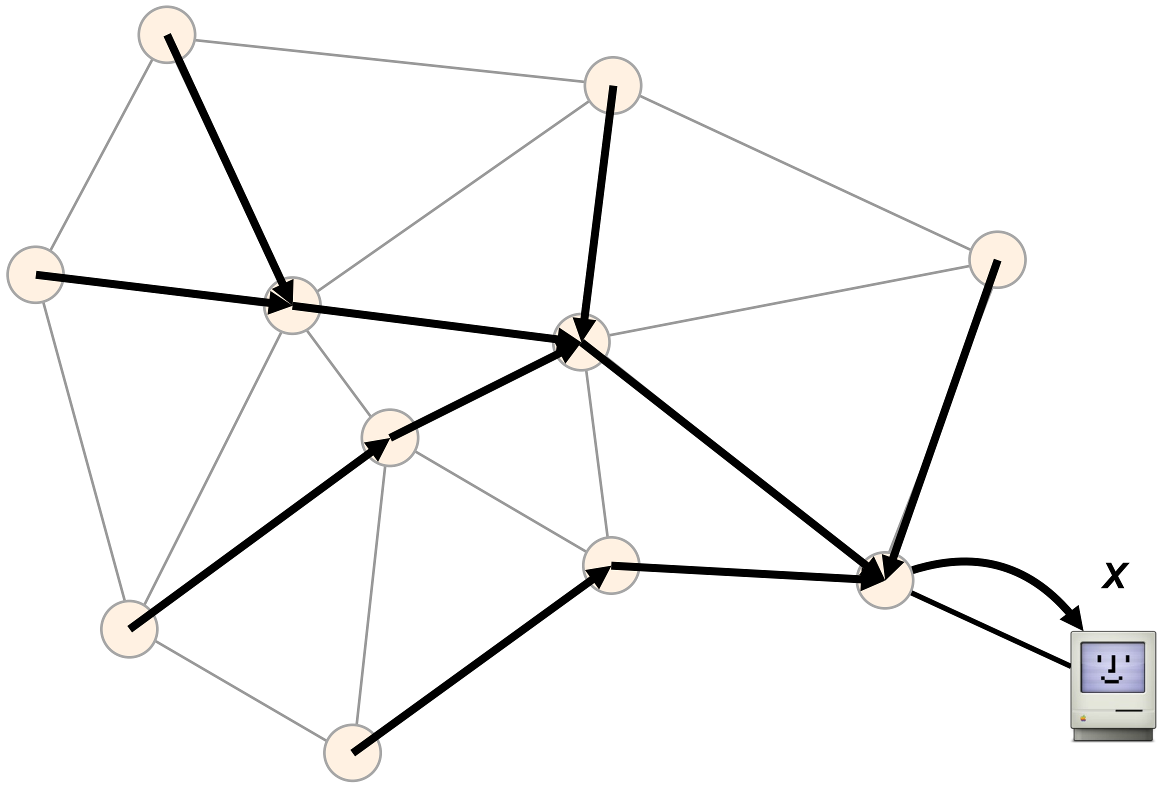
Once paths to destination meet, they will *never* split

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

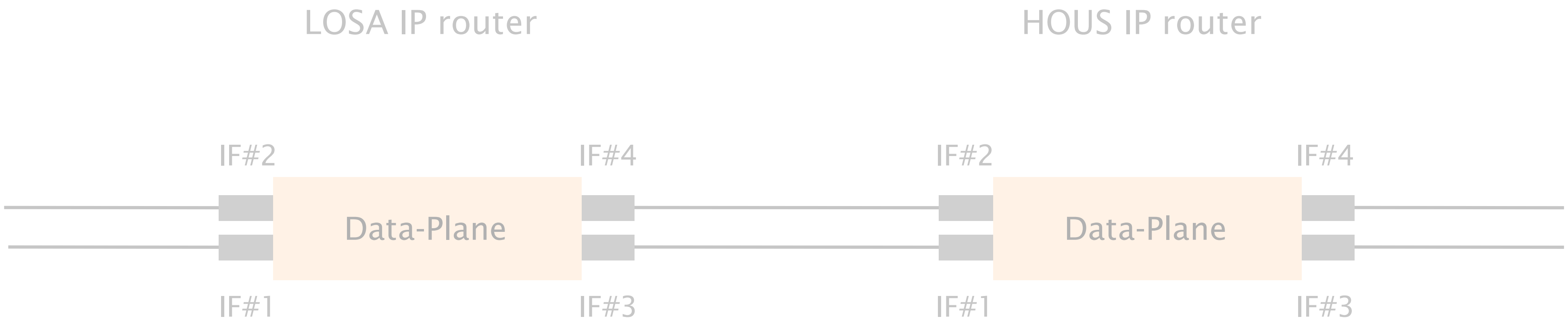
Here is an example of a spanning tree for destination *X*



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
Jan	IF#1
Google	IF#4

Forwarding table

destination	output
Jan	IF#1
Google	IF#3


Data-Plane
Data-Plane

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

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

Roles

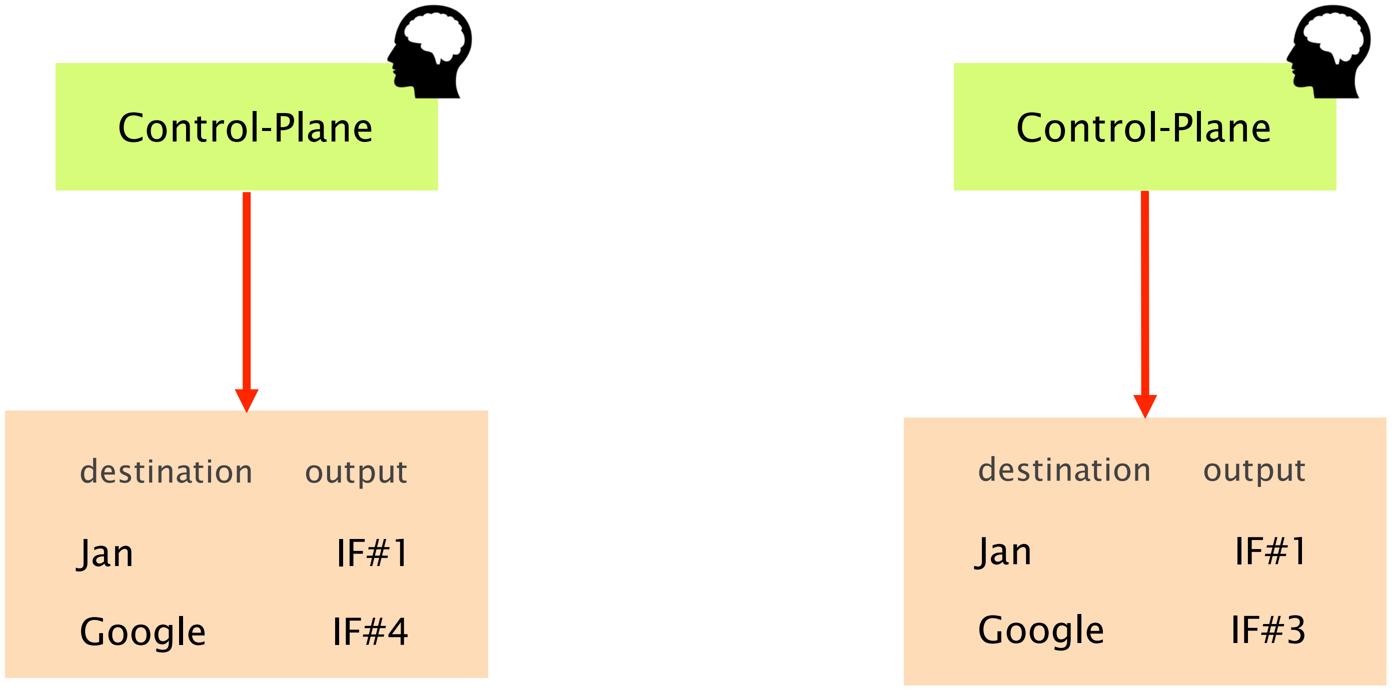
Routing

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 usually
timescale	nanoseconds	milliseconds (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

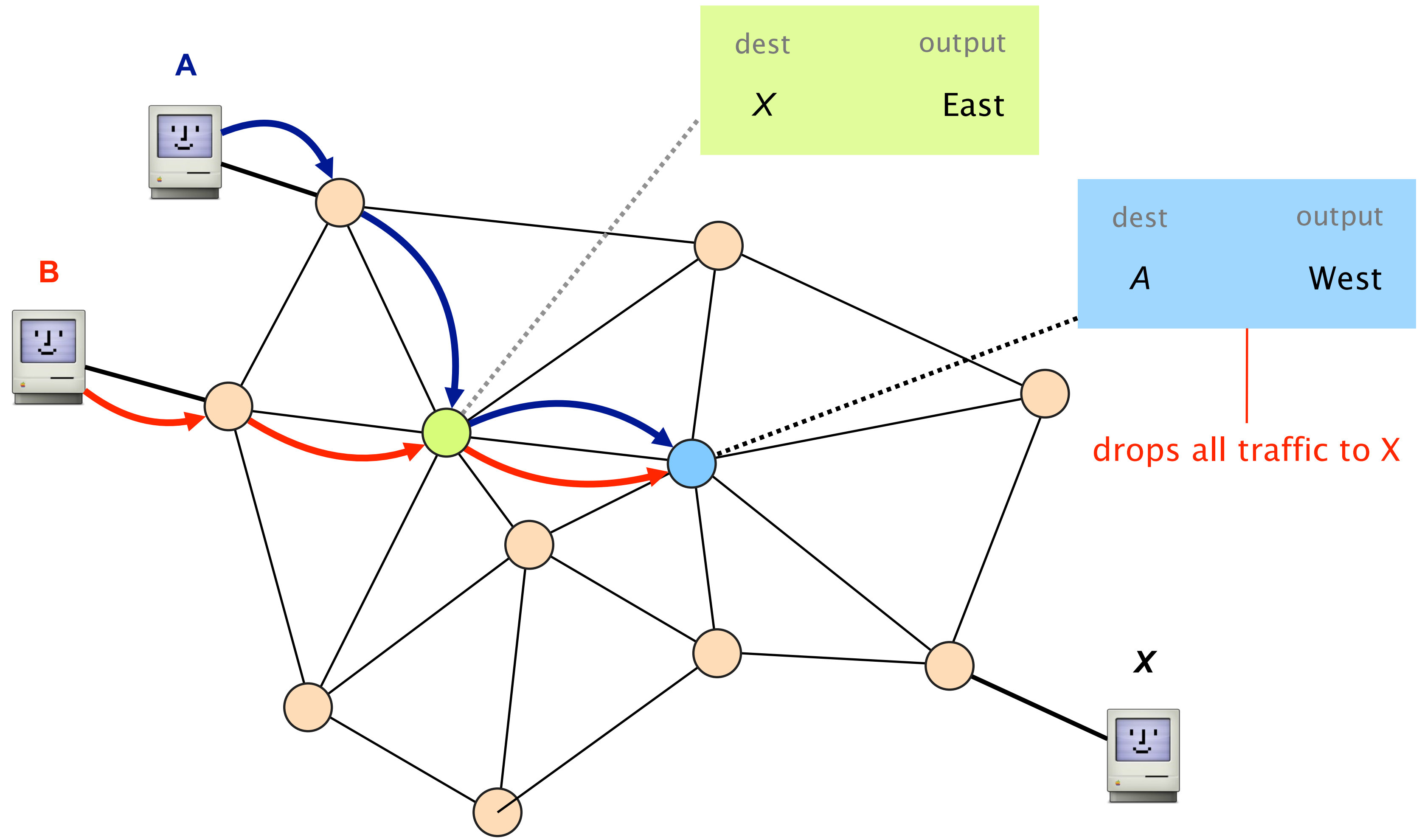
- there are no dead ends

  no outgoing port defined in the table

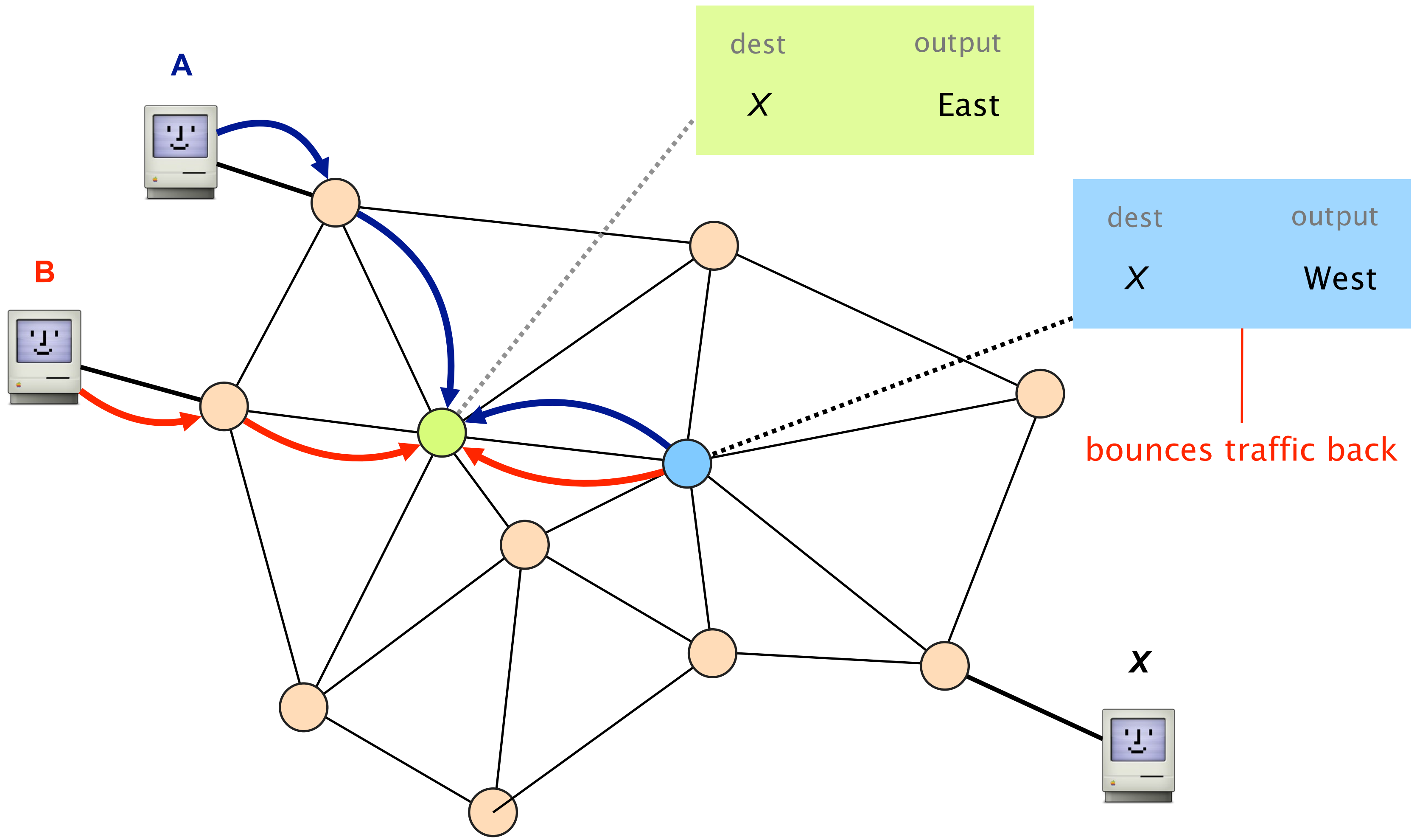
- there are no loops

  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

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

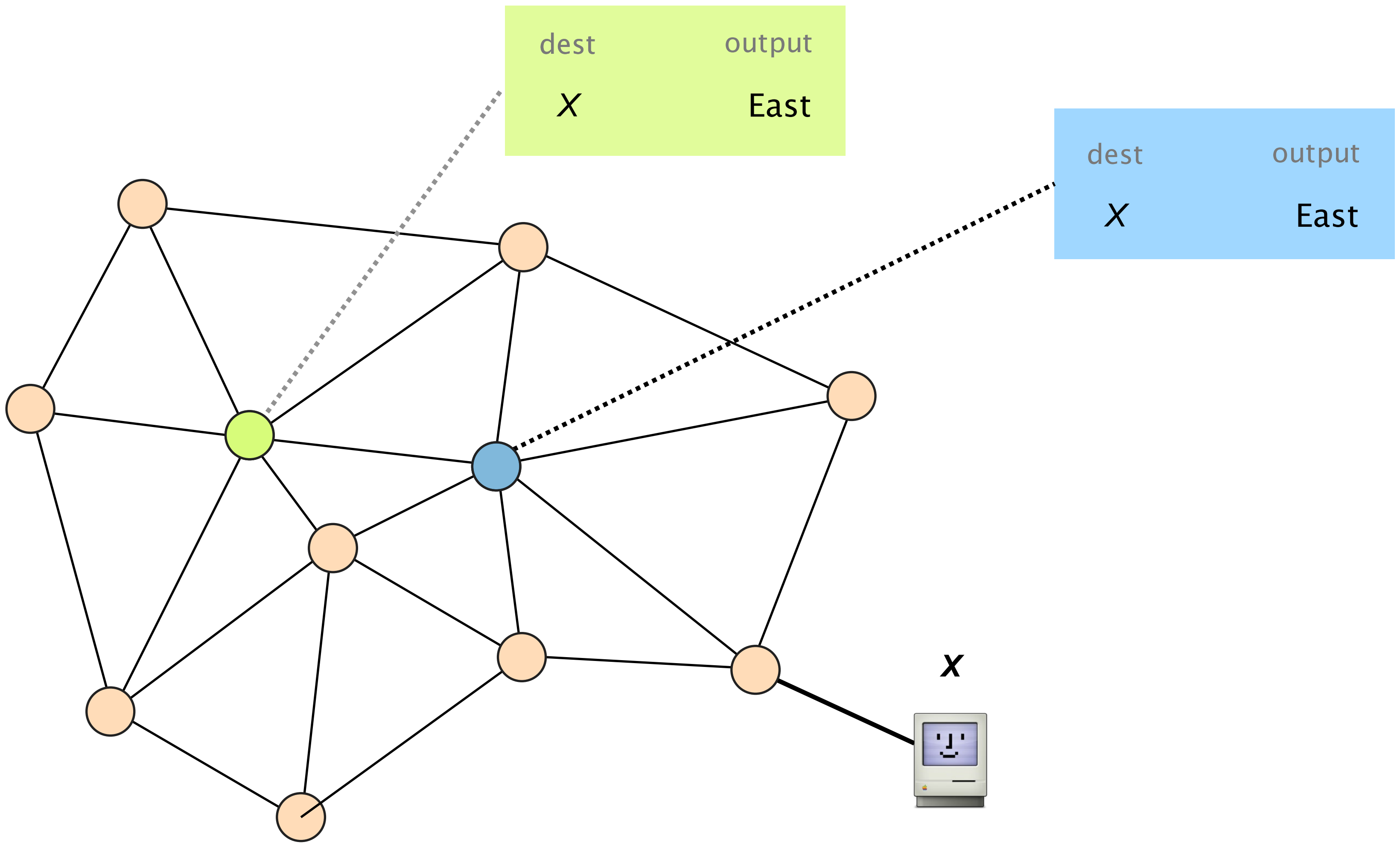
for one destination

Mark all outgoing ports with an arrow

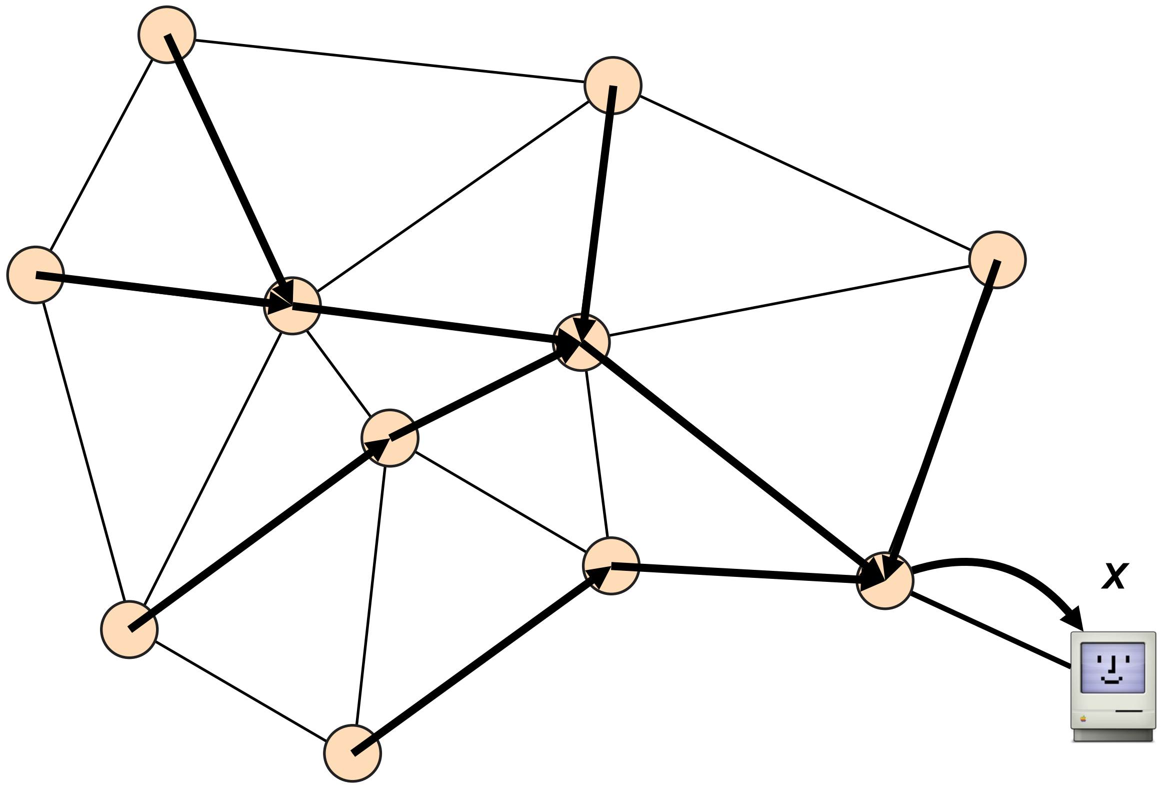
Eliminate all links with no arrow

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

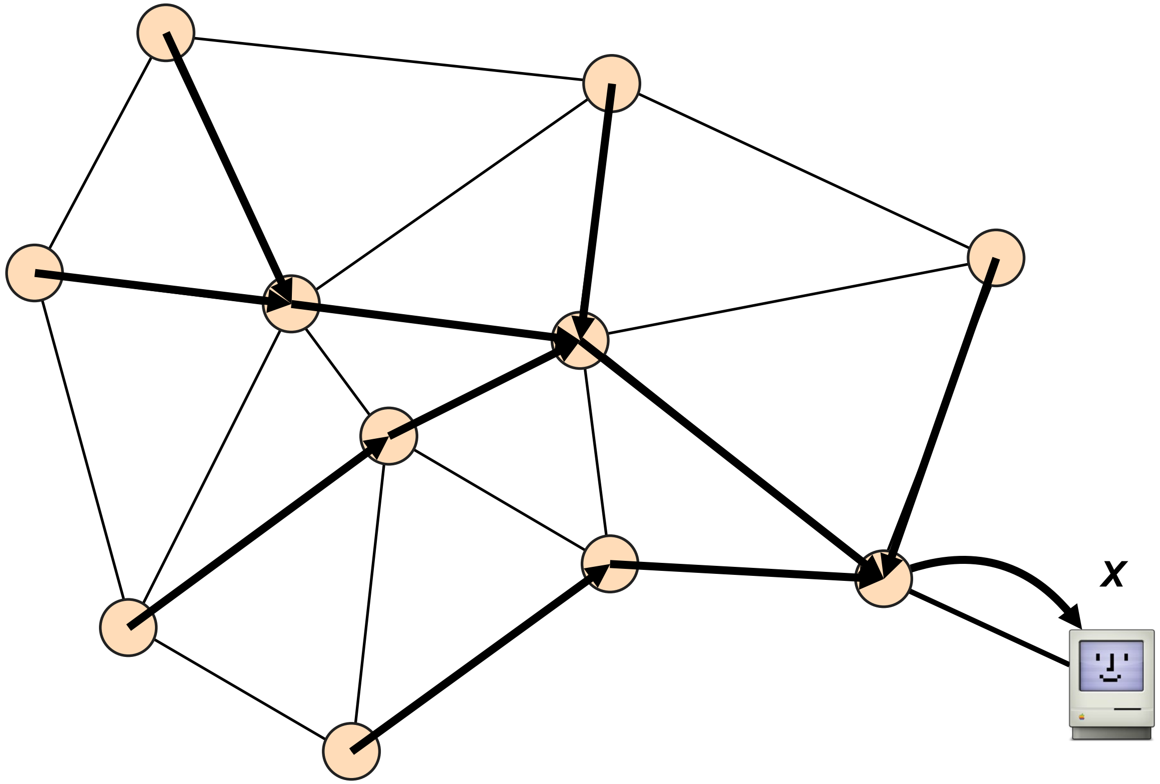
Given a graph with the corresponding forwarding state

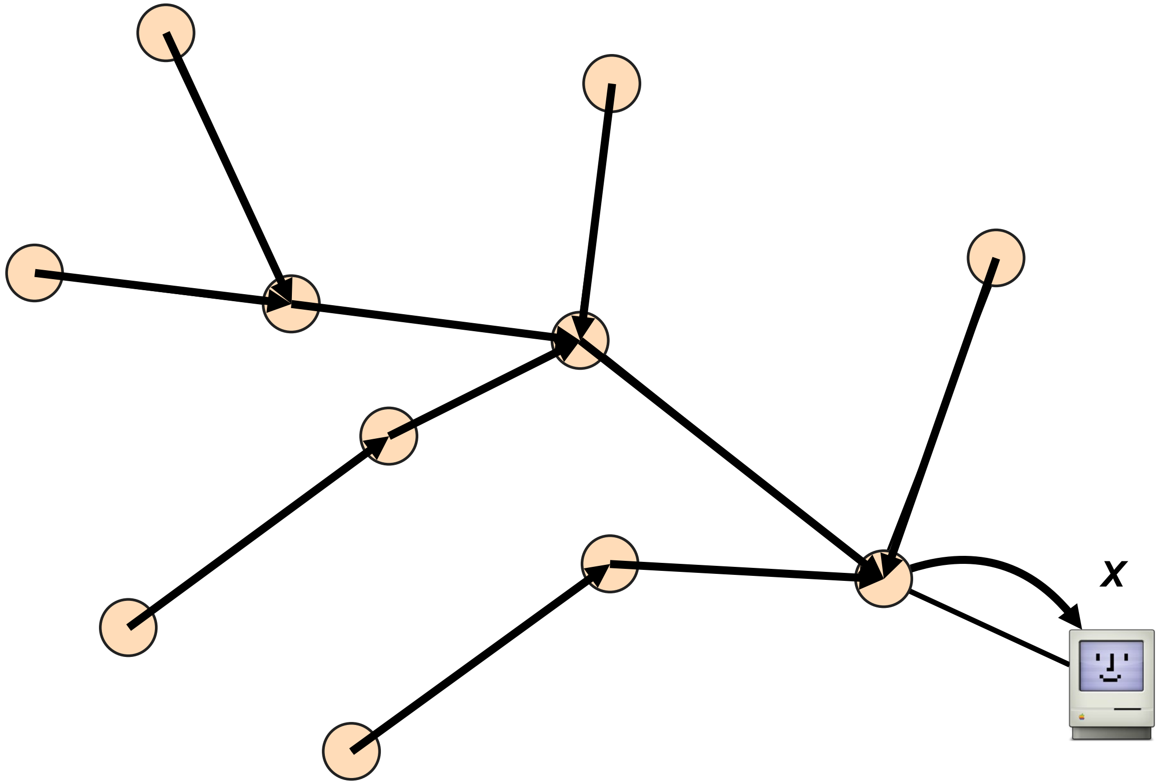


Mark all outgoing ports with an arrow



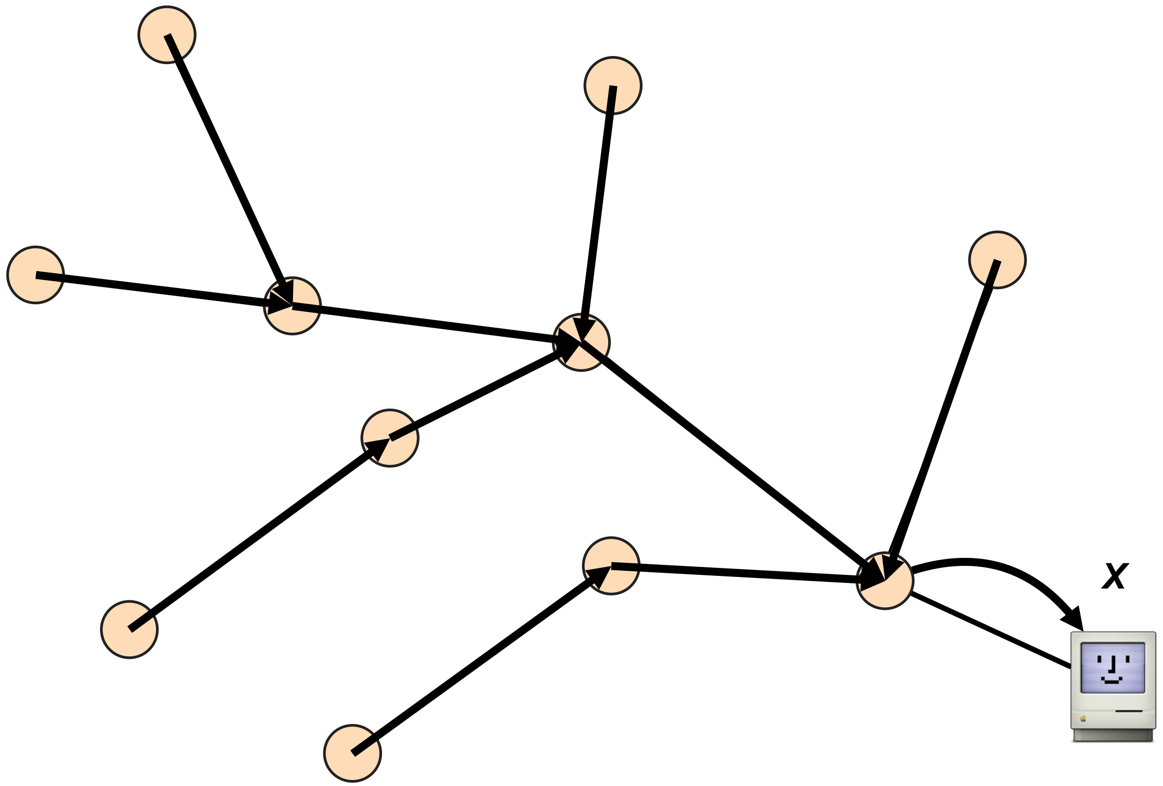
Eliminate all links with no arrow



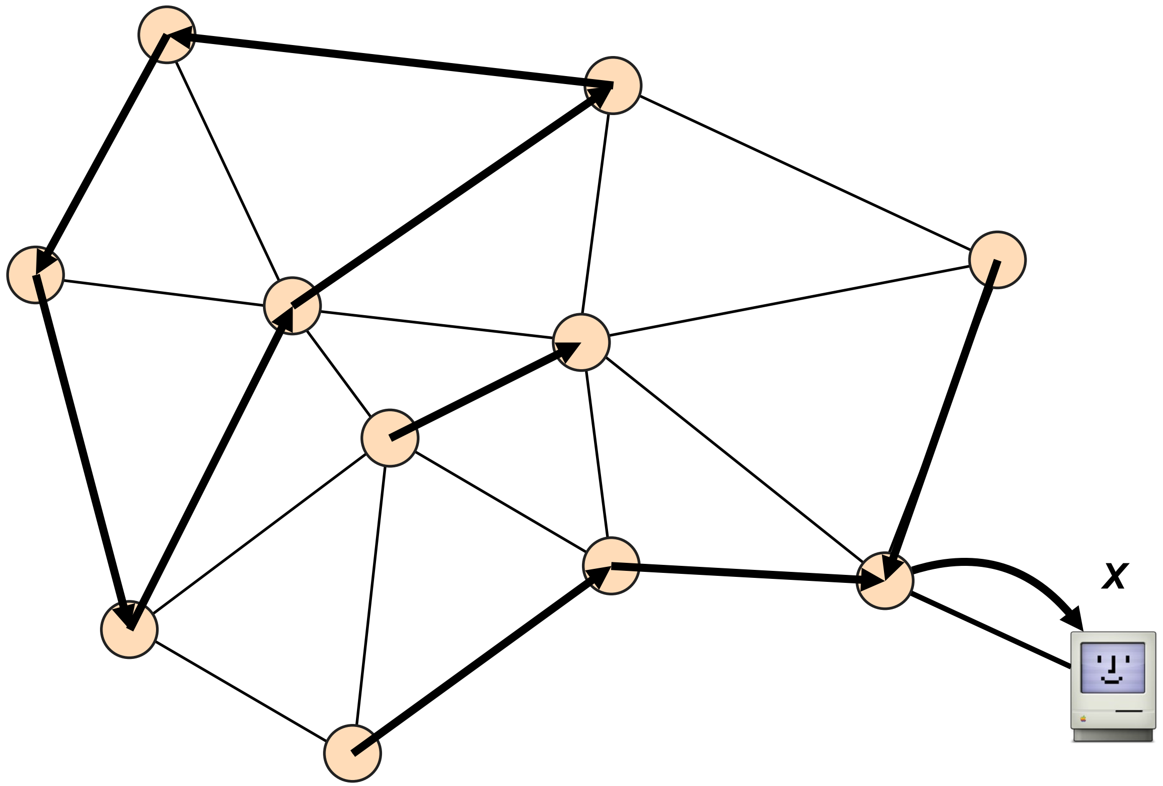

X

The result is a spanning tree.

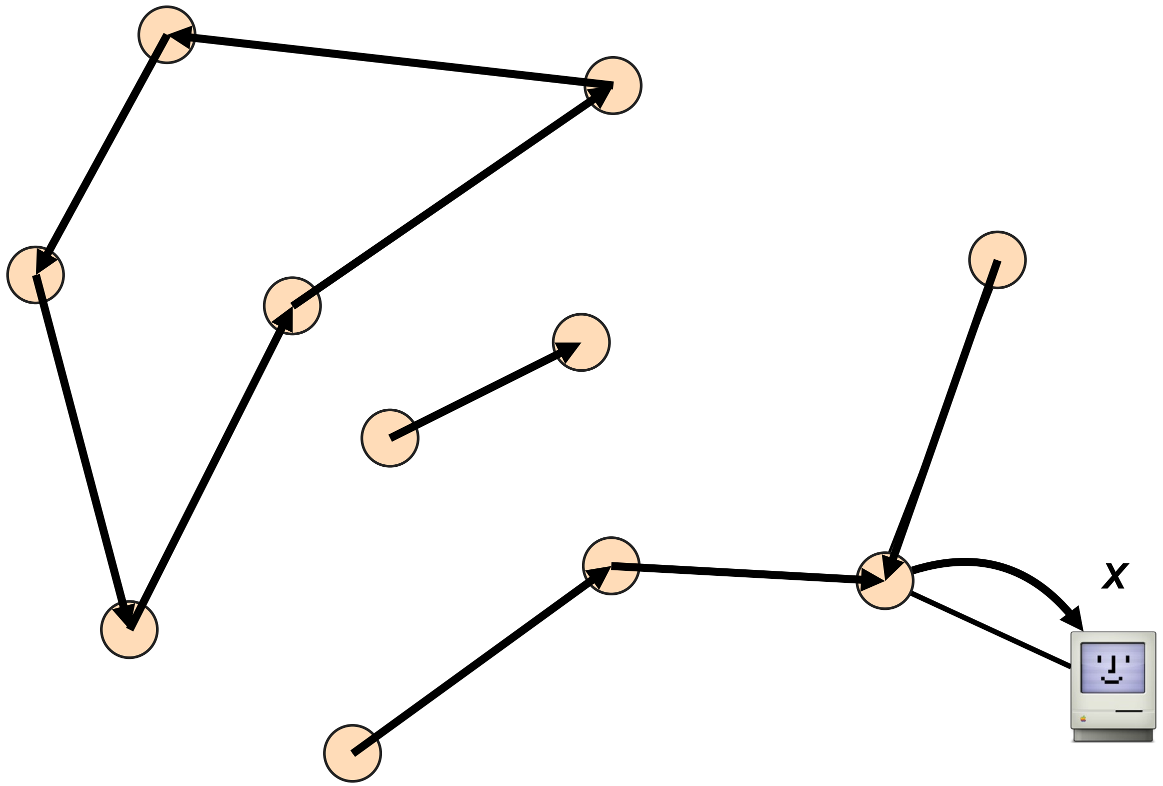
This is a valid routing state



Mark all outgoing ports with an arrow

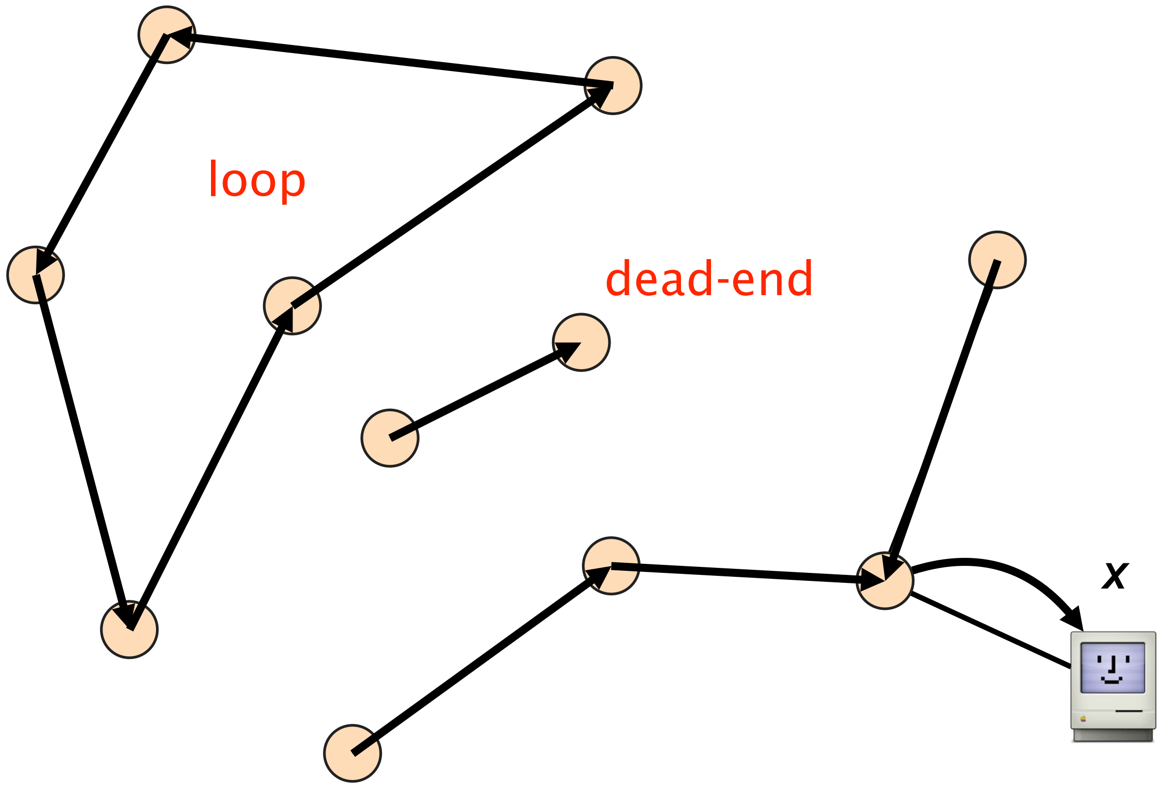


Eliminate all links with no arrow



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

Existing routing protocols differ in

how they avoid loops

prevent loops

hard

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 route traffic on a loop-free topology

simple algorithm

Take an arbitrary topology

Build a spanning tree and ignore all other links

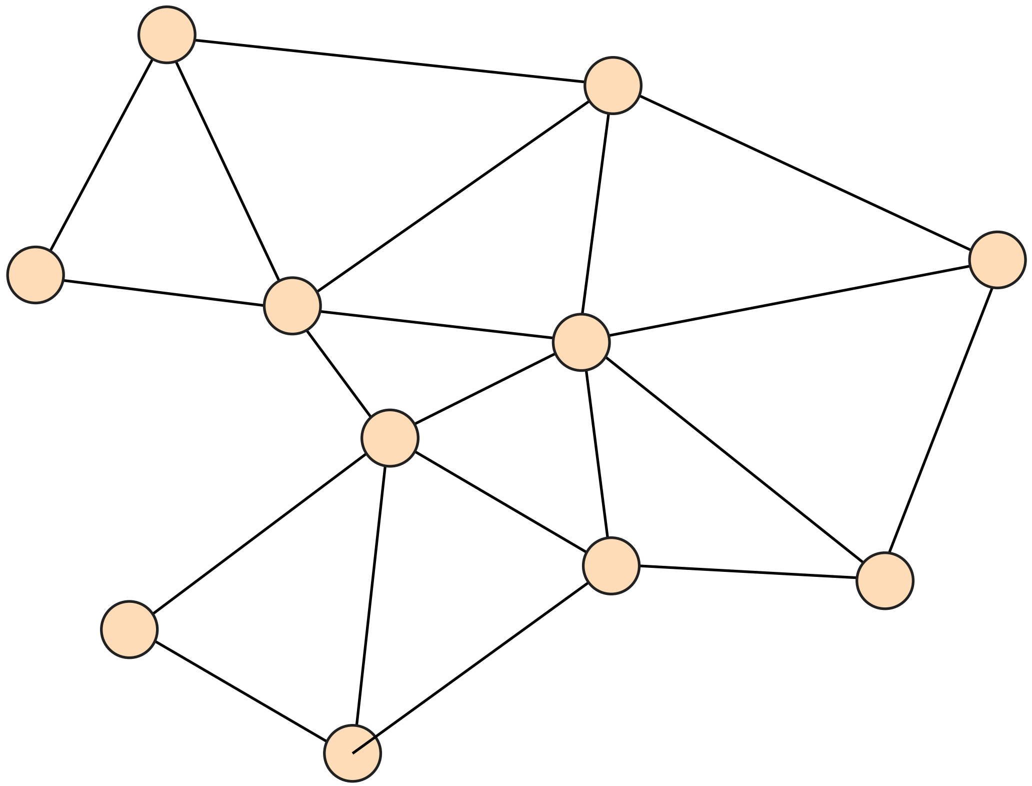
Done!

Why does it work?

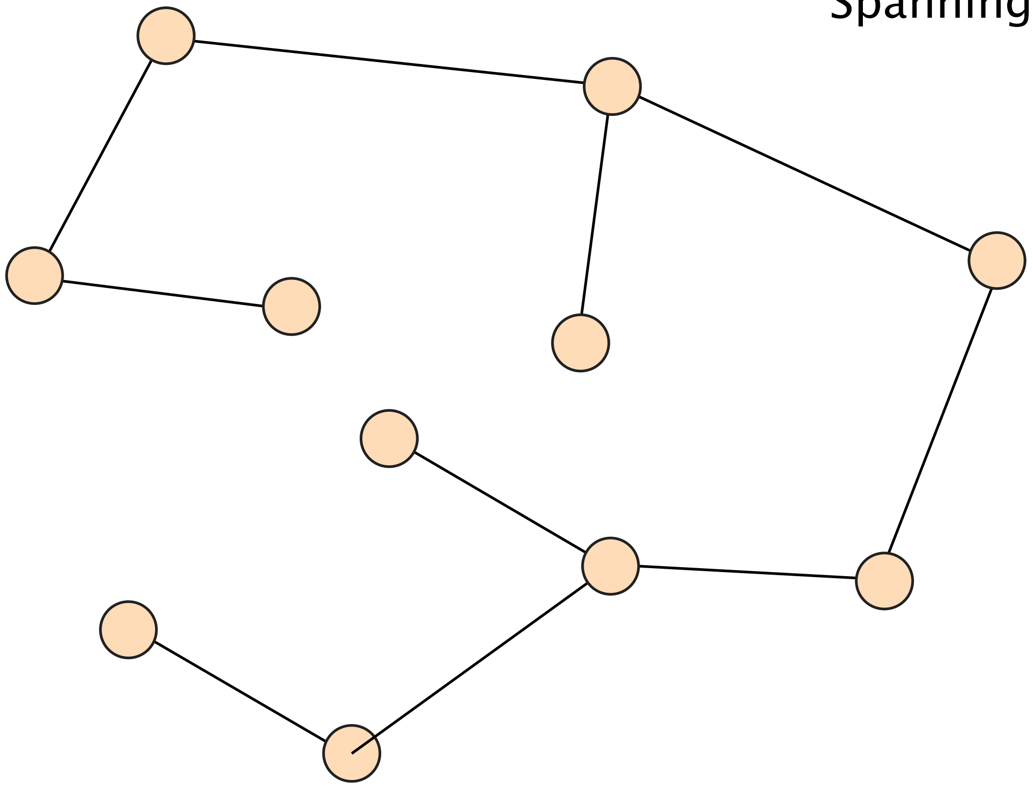
Spanning-trees have only one path between any two nodes

In practice,

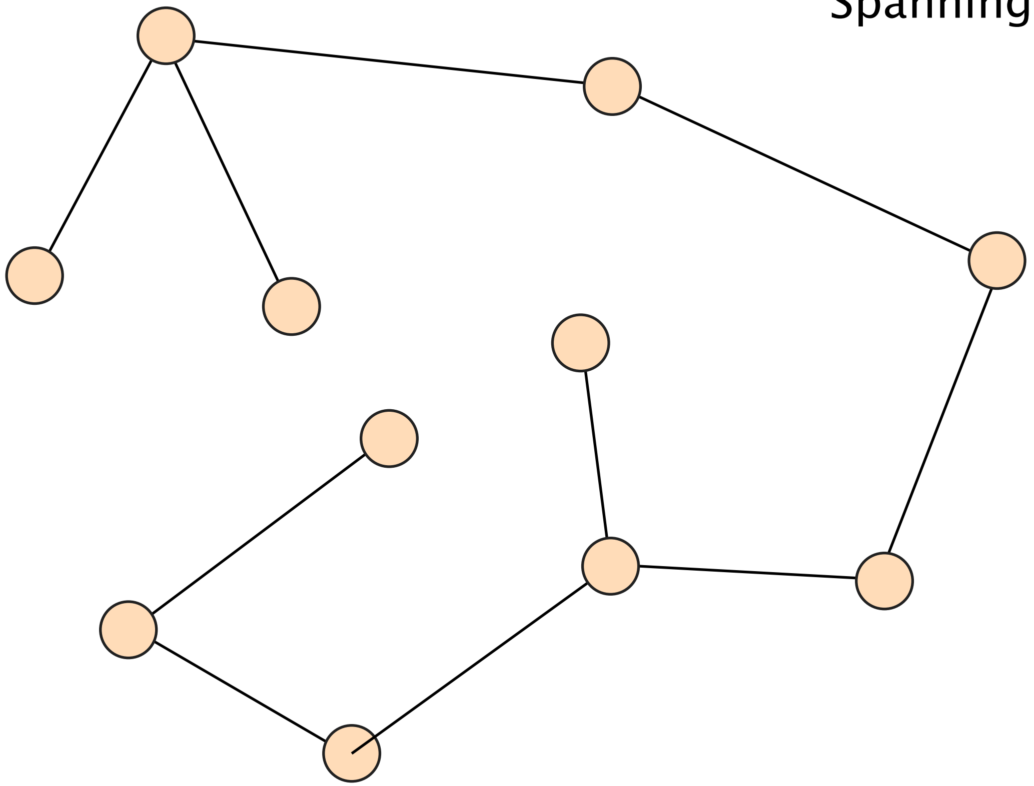
there can be *many* spanning-trees for a given topology



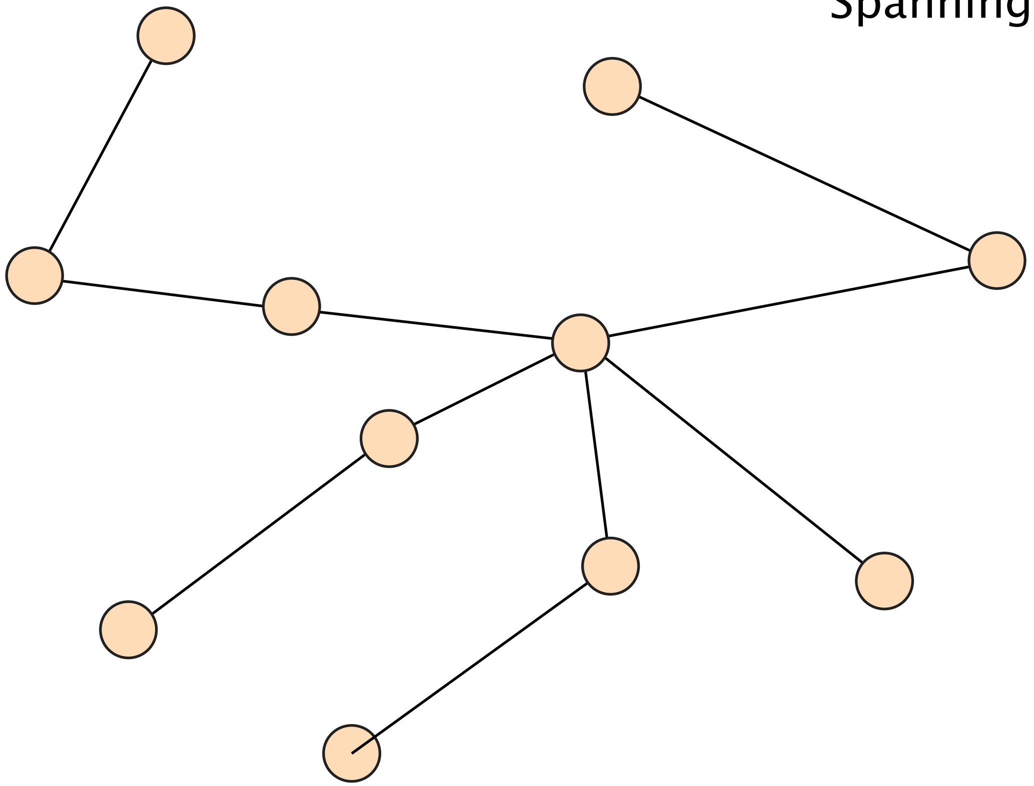
Spanning-Tree #1



Spanning-Tree **#2**



Spanning-Tree **#3**



We'll see how to compute spanning-trees in 2 weeks.

For now, assume it is possible

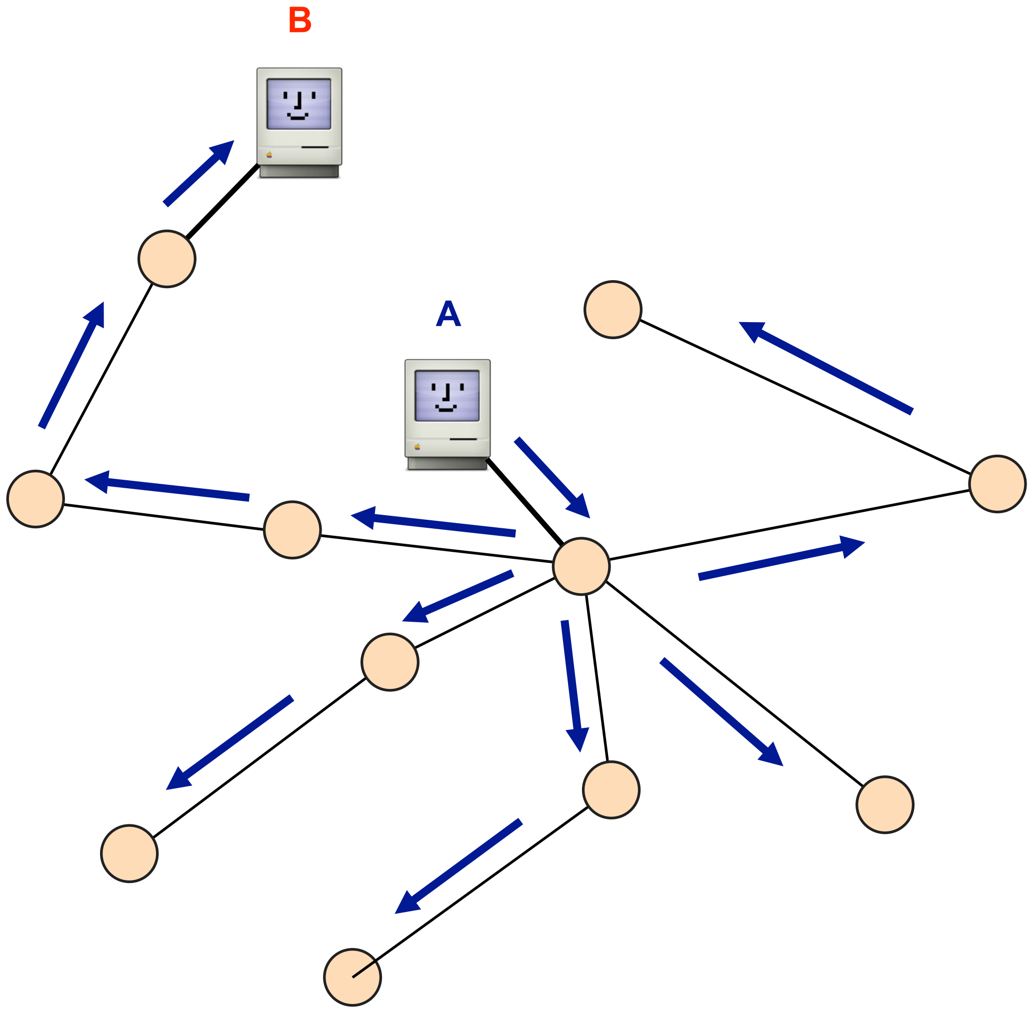
Once we have a spanning tree,

forwarding on it is easy

literally just flood

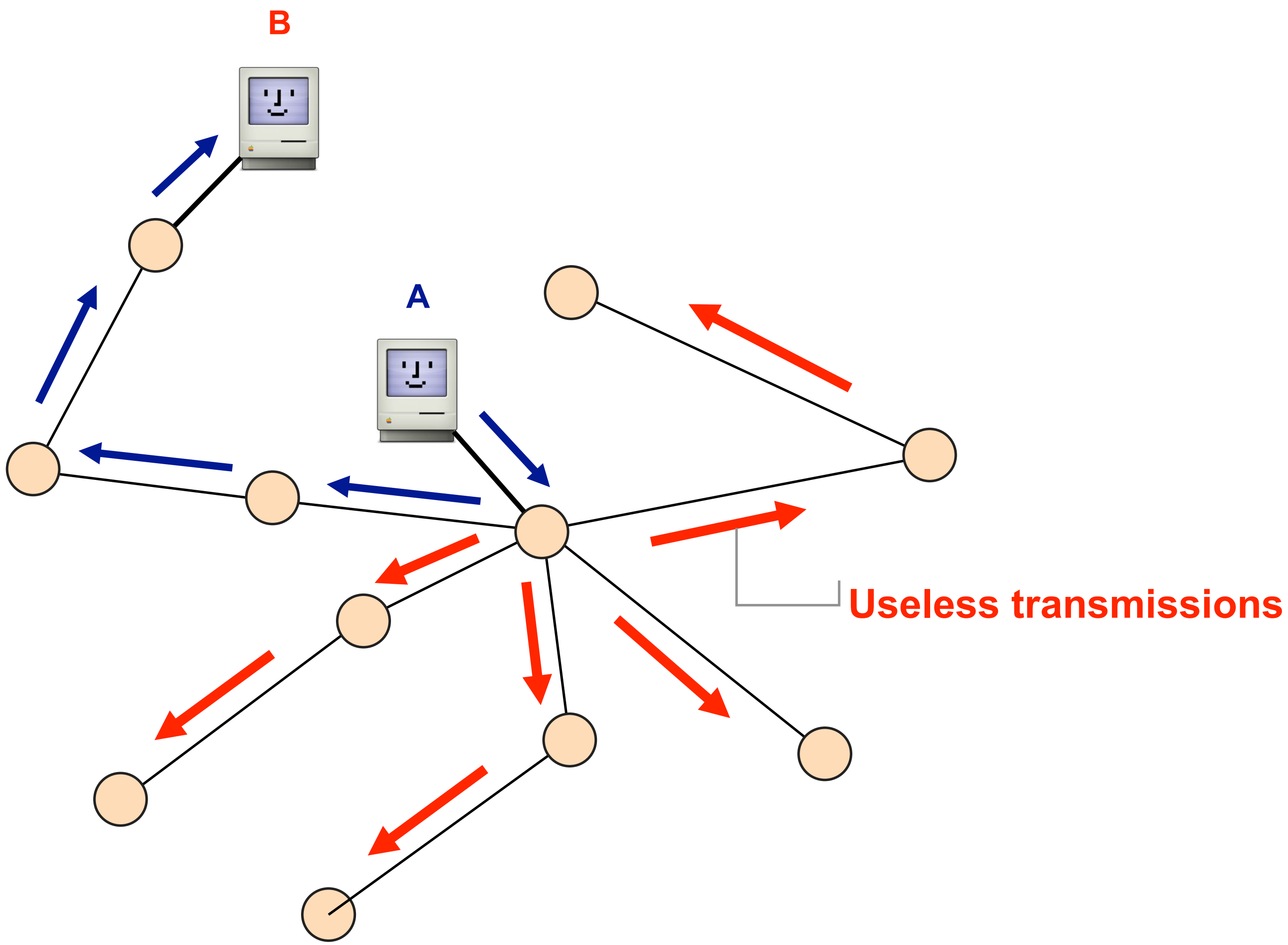
the packets everywhere

When a packet arrives,
simply **send it on all ports**



While flooding works,

it is quite wasteful



The issue is that nodes do not know their

respective locations

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

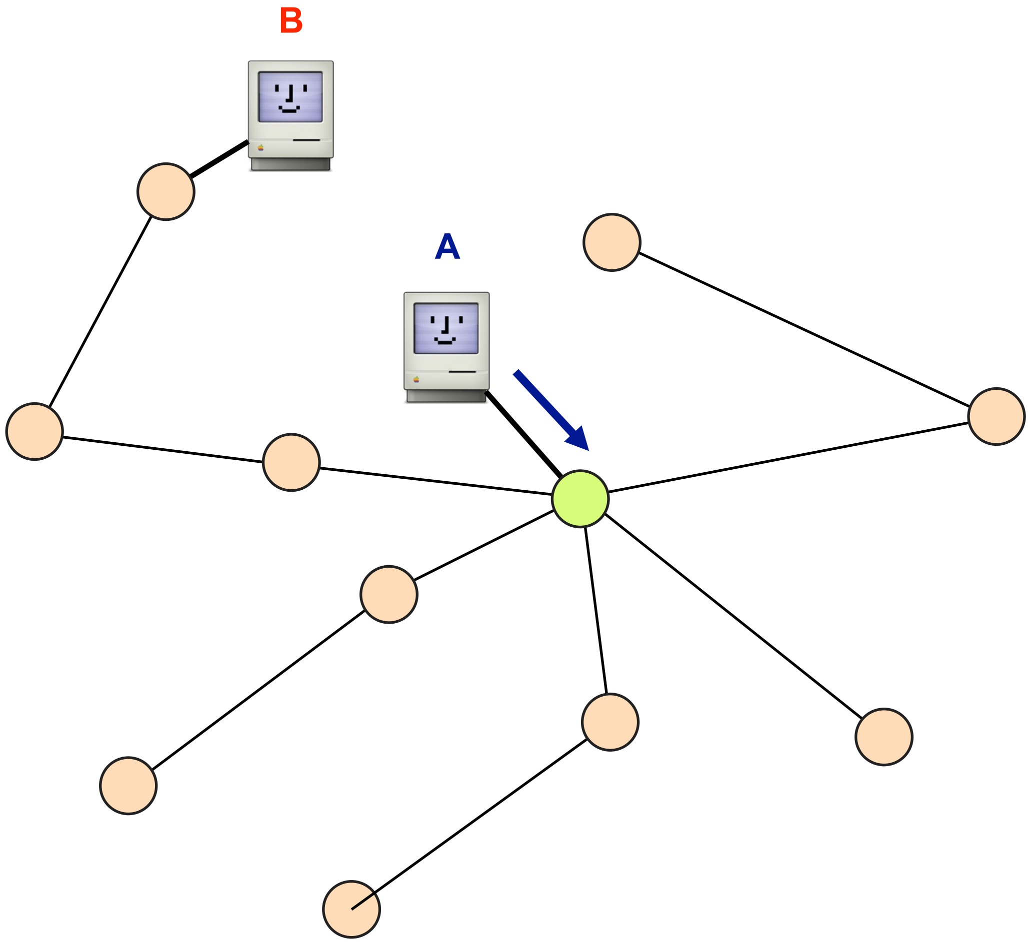
intuition

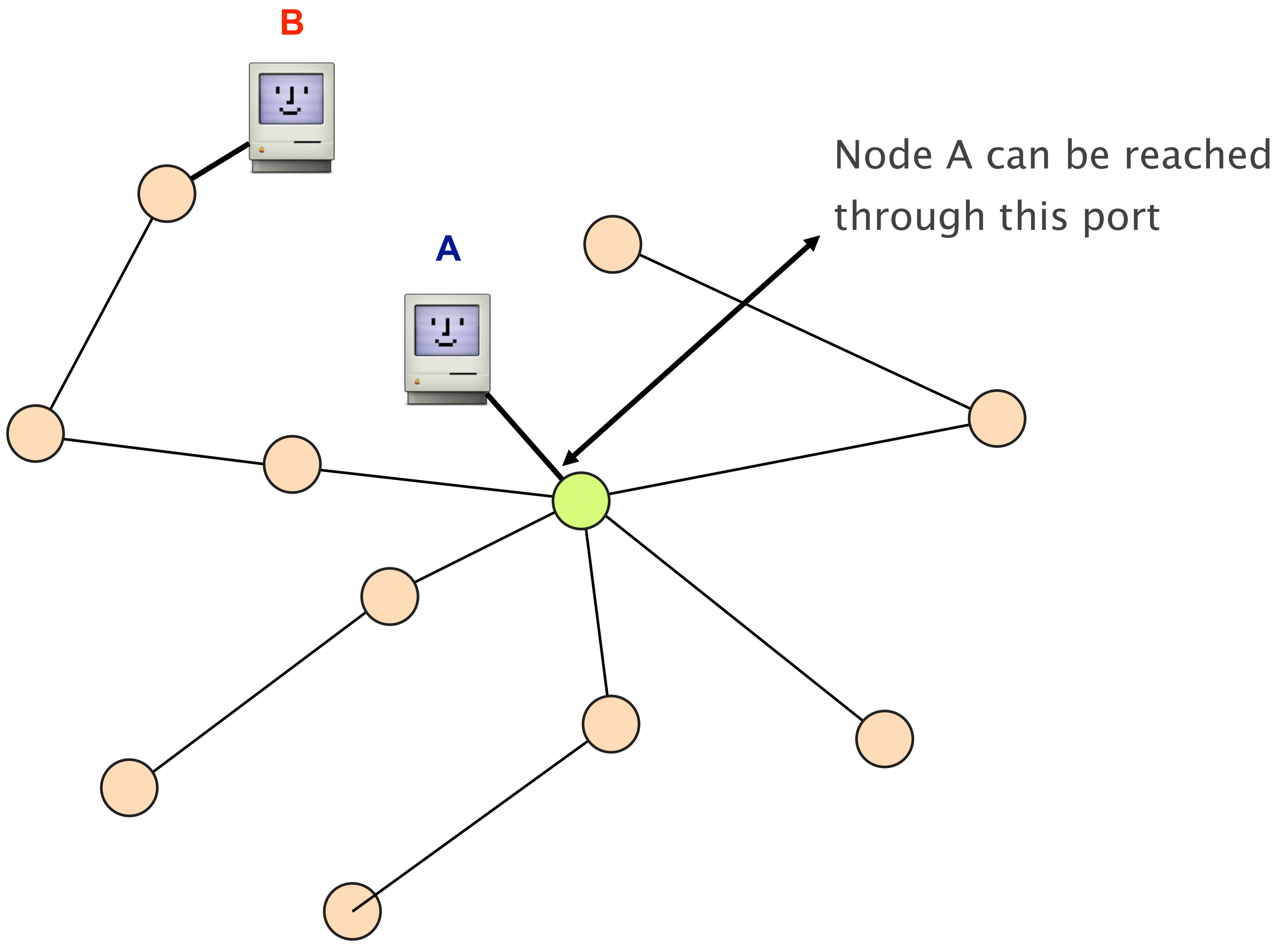
if

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

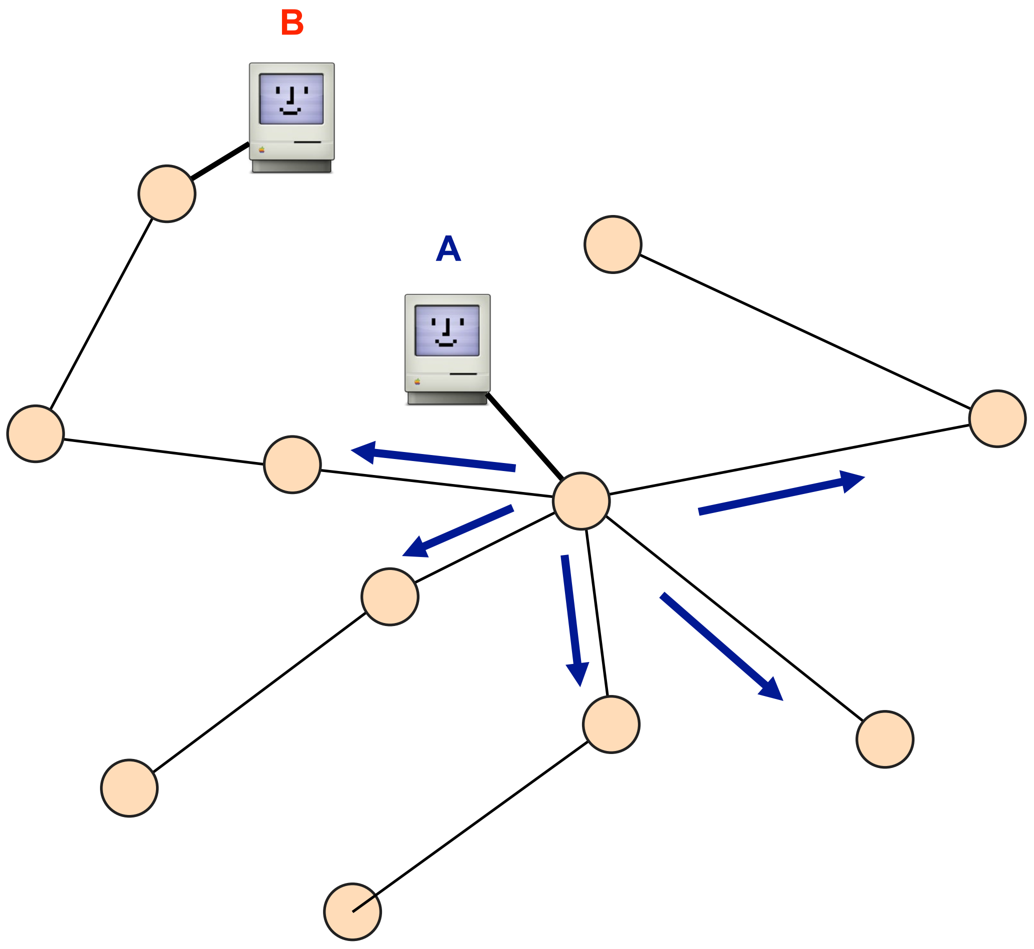
then

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

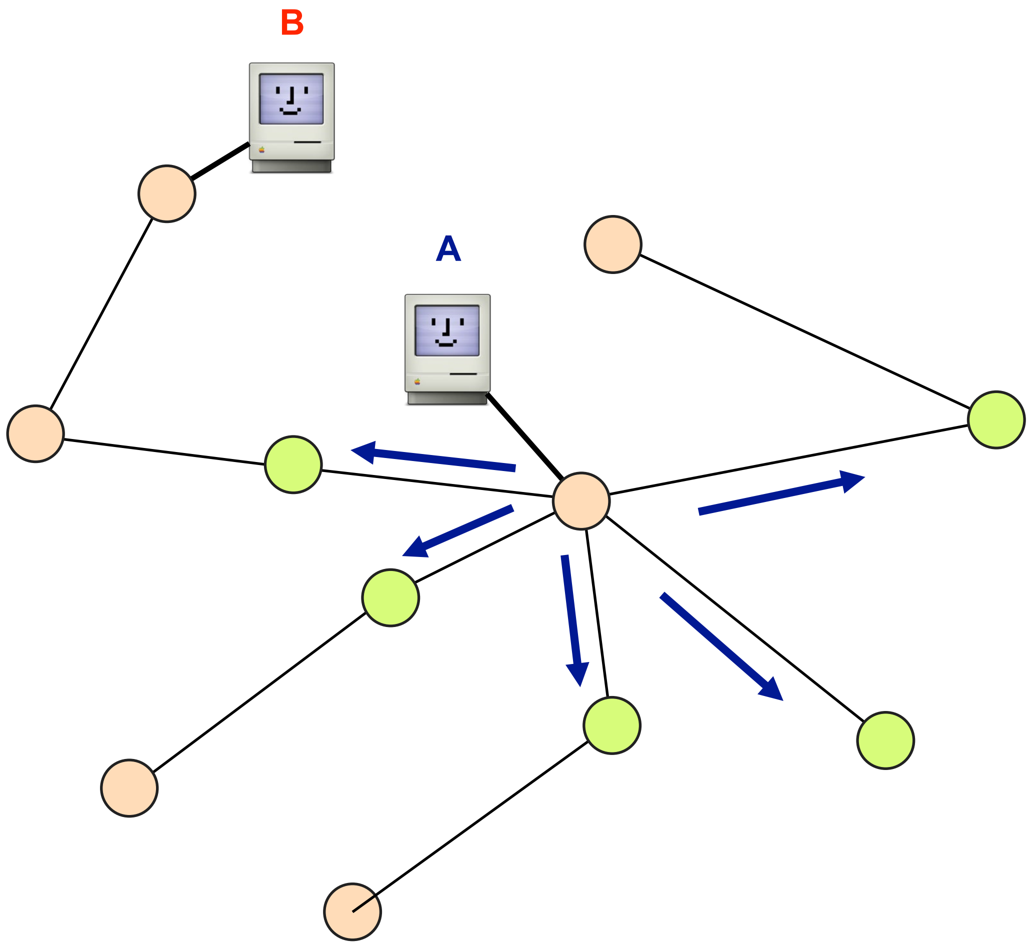

B
A



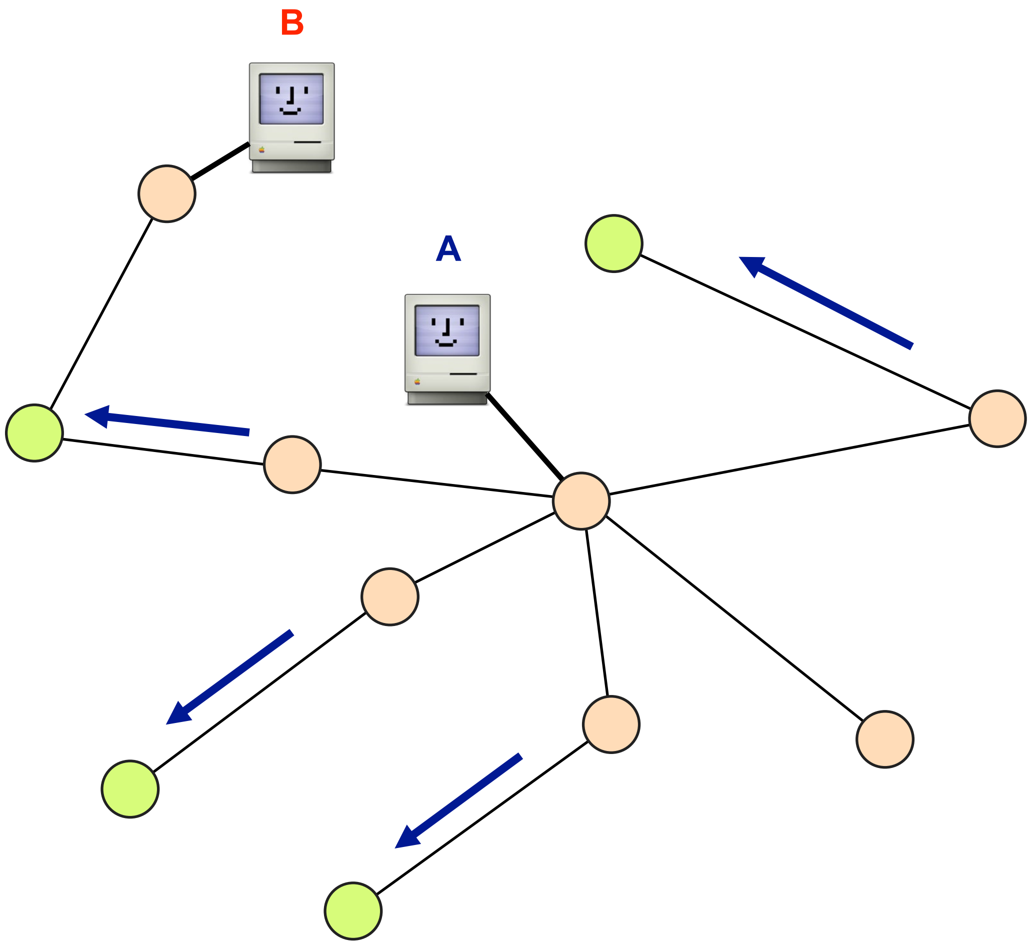
B
A
Node A can be reached
through this port


B
A

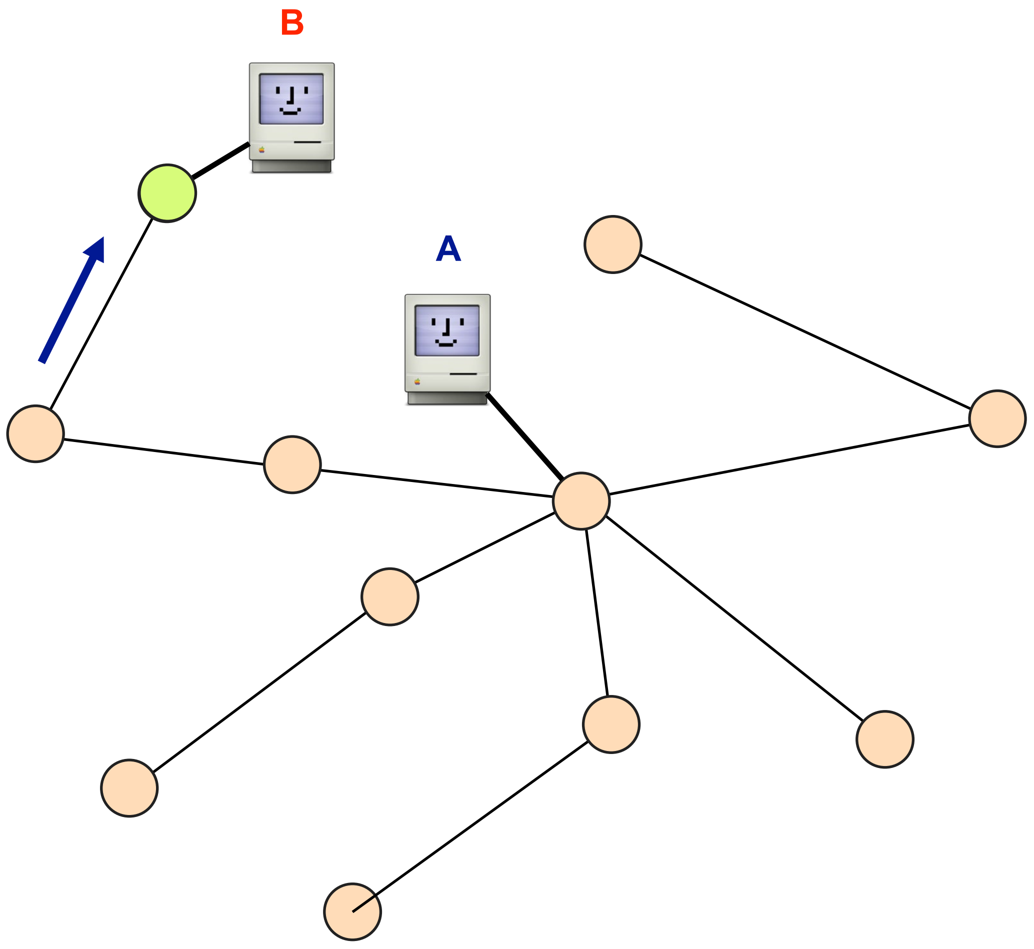
All the green nodes learn how to reach A



All the green nodes learn how to reach A

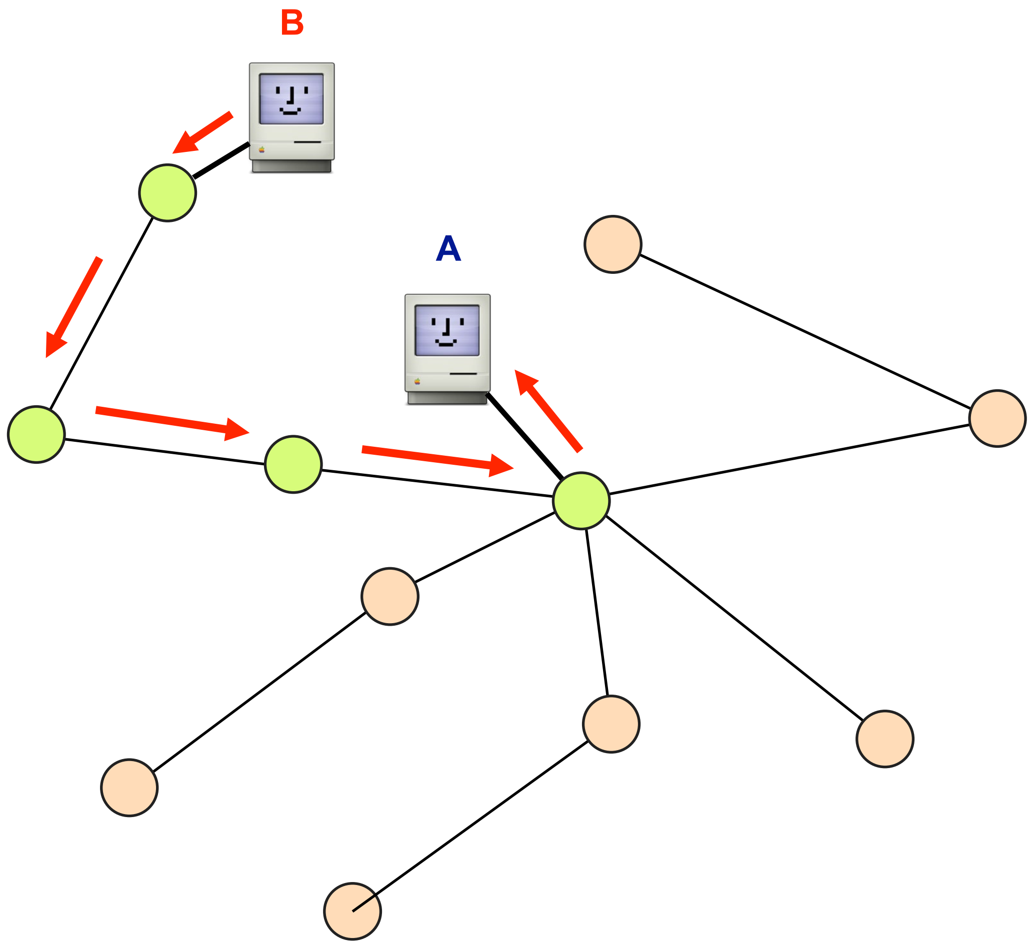


All the nodes know on which port A can be reached



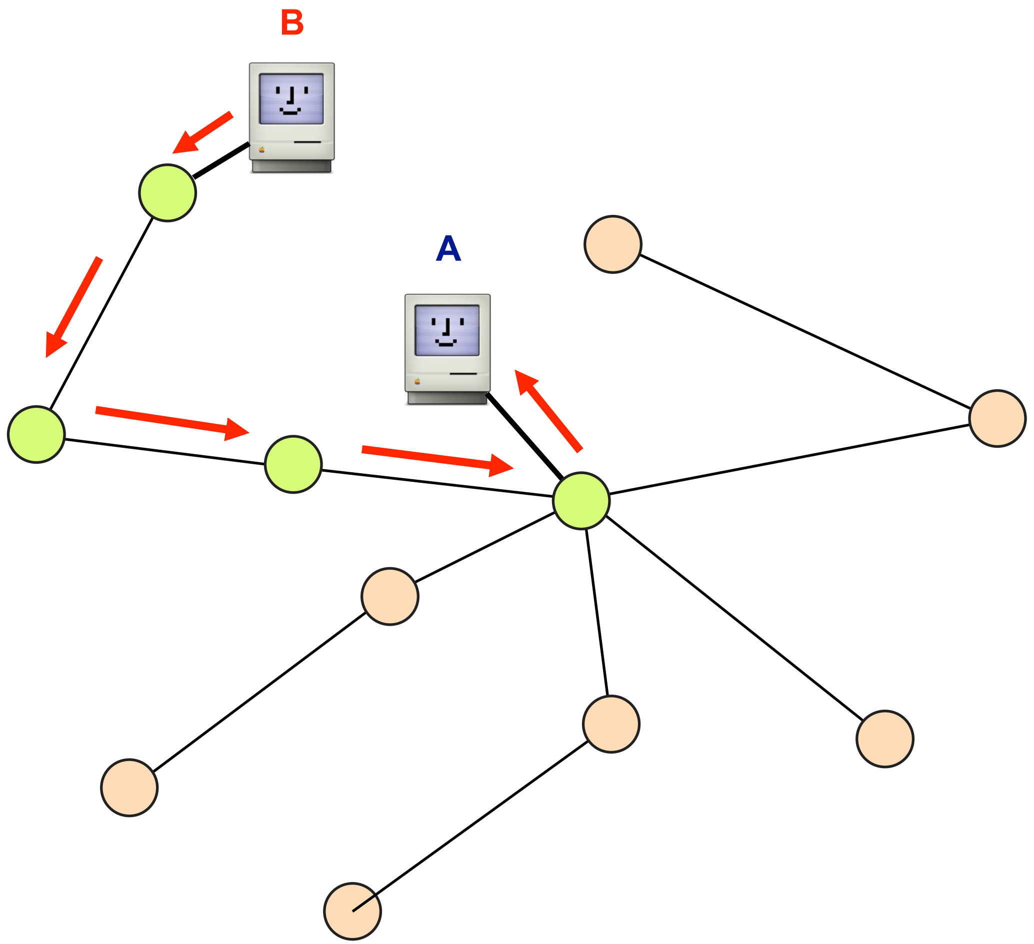
B answers back to A

enabling the green nodes to also learn where B is



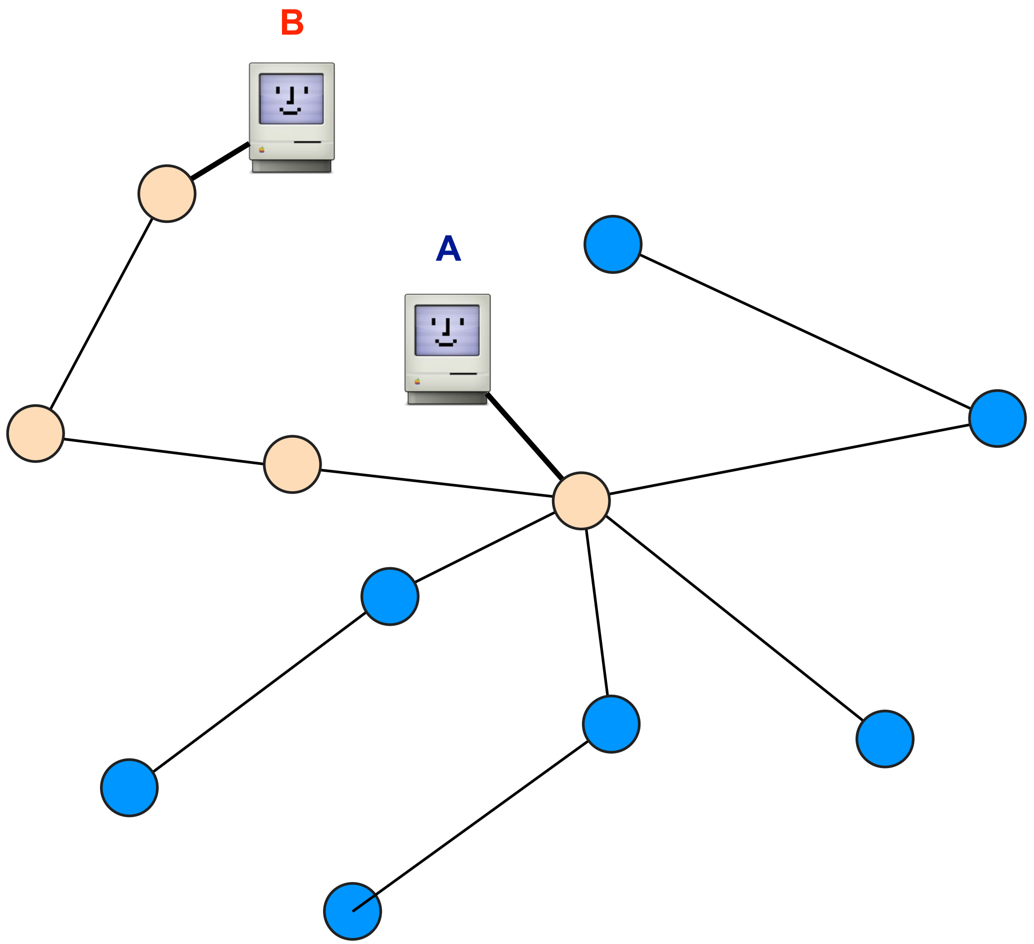
There is no need for flooding here

as the position of A is already known by everybody



Learning is topology-dependent

The blue nodes only know how to reach A (not B)



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

plug-and-play
configuration-free

automatically adapts
to moving host

disadvantages

mandate a spanning-tree
eliminate many links from the topology

slow to react to failures
host movement

Essentially,
there are three ways to compute valid routing state

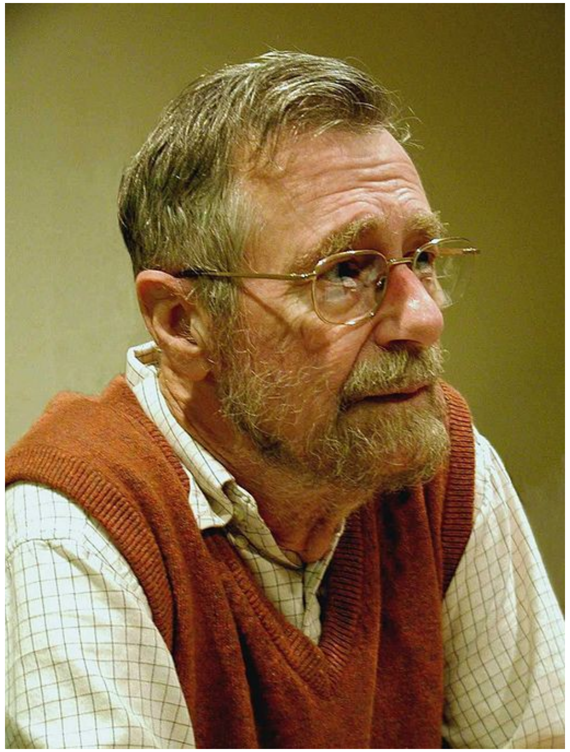
	Intuition	Example
	Use tree-like topologies	Spanning-tree
#2	Rely on a global network view	Link-State SDN
	Rely on distributed computation	Distance-Vector BGP

If each router knows the entire graph,
it can locally compute paths to all other nodes

Edsger W. Dijkstra (1930-2002)

- Famous computer scientist
  - Programming languages
  - Distributed algorithms
  - Program verification

- Dijkstra’s algorithm, 1959
  - Single-source shortest paths,
    given network with non-negative link costs



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*)

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

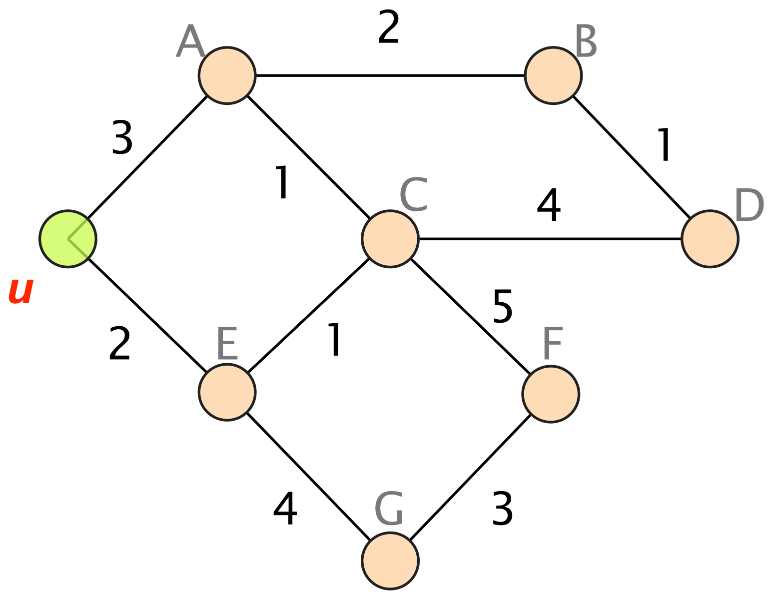
    else:

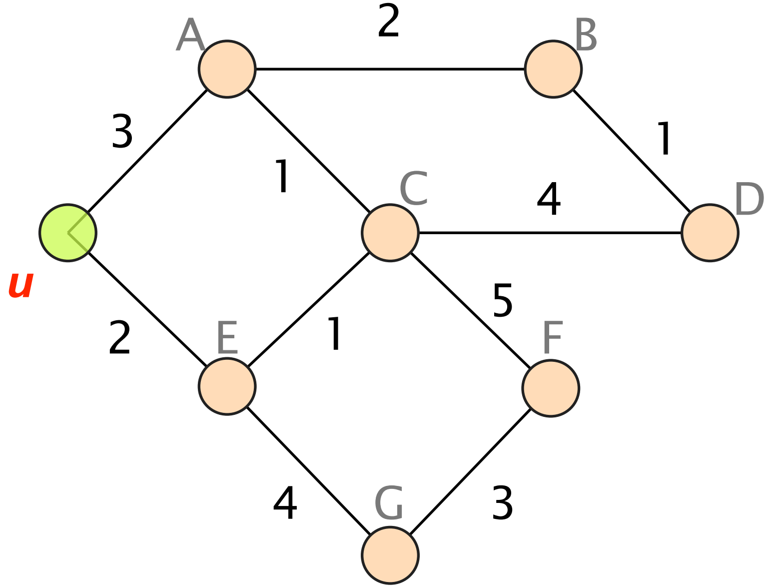
        D(*v*) = ∞

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:

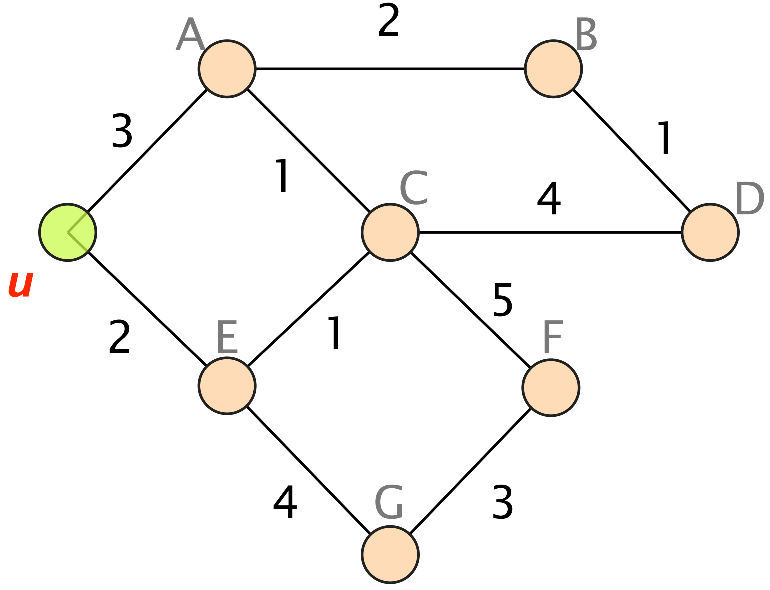
  if (v is adjacent to u):

    D(v) = c(u,v)

  else:

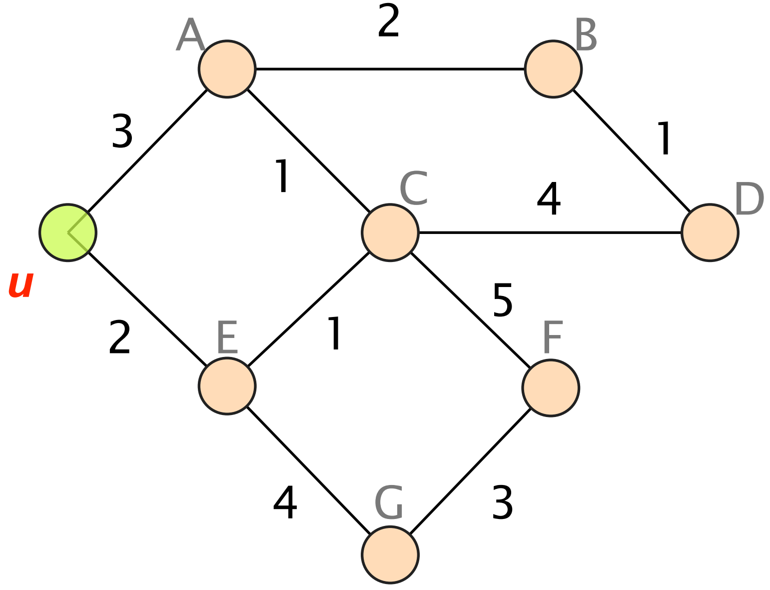
    D(v) = ∞

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

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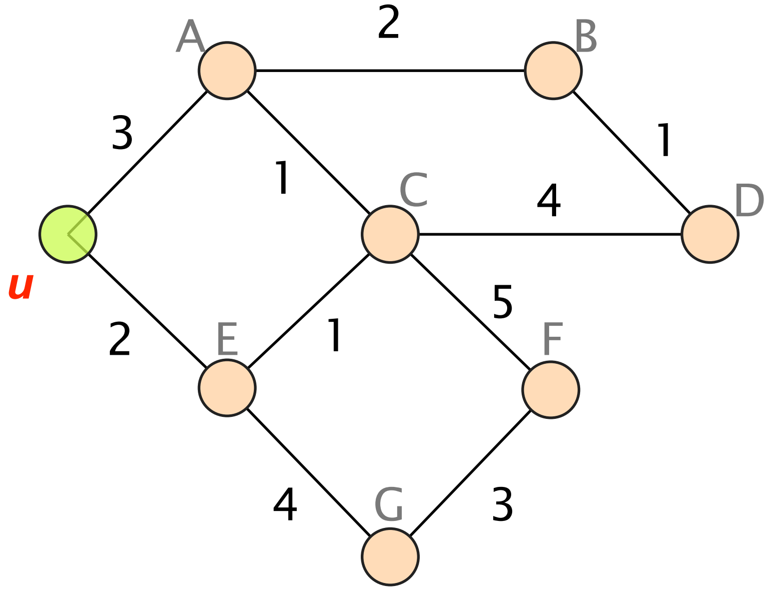
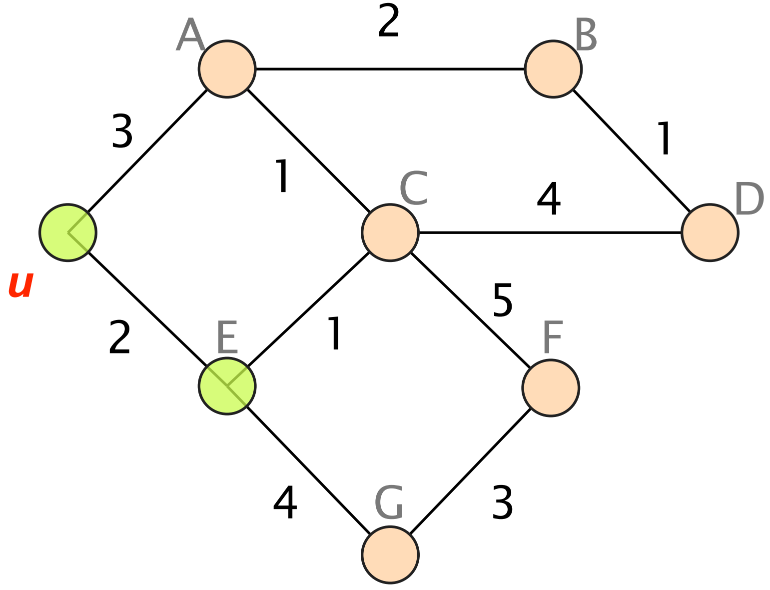
D(v) = min{D(v), D(w) + c(w,v)}



D(.) = S = {u}

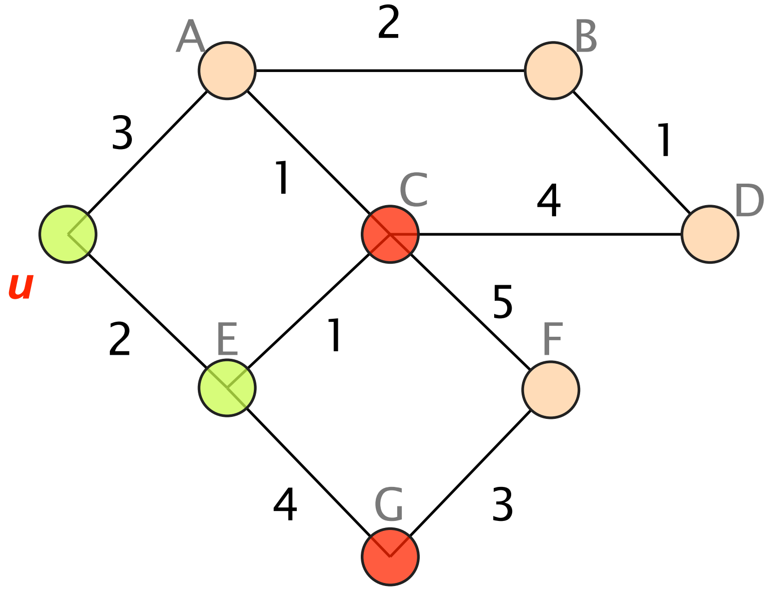
A	3	
B	∞	
C	∞	
D	∞	
E	2	smallest D(w)
F	∞	
G	∞	



add E to S

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

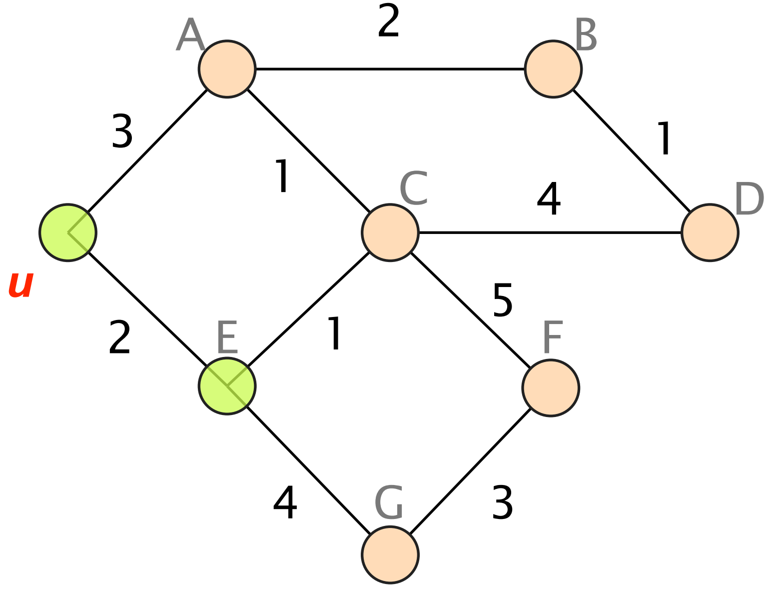
A	3
B	∞
C	∞
D	∞
E	2
F	∞
G	∞



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

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

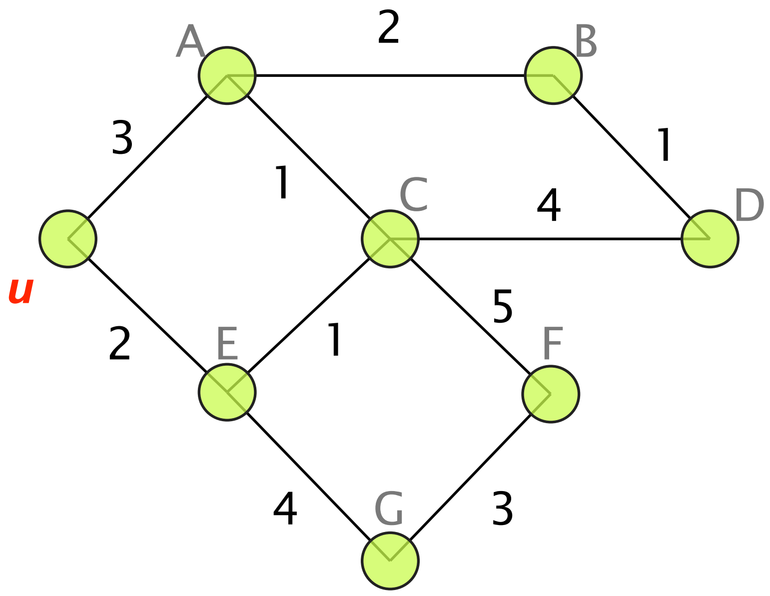
Now, do it by yourself



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}

This algorithm has a $O(n^2)$ complexity

where n is the number of nodes in the graph

iteration #1	search for minimum through n nodes
iteration #2	search for minimum through $n-1$ nodes
iteration n	search for minimum through 1 node

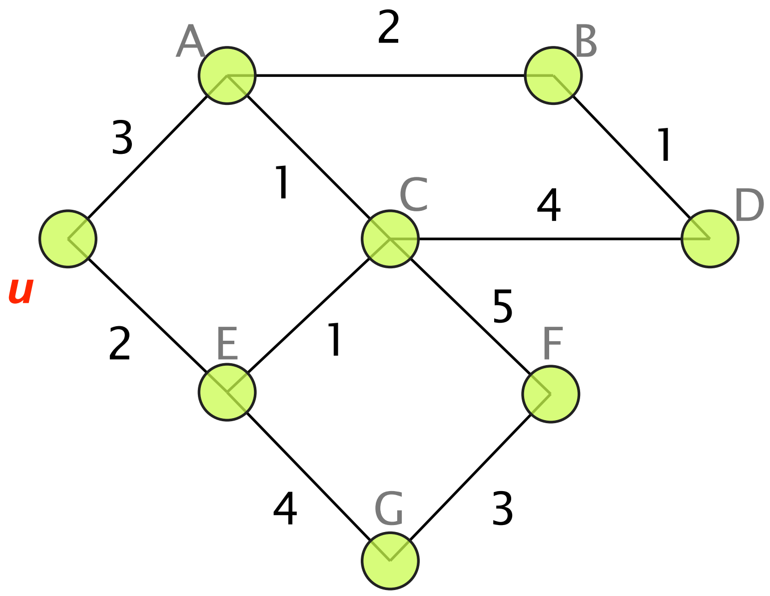
$\frac{n(n+1)}{2}$ operations => $O(n^2)$

This algorithm has a $O(n^2)$ complexity
where n is the number of nodes in the graph

Better implementations rely on a heap
to find the next node to expand,
bringing down the complexity to $O(n \log n)$

From the shortest-paths,

u can directly compute its forwarding table



Forwarding table

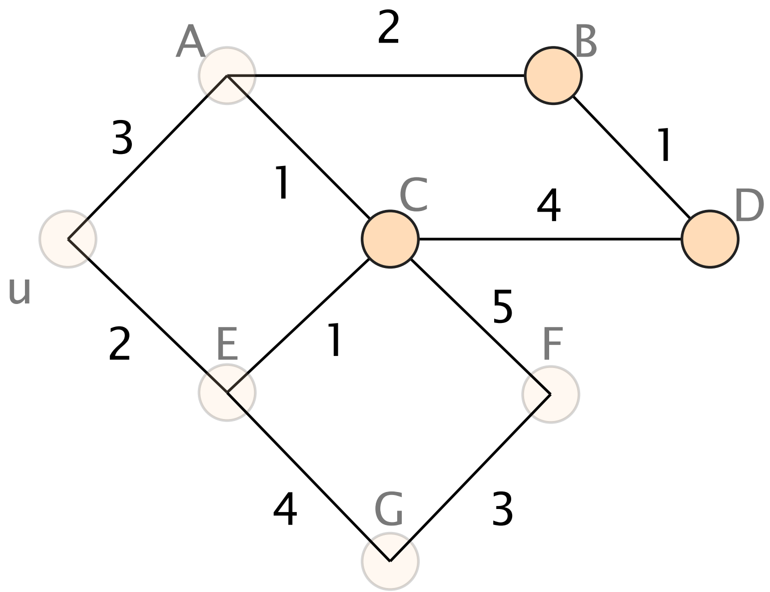
destination	*next-hop*
A	A
B	A
C	E
D	A
E	E
F	E
G	E

To build this global view

routers essentially solve a jigsaw puzzle

Initially,

routers only know **their ID and their neighbors**



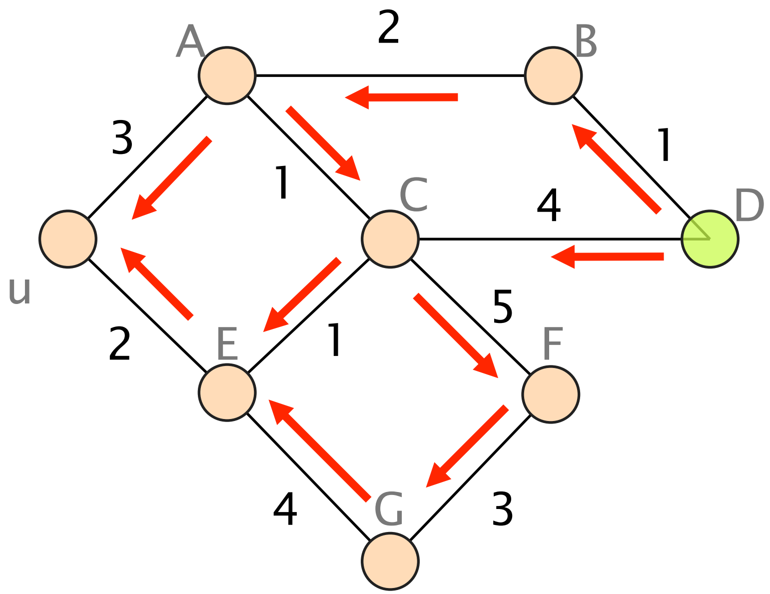
D only knows,

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



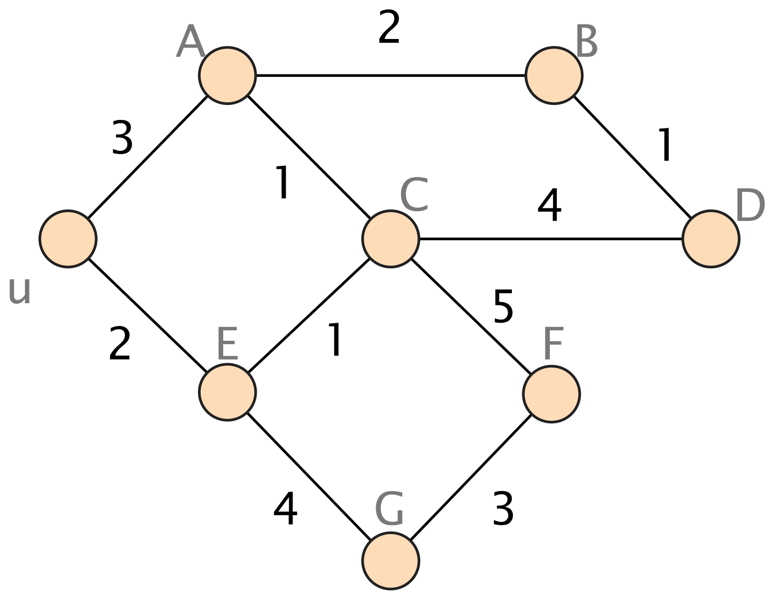
D's Advertisement

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

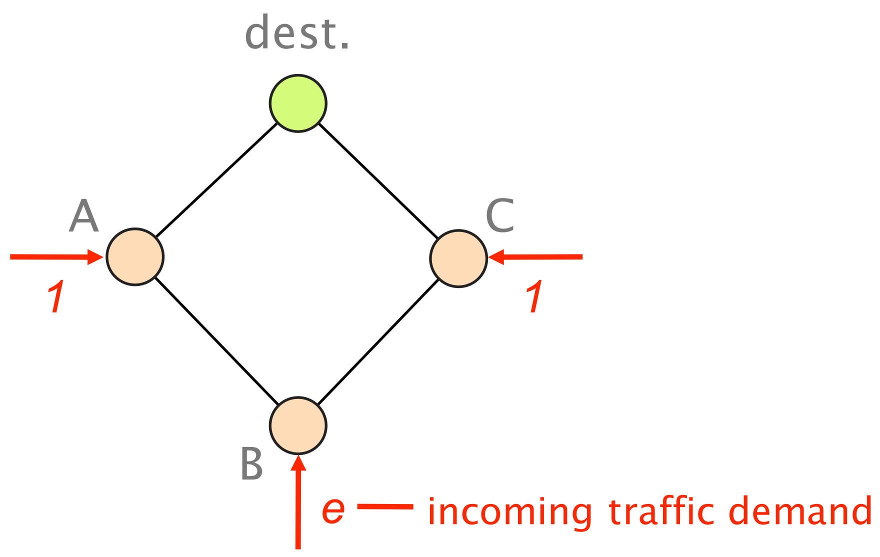
see exercise



Dijkstra will always converge to a unique stable state when run on *static* weights

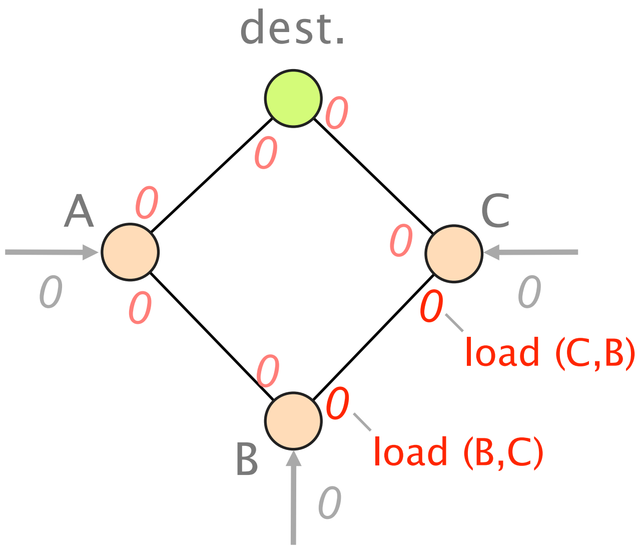
cf. exercise session
for the dynamic case

Consider this network where A, B, C send traffic to the green destination

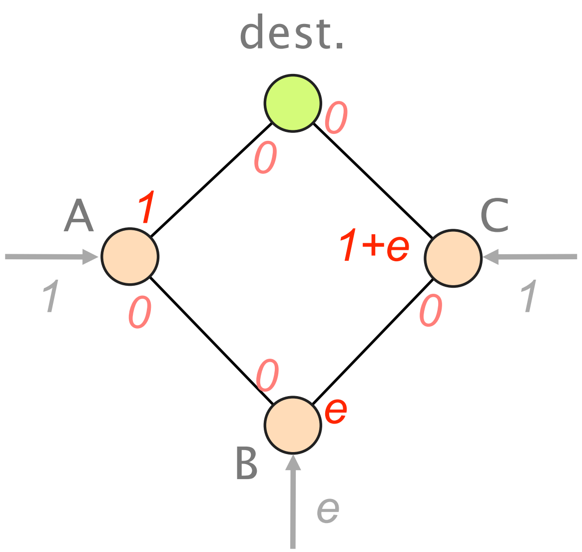


Unlike before,

weights are bidirectional and represent link load



Let’s assume the network starts from this initial state

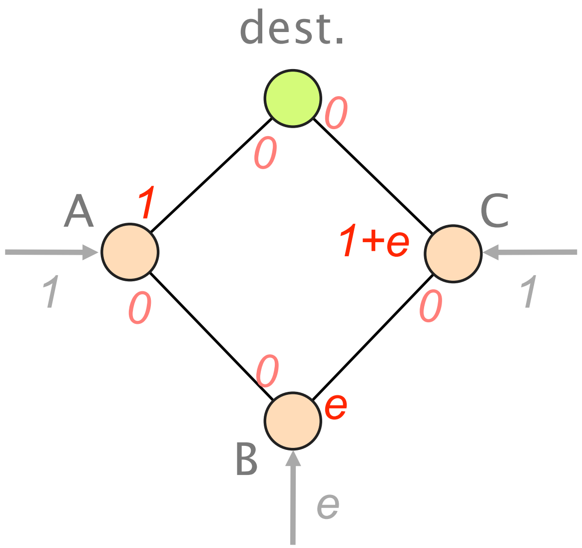


B & C sends counterclockwise

A sends clockwise

After some time,

B and C detect a better path clockwise



For B

cost(↺): *1+e*

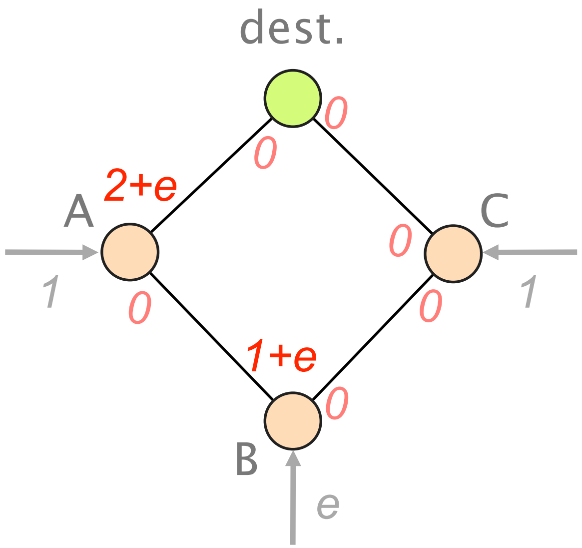
cost(↻): ***1***

For C

cost(↺): *1+e*

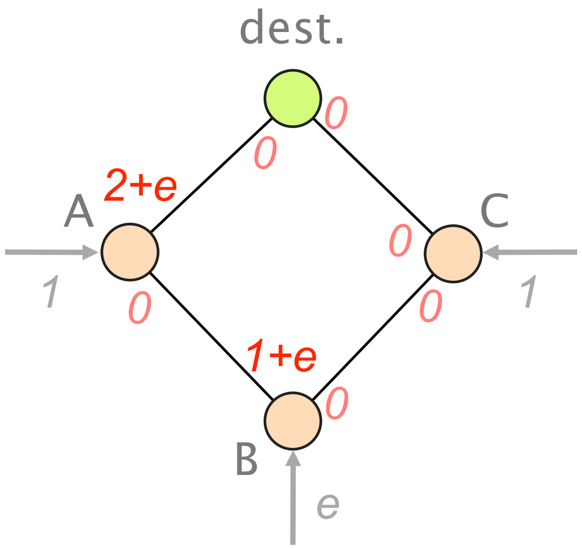
cost(↻): ***1***

Now, everybody sends clockwise...



After some time,

A, B, and C switch to the better path counterclockwise



For A

cost( ): ***0***

cost( ): *2+e*

For B

cost( ): ***0***

cost( ): *2+e*

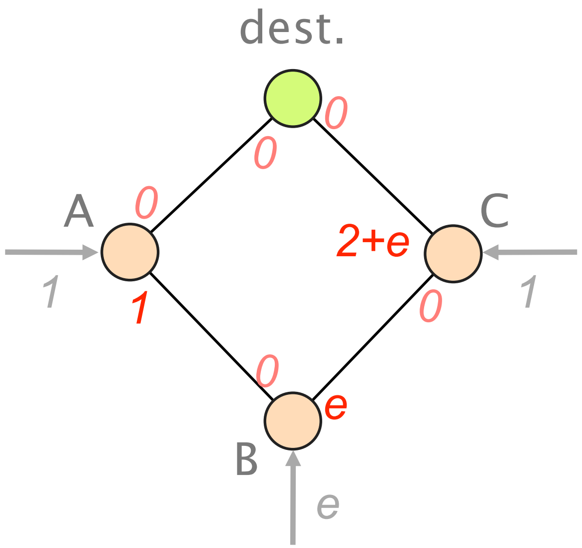
For C

cost( ): ***0***

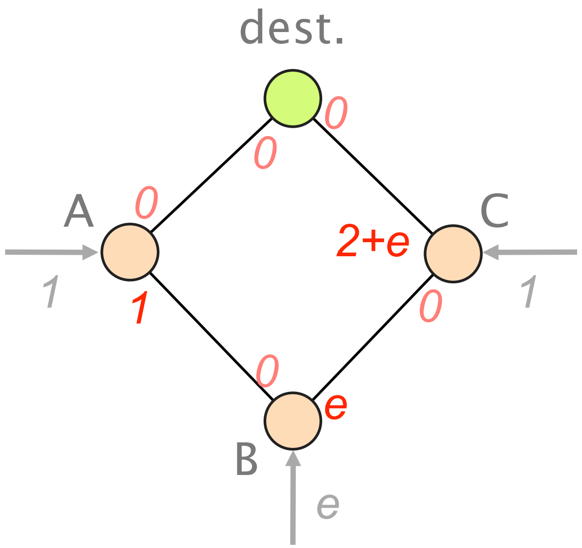
cost( ): *2+e*

After some time,

A, B, and C switch to the better path counterclockwise



The network is now trapped in an oscillation, sending all traffic left, then right



For A

cost( ): 2+e

cost( ): 0

For B

cost( ): 2+e

cost( ): 0

For C

cost( ): 2+e

cost( ): 0

The problem of oscillation is fundamental to congestion-based routing with local decisions

solution #1

Use static weights

i.e. don't do congestion-aware routing

solution #2

Use randomness to break self-synchronization

wait(random(0,50ms)); send(new_link_weight);

solution #3

Have the routers agree on the paths to use

essentially meaning to rely on circuit-switching

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

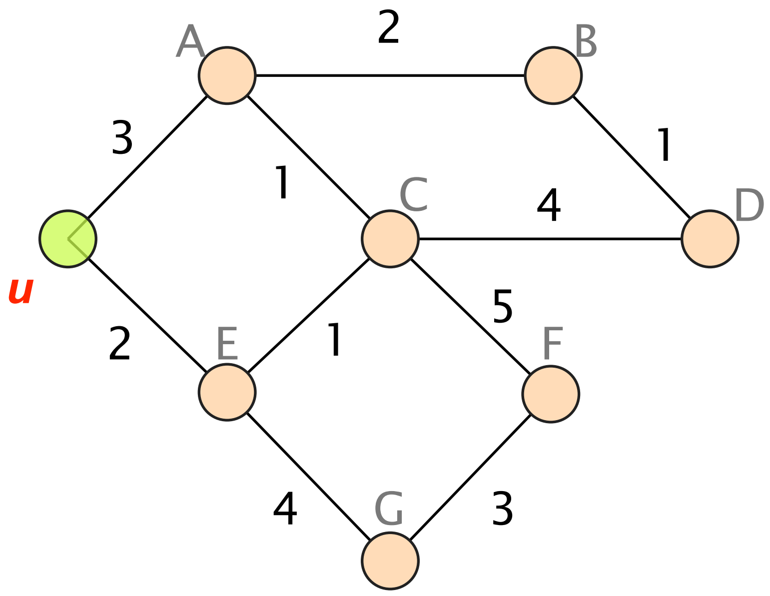
Each node bundles these distances into one message (called a vector) that it repeatedly sends to all its neighbors

until convergence

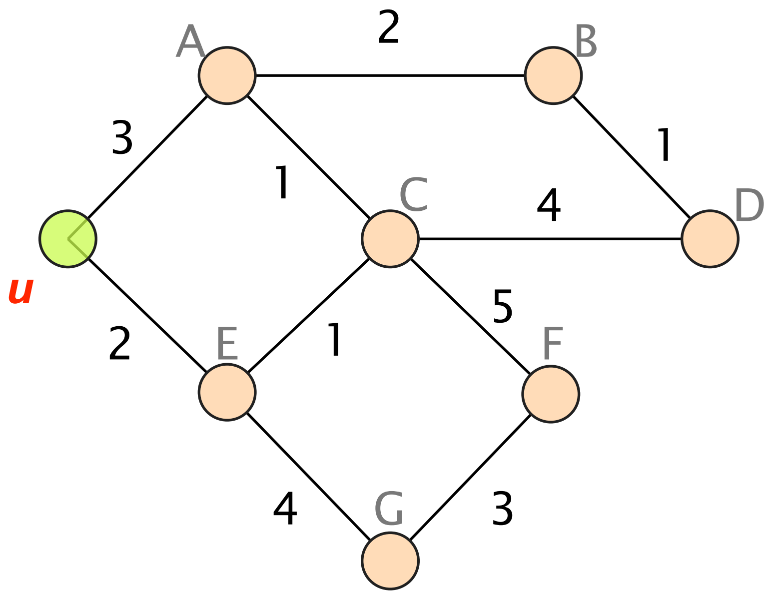
Each node updates its distances based on neighbors' vectors:

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



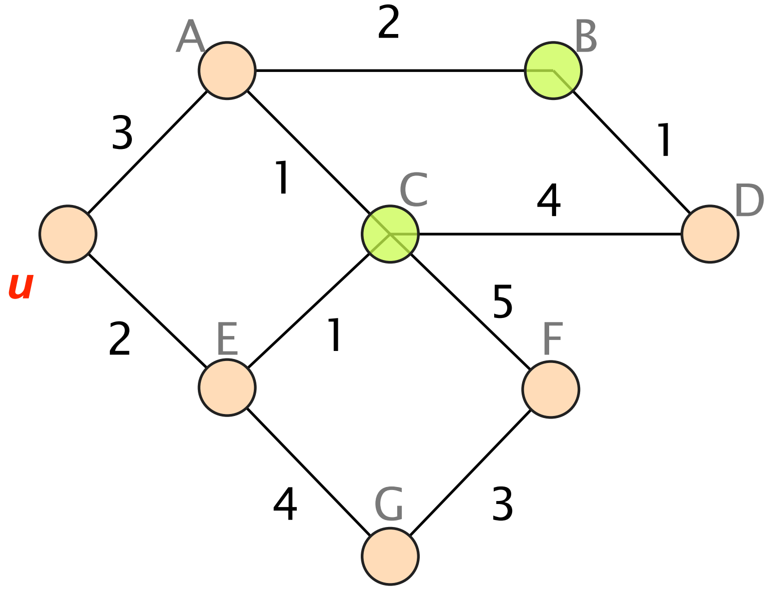
$$d_x(y) = \min\{ c(x,v) + d_v(y) \}$$

over all neighbors *v*

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

To unfold the recursion,

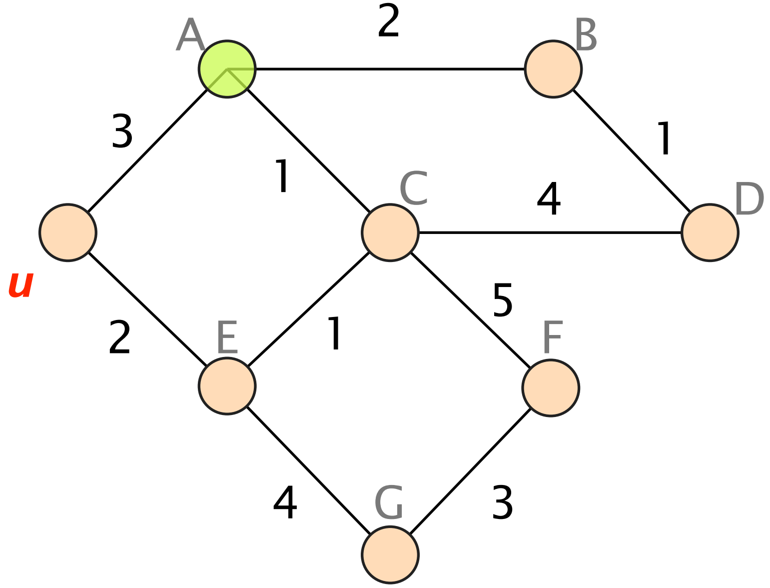
let's start with the direct neighbor of D



$d_B(D) = 1$

$d_C(D) = 4$

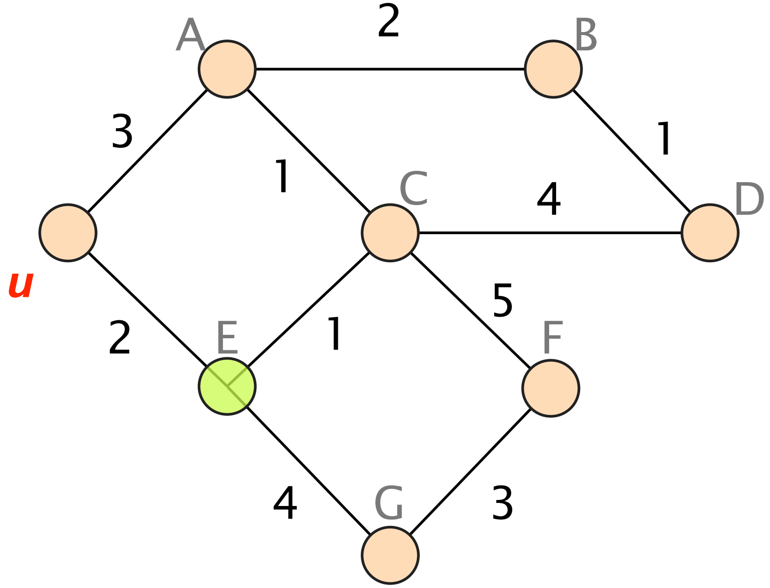
B and C announce their vector to their neighbors, enabling A to compute its shortest-path



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

$$= 3$$

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

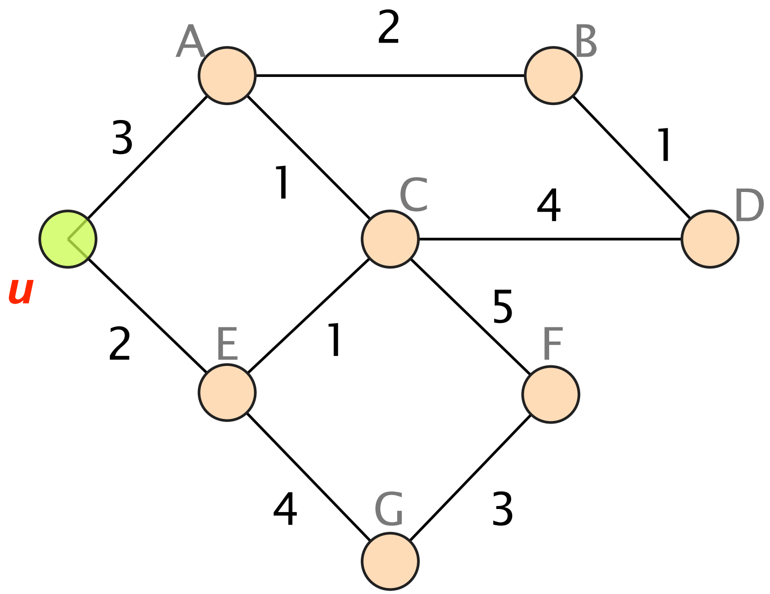


$$d_E(D) = \min \{ 1 + d_C(D),\ 4 + d_G(D),\ 2 + d_u(D) \}$$

$$= 5$$

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

Communication Networks and Internet Technology

Short Recap on this weeks lecture

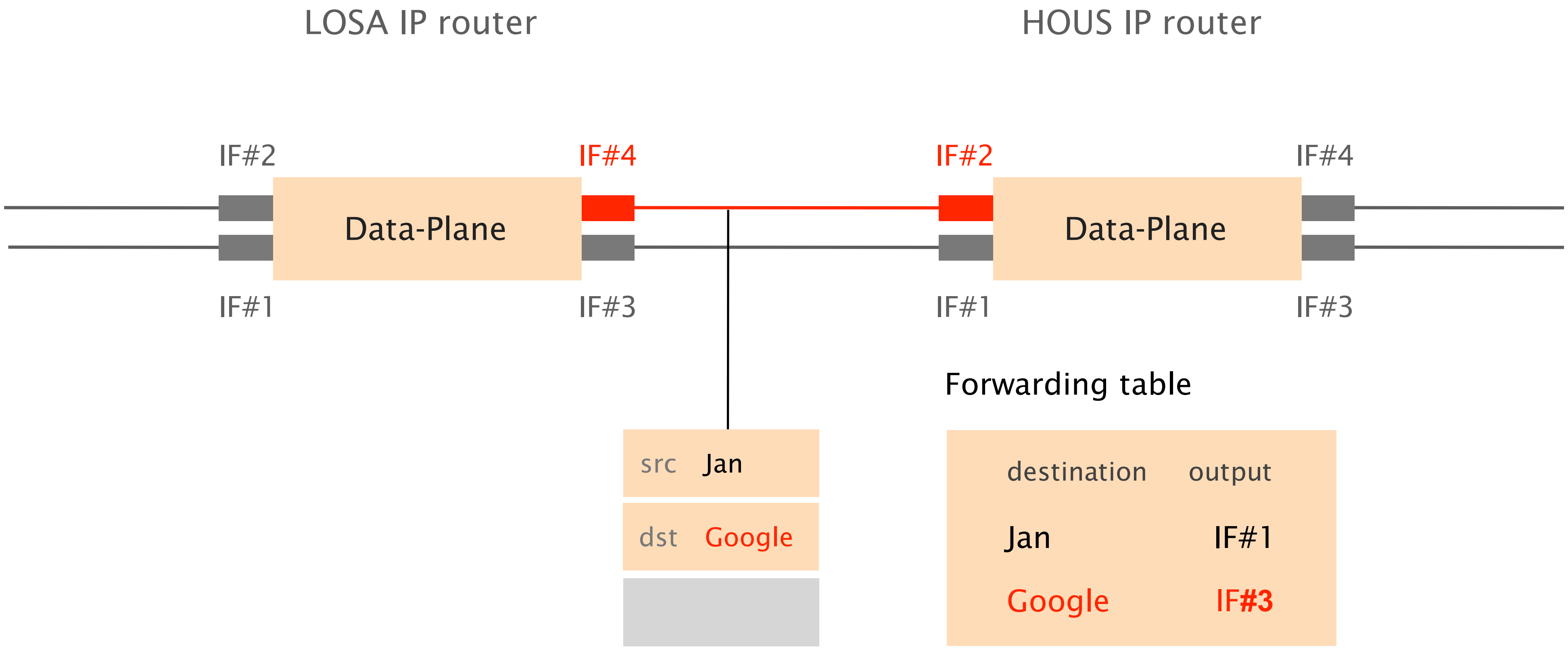
Communication Networks and Internet Technology

Part 2: Concepts

routing

reliable delivery

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



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 Jan
dst Google
destination output
Jan IF#1
Google IF#3

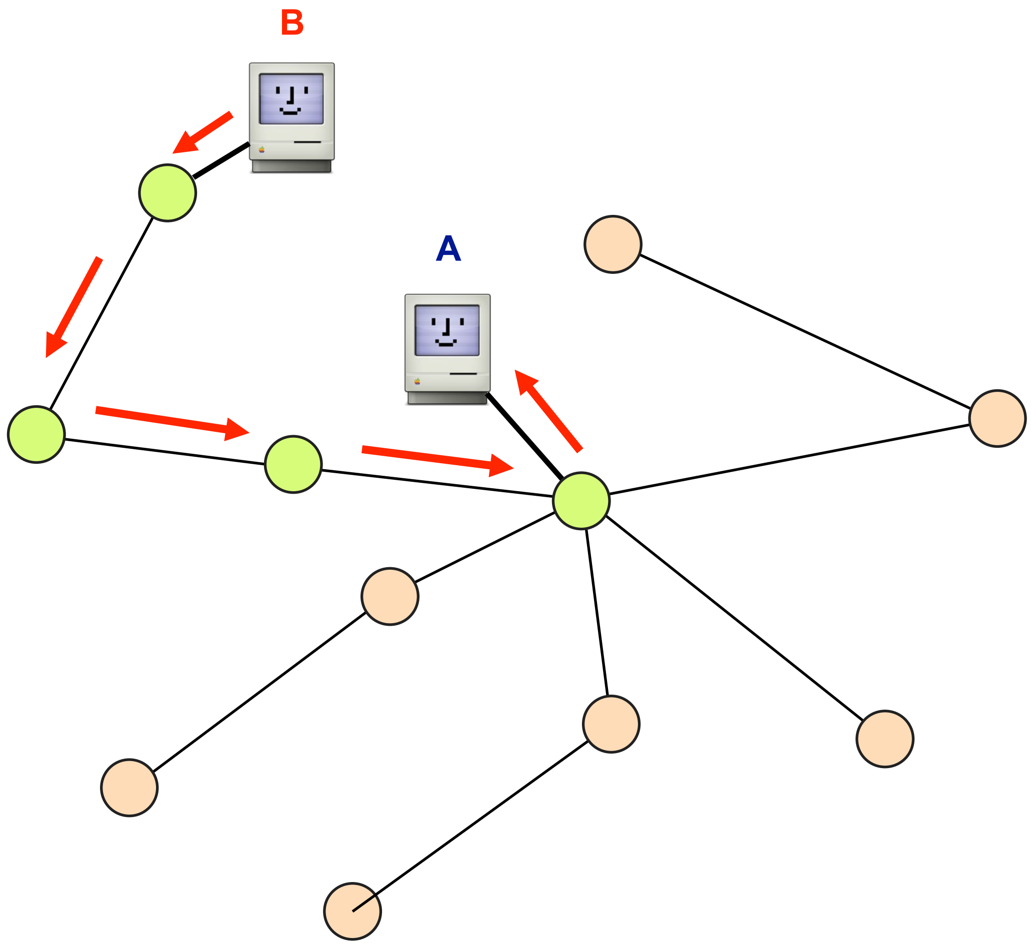
Forwarding *vs* Routing

summary

	forwarding	routing
goal	directing packet to an outgoing link	computing the paths packets will follow
scope	local	network-wide
implem.	hardware usually	software usually
timescale	nanoseconds	milliseconds (hopefully)

There is no need for flooding here

as the position of A is already known by everybody



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

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    else:

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Loop

while *not* all nodes in S:

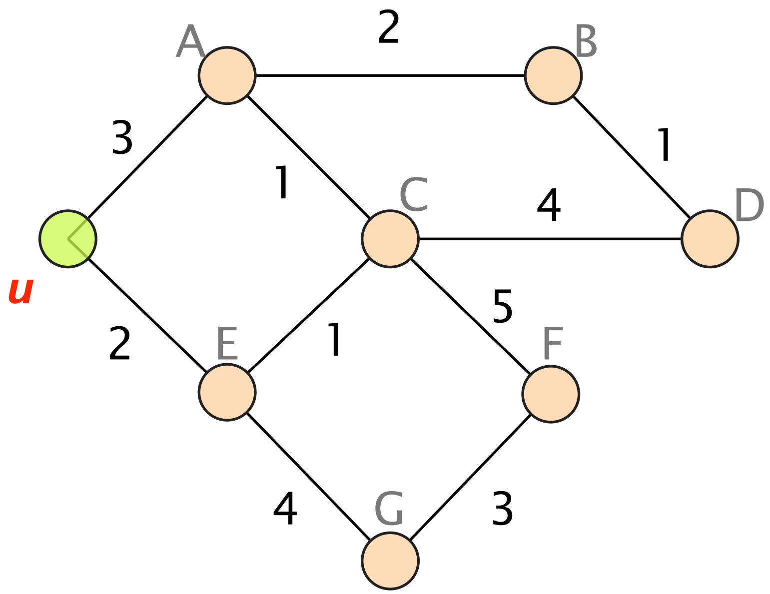
    add *w* with the smallest D(*w*) to S

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

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

Eventually, the process converges

to the shortest-path distance to each destination

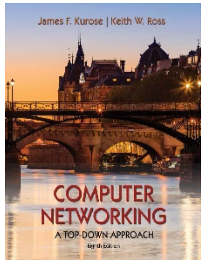


$$d_{u}(D) = \min \{ 3 + d_{A}(D), 2 + d_{E}(D) \}$$

$$= 6$$

Reading: Book Kurose & Ross

Class textbook:
Computer Networking: A Top-Down Approach (8^{th} *ed.)*
J.F. Kurose, K.W. Ross
Pearson, 2020
http://gaia.cs.umass.edu/kurose_ross



- Week 01
  - 1.1 (The Internet), 1.2 (The Network Edge), 1.3 (The Network Core) and 1.5 (Protocol Layers)
- Week 02
  - 1.4 (Delay, Loss and Throughput), 1.5 (Protocol Layers), 4.2 (What's Inside a Router)
- Week 03
  - 5.2 (Routing Algorithms), 5.4 (Routing Among the ISPs: BGP)

Check Your Knowledge

PROBLEM SOLVING HOME

TRY A RANDOM PROBLEM

INTERACTIVE END-OF-CHAPTER EXERCISES

Supplement to Computer Networking: A Top Down Approach 8th Edition

"Tell me and I forget. Show me and I remember. Involve me and I understand." Chinese proverb

The links below will take you to end-of-chapter exercises where you'll be presented with an exercise whose solution can then be displayed (hopefully

CHAPTER 5: NETWORK LAYER: CONTROL PLANE

- Dijkstra's Link State Algorithm (similar to Chapter 5, P3)
- Dijkstra's Link State Algorithm - Advanced
- Bellman Ford Distance Vector algorithm (similar to Chapter 5, P5)
- Openflow Flow Tables

http://gaia.cs.umass.edu/kurose_ross/interactive/

Communication Networks and Internet Technology

Part 2: Concepts

routing

reliable
delivery

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