Communication Networks

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Materials inspired from Scott Shenker & Jennifer Rexford

Last week on

Communication Networks

Communication Networks

Part 1: General overview

What is a network made of?

How is it shared?

How is it organized?

#4 **How does communication happen?**

How do we characterize it?

The Internet should allow

processes on different hosts
to exchange data

everything else is just commentary…

In practice, there exists **a lot** of network protocols.

How does the Internet organize **this?**

Each layer provides a service to the layer above
by using the services of the layer directly below it

Applications

...built on...

Reliable (or unreliable) transport

...built on...

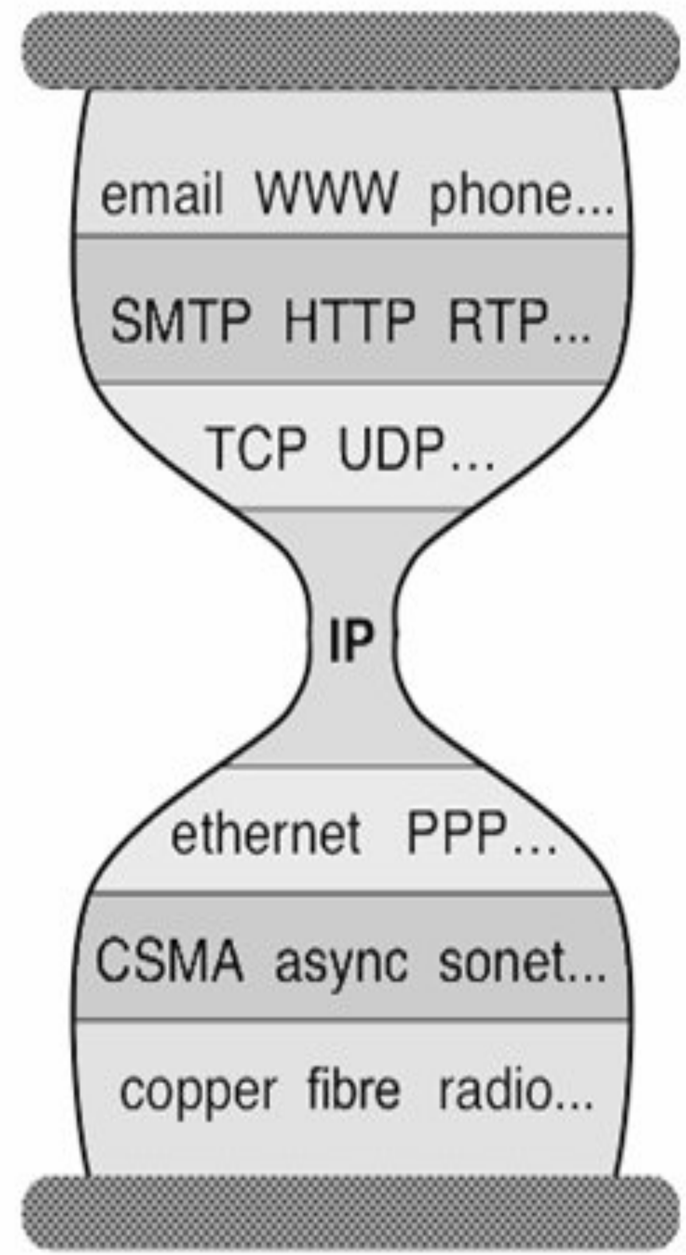
Best-effort global packet delivery

...built on...

Best-effort local packet delivery

...built on...

Physical transfer of bits



Communication Networks

Part 1: General overview

What is a network made of?

How is it shared?

How is it organized?

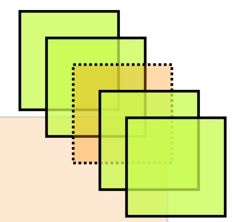
How does communication happen?

#5 How do we characterize it?

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?

Communication Networks

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?

Last week

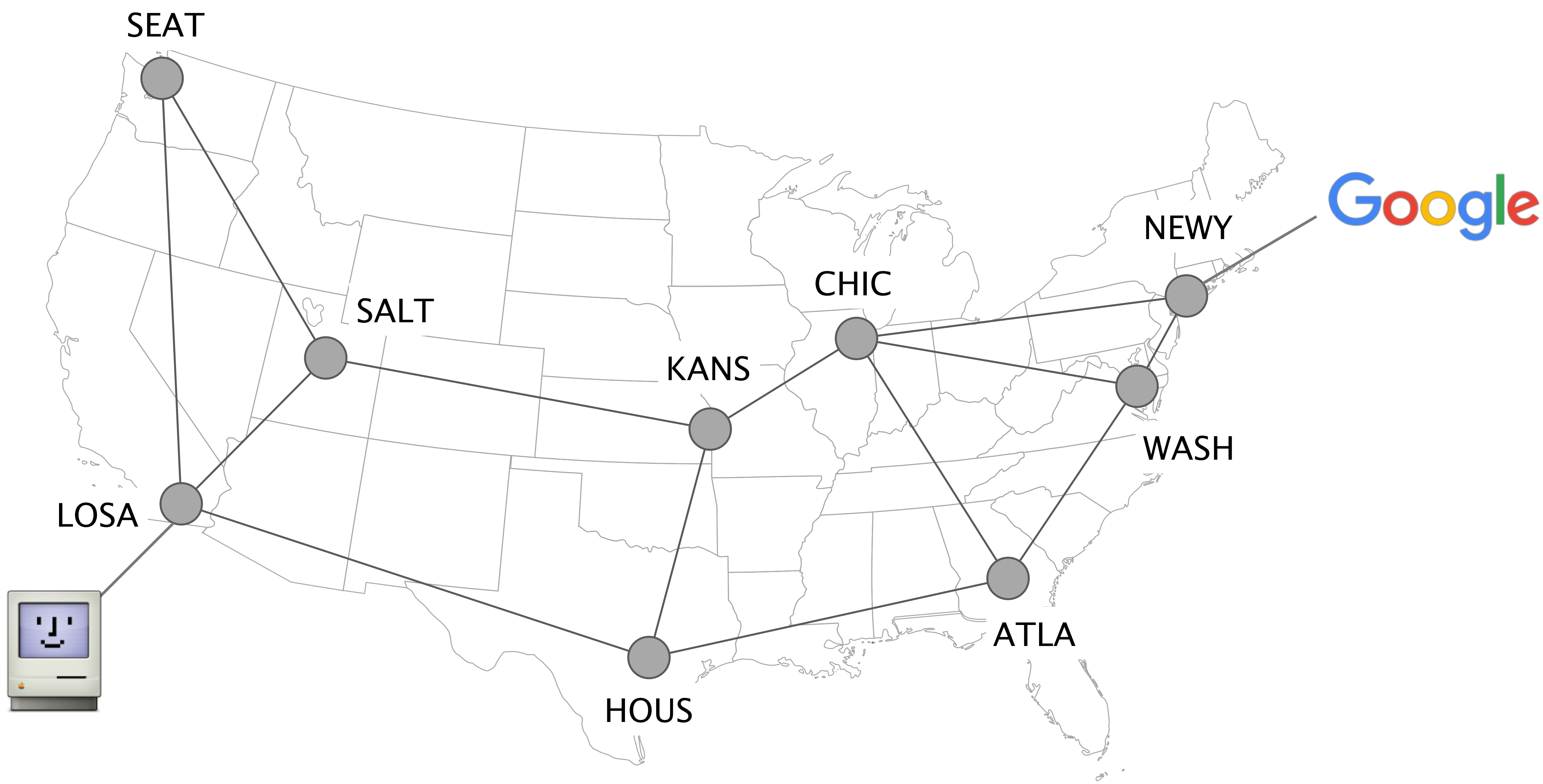
routing

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

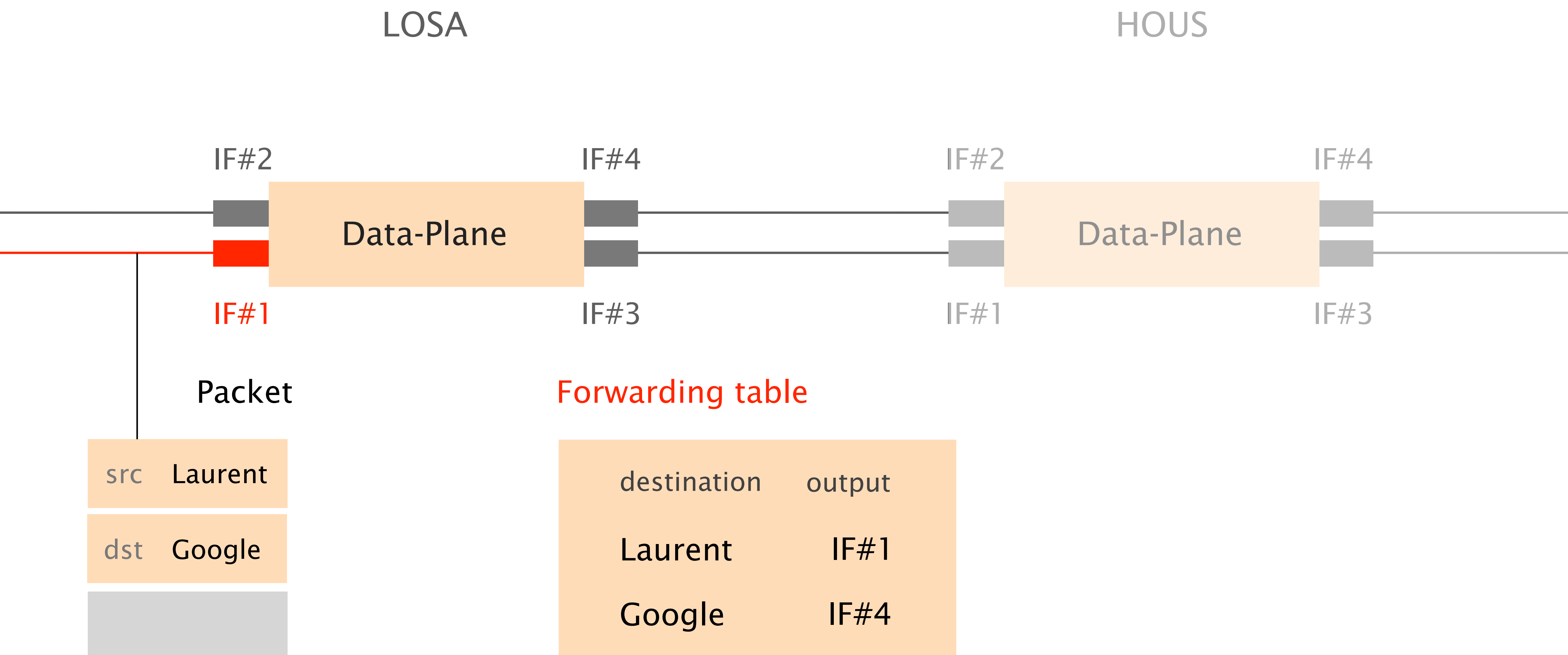
This week

reliable
delivery

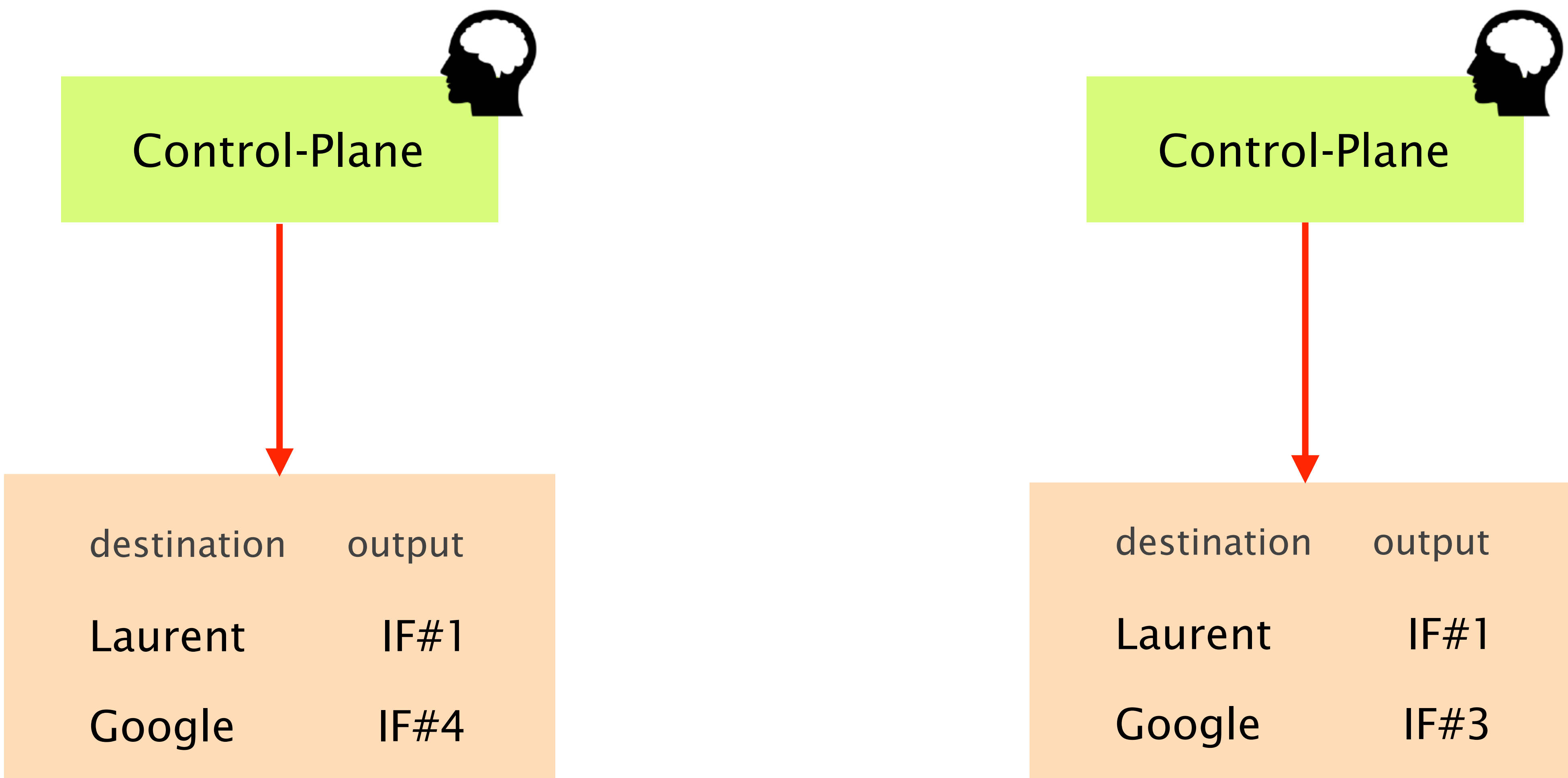
Routers forward IP packets **hop-by-hop** towards their destination



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



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



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 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

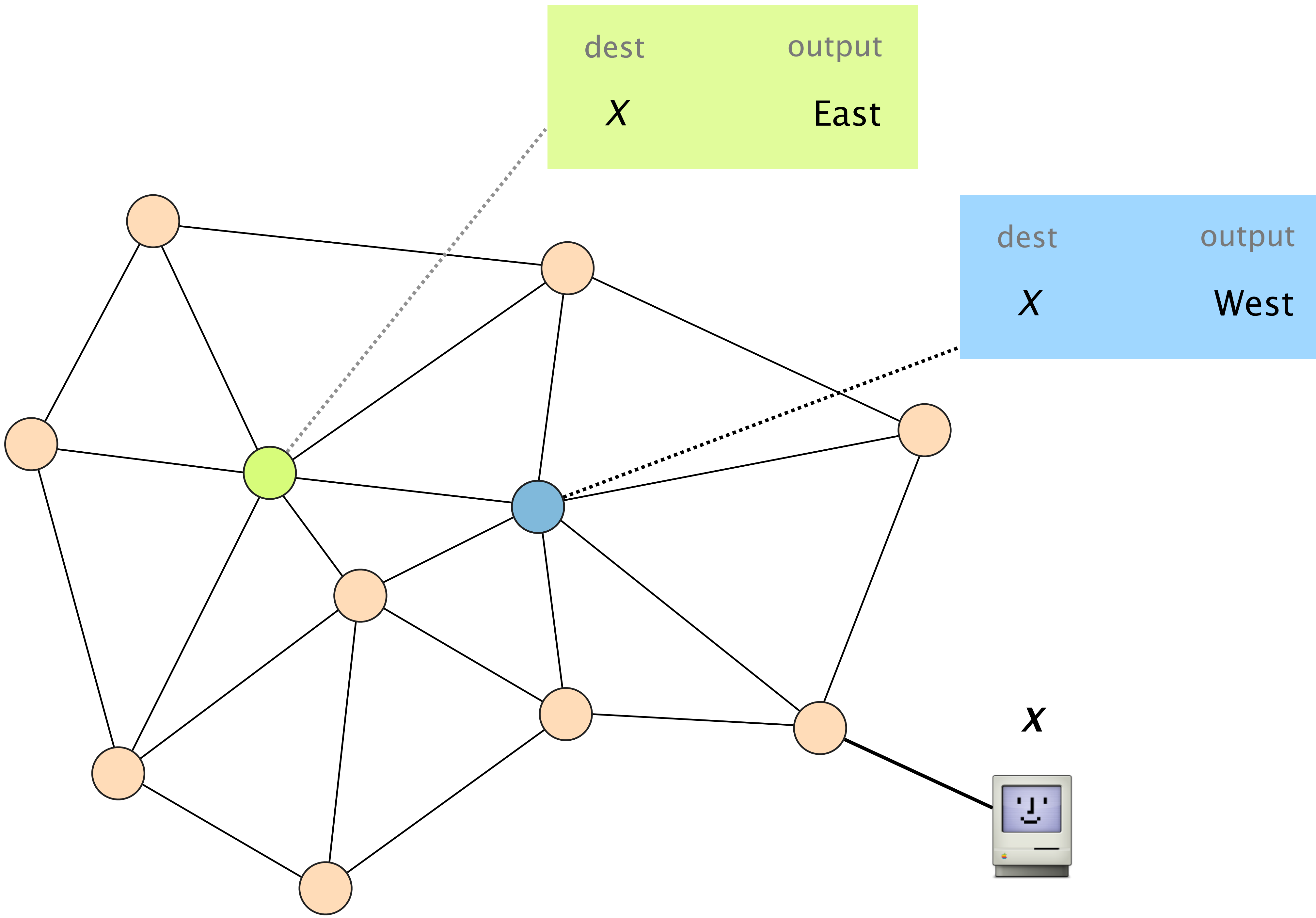
for one destination

Mark all outgoing ports with an arrow

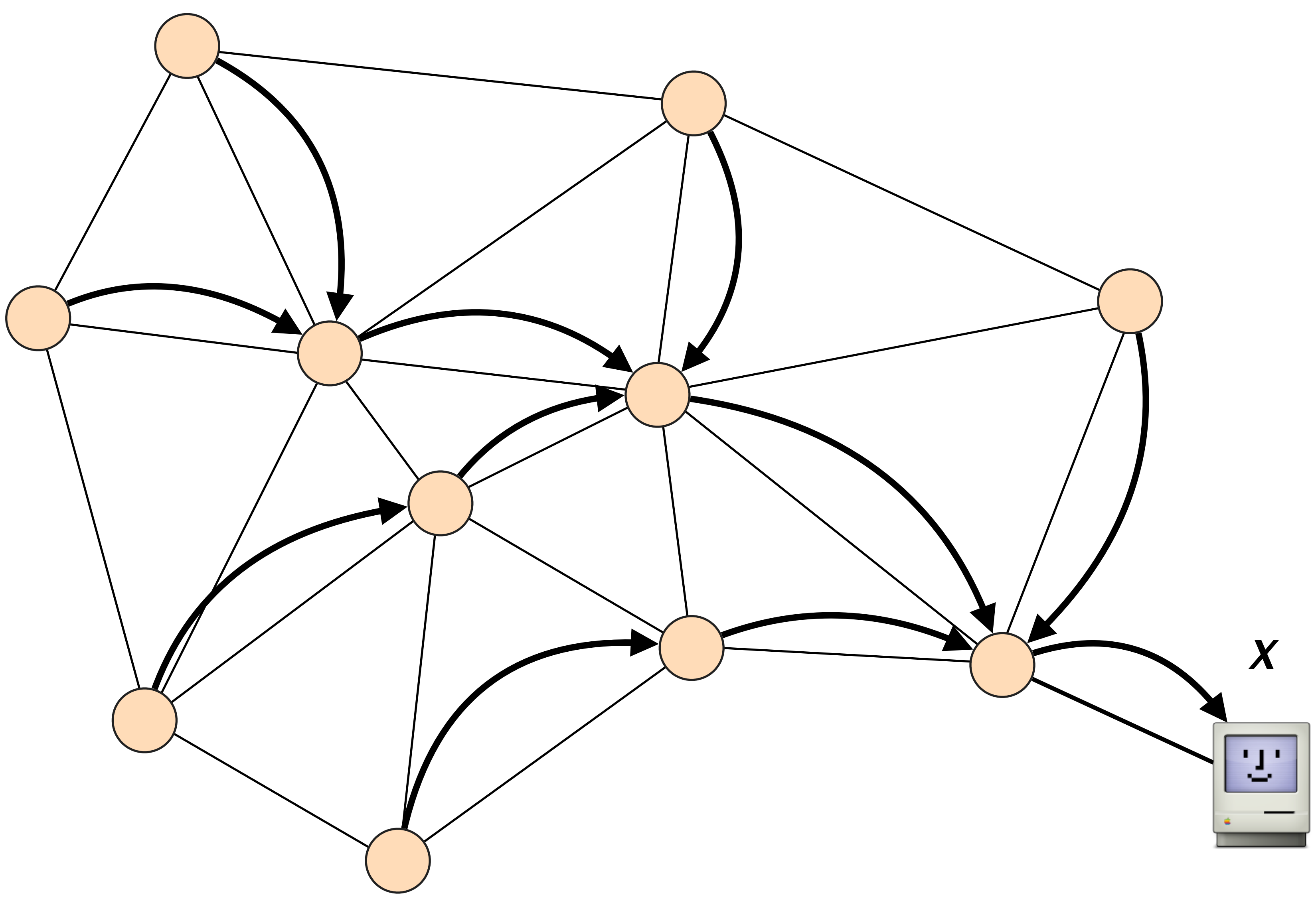
Eliminate all links with no arrow

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

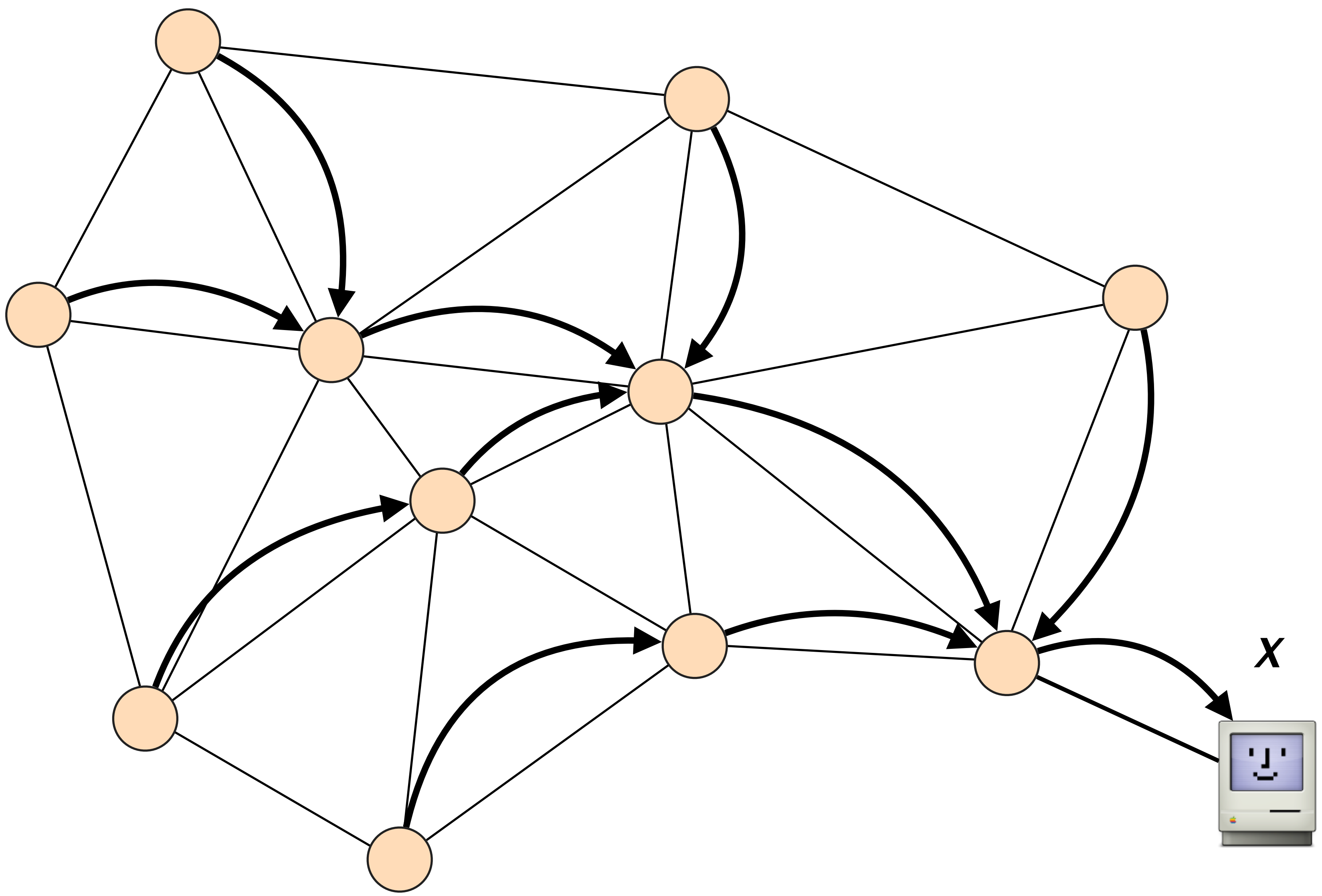
Given a graph with the corresponding forwarding state

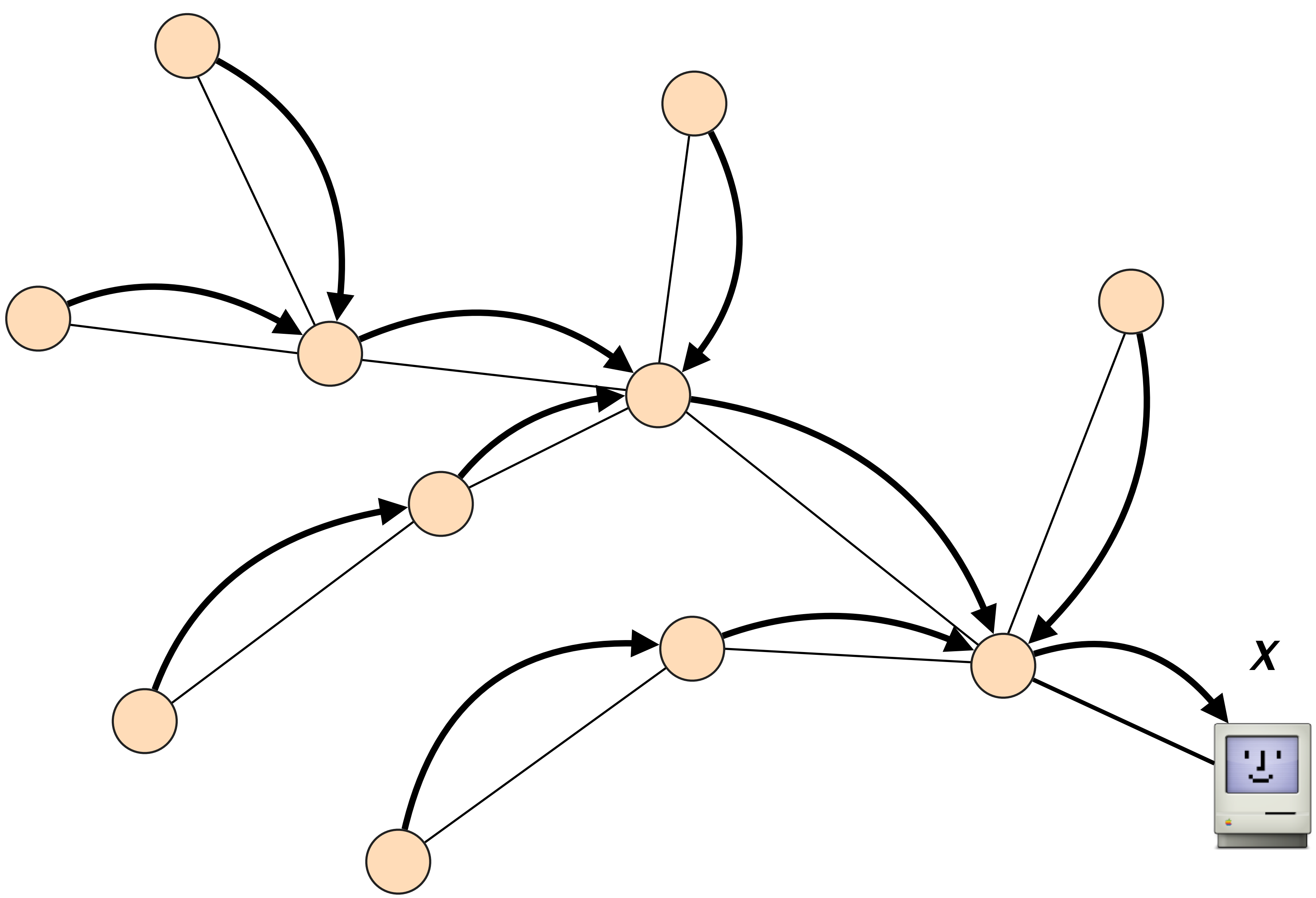


Mark all outgoing ports with an arrow



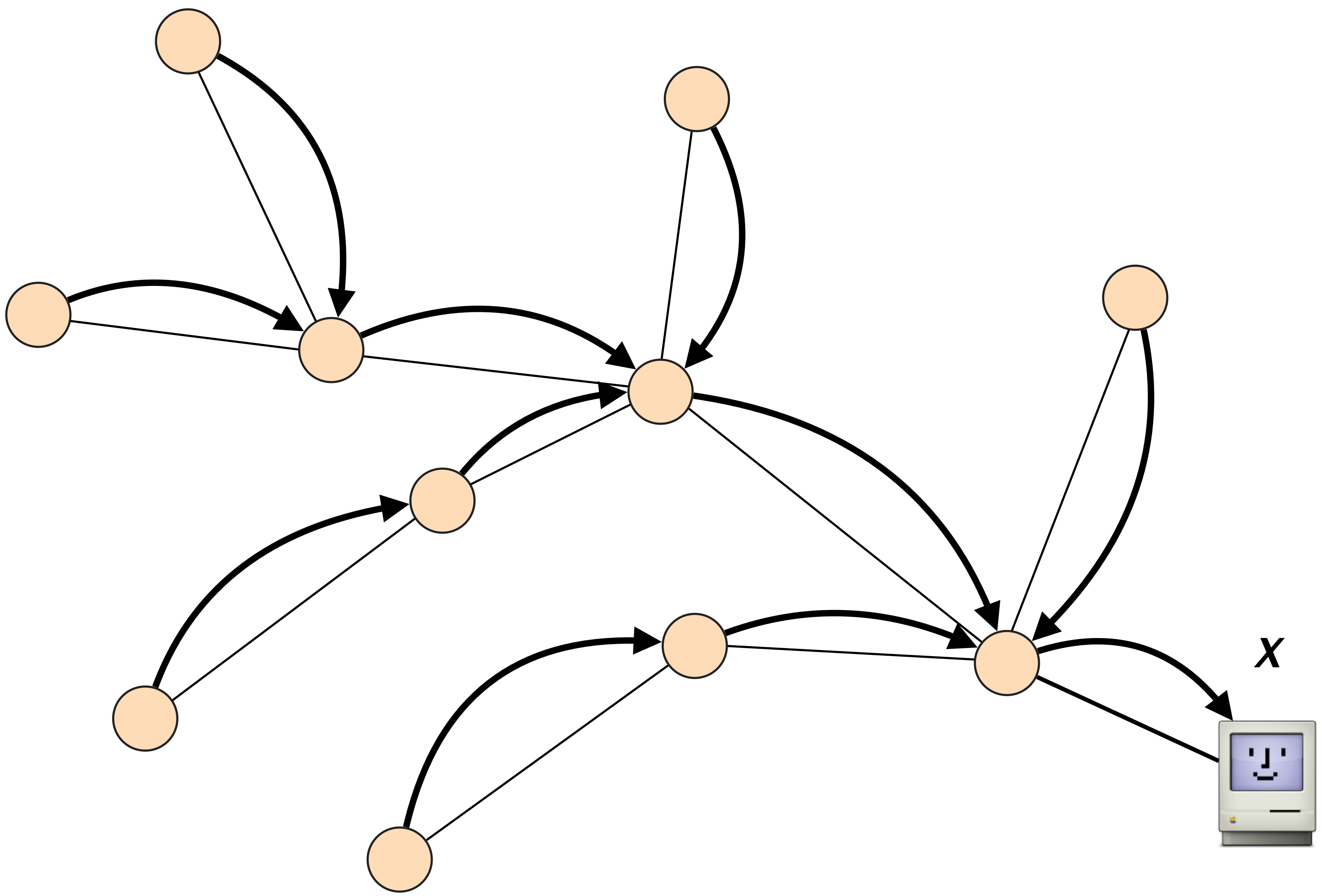
Eliminate all links with no arrow



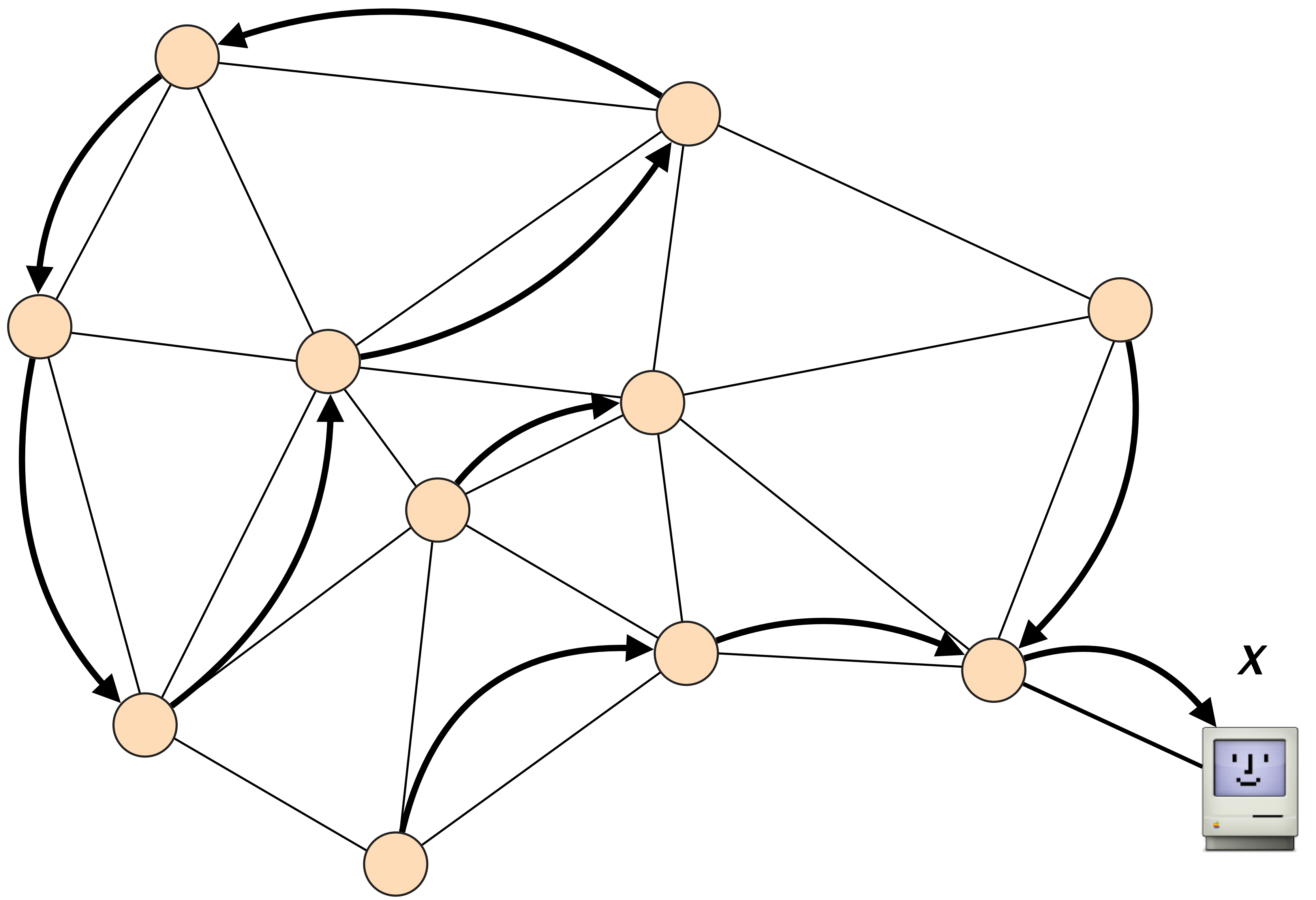

X

The result is a spanning tree.

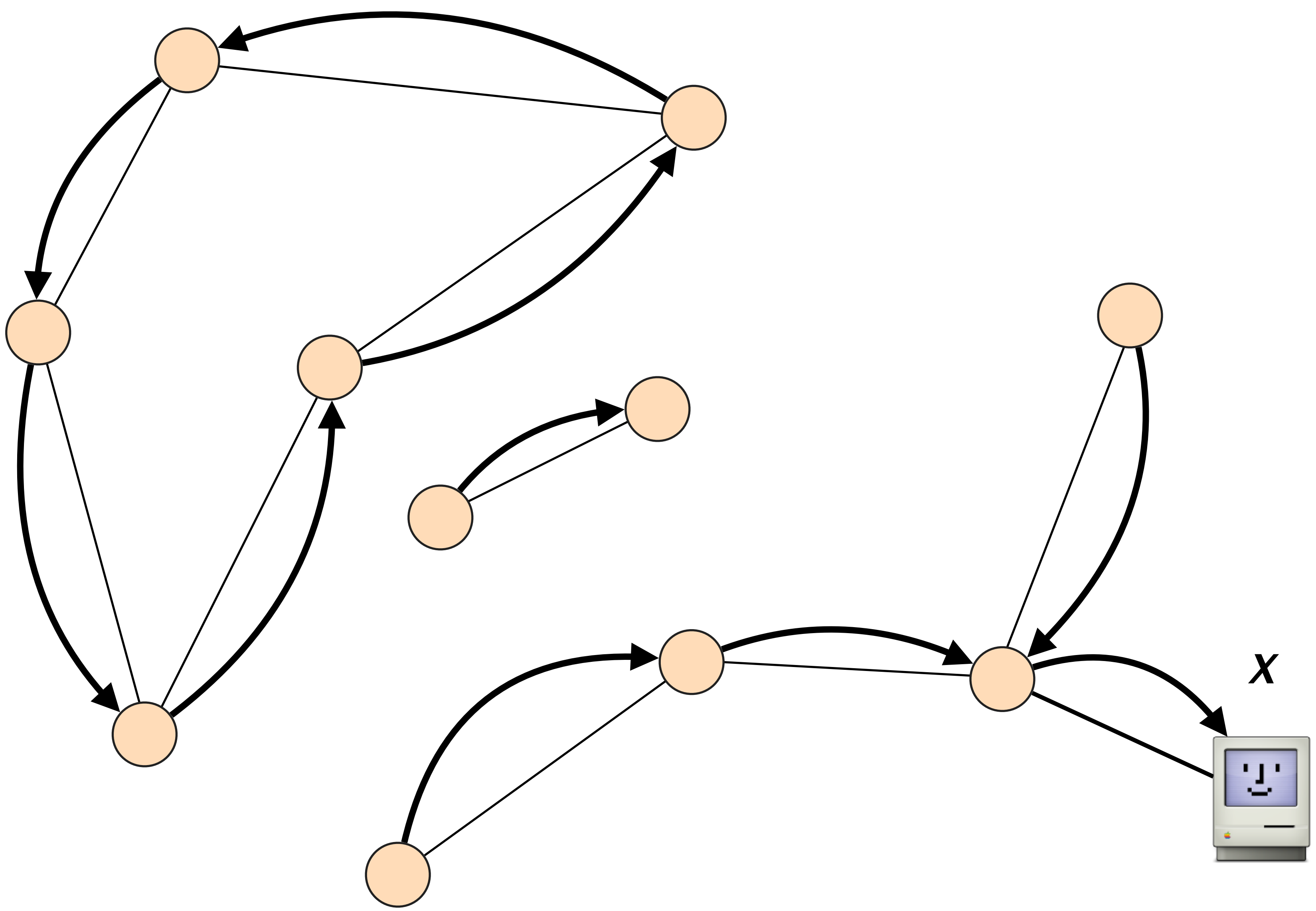
This is a valid routing state



Mark all outgoing ports with an arrow

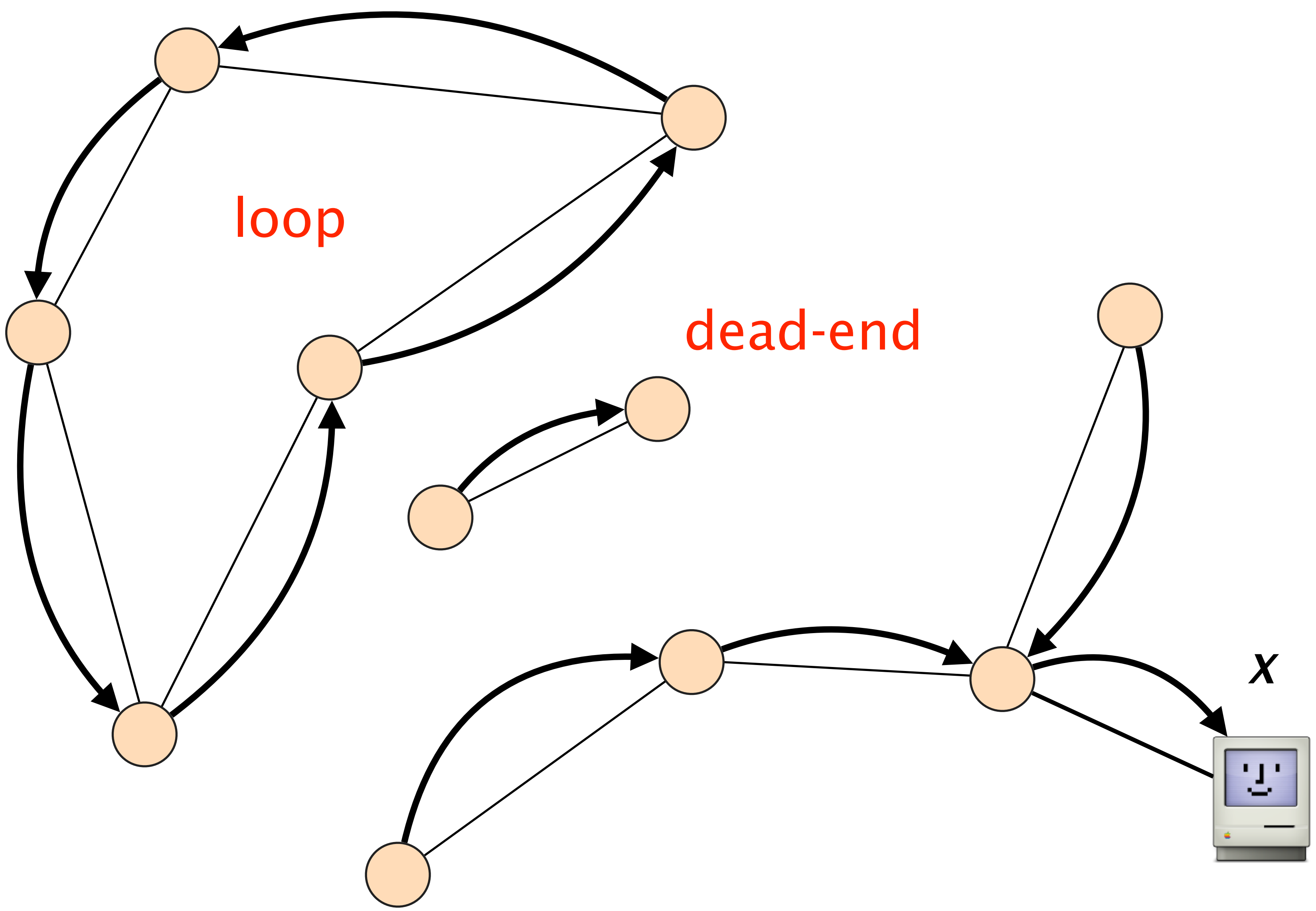


Eliminate all links with no arrow



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 one a loop-free topology

simple algorithm

Take an arbitrary topology

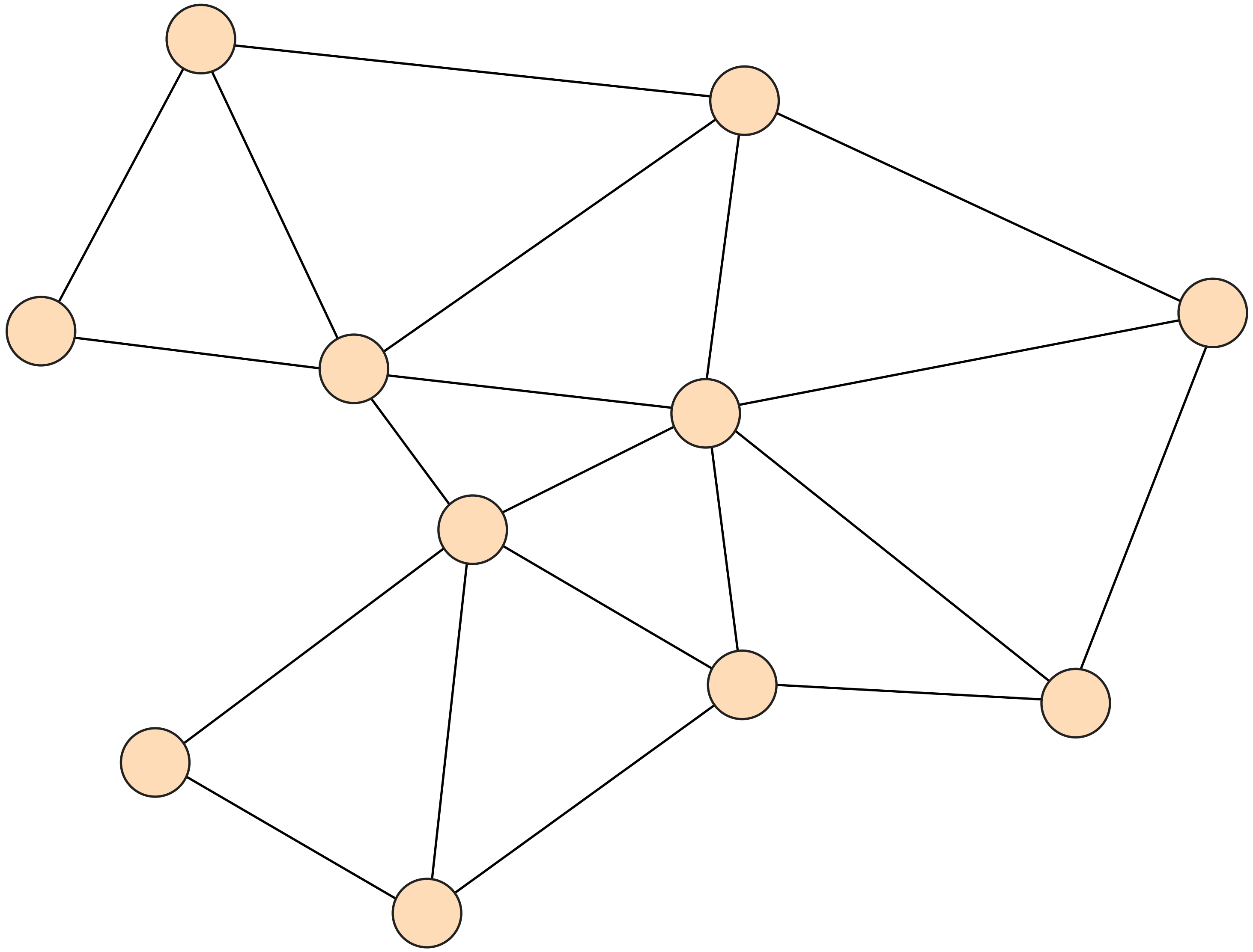
Build a spanning tree and
ignore all other links

Done!

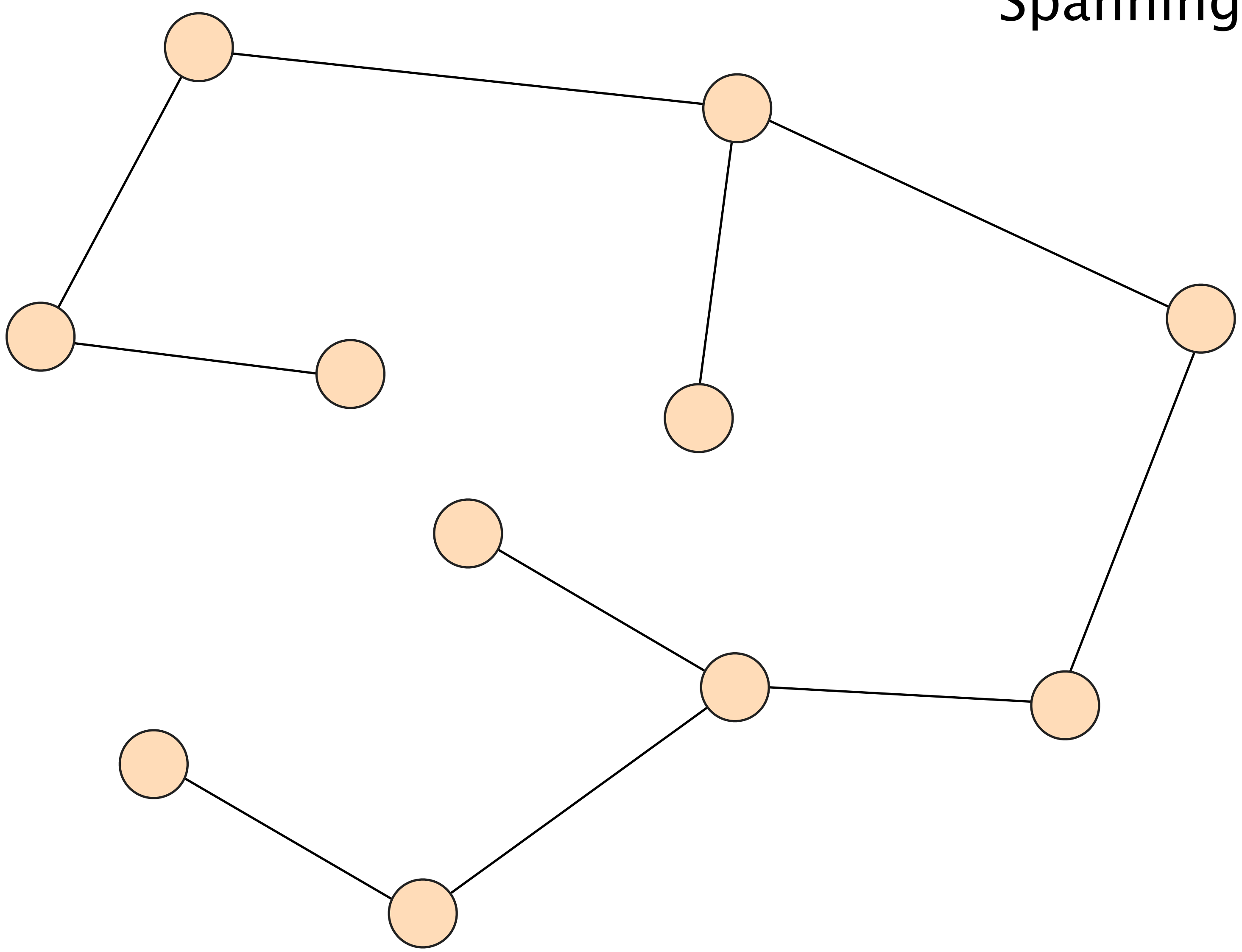
Why does it work?

Spanning-trees have only one path
between any two nodes

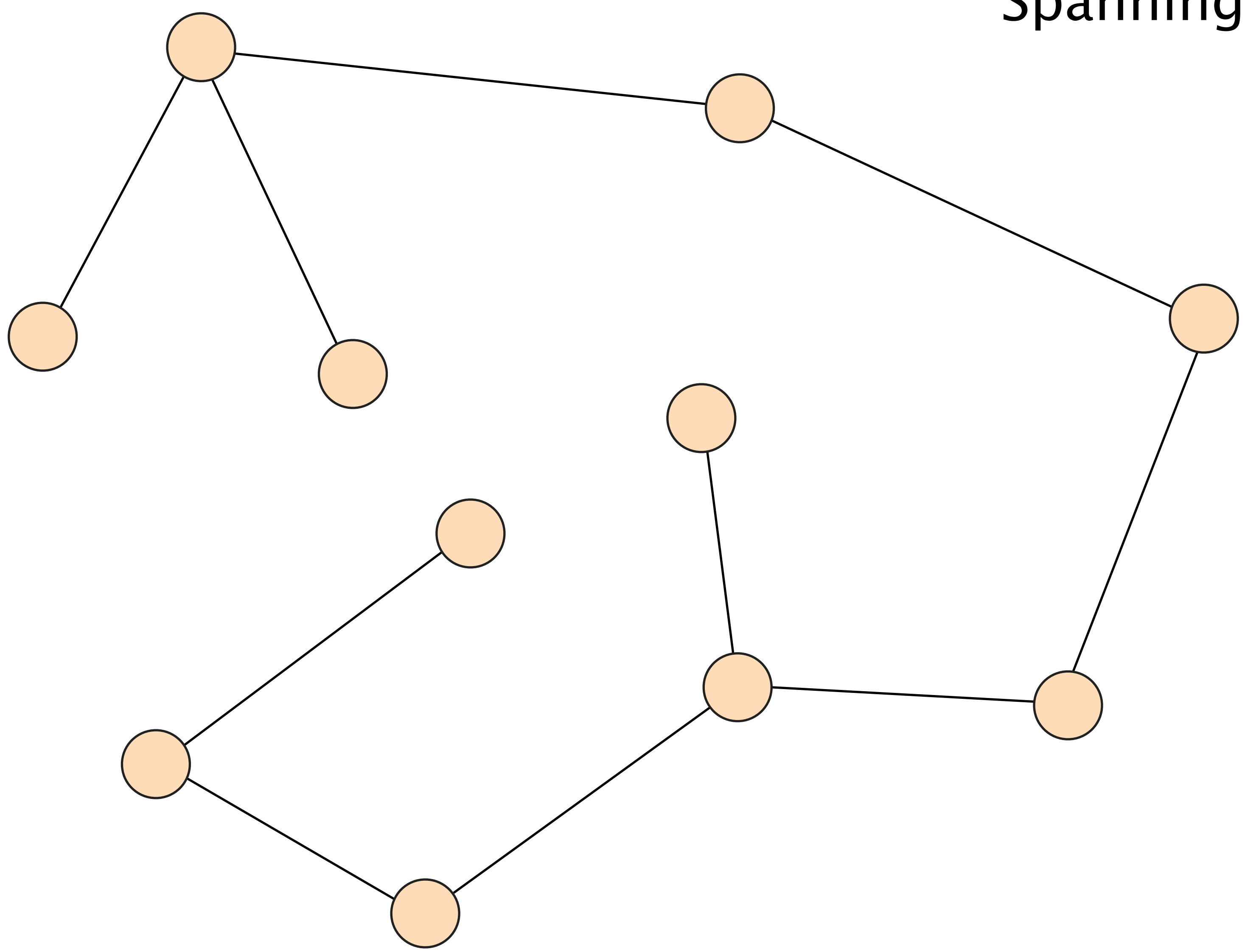
In practice,
there can be *many* spanning-trees for a given topology



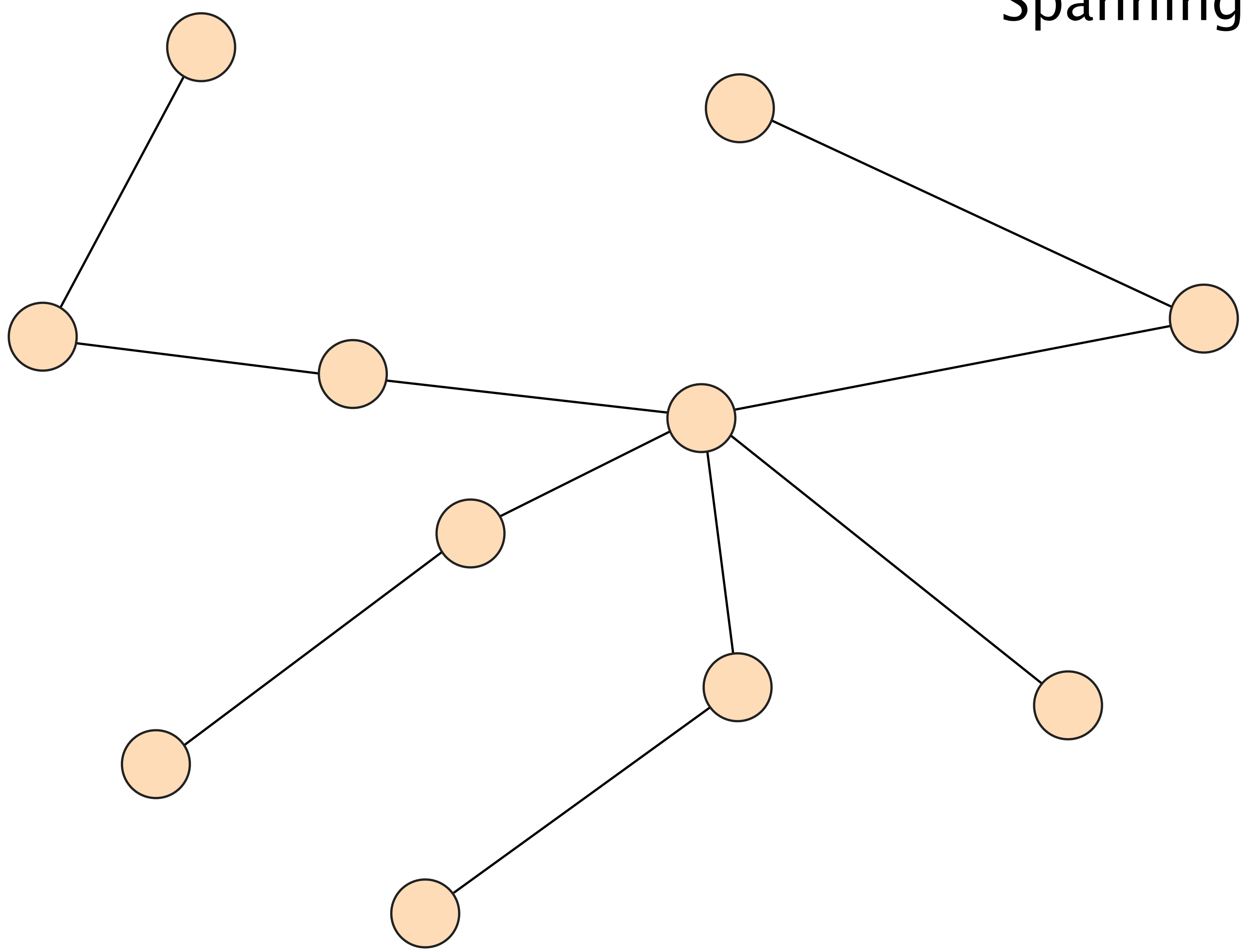
Spanning-Tree #1



Spanning-Tree #2



Spanning-Tree #3



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

For now, assume it is possible

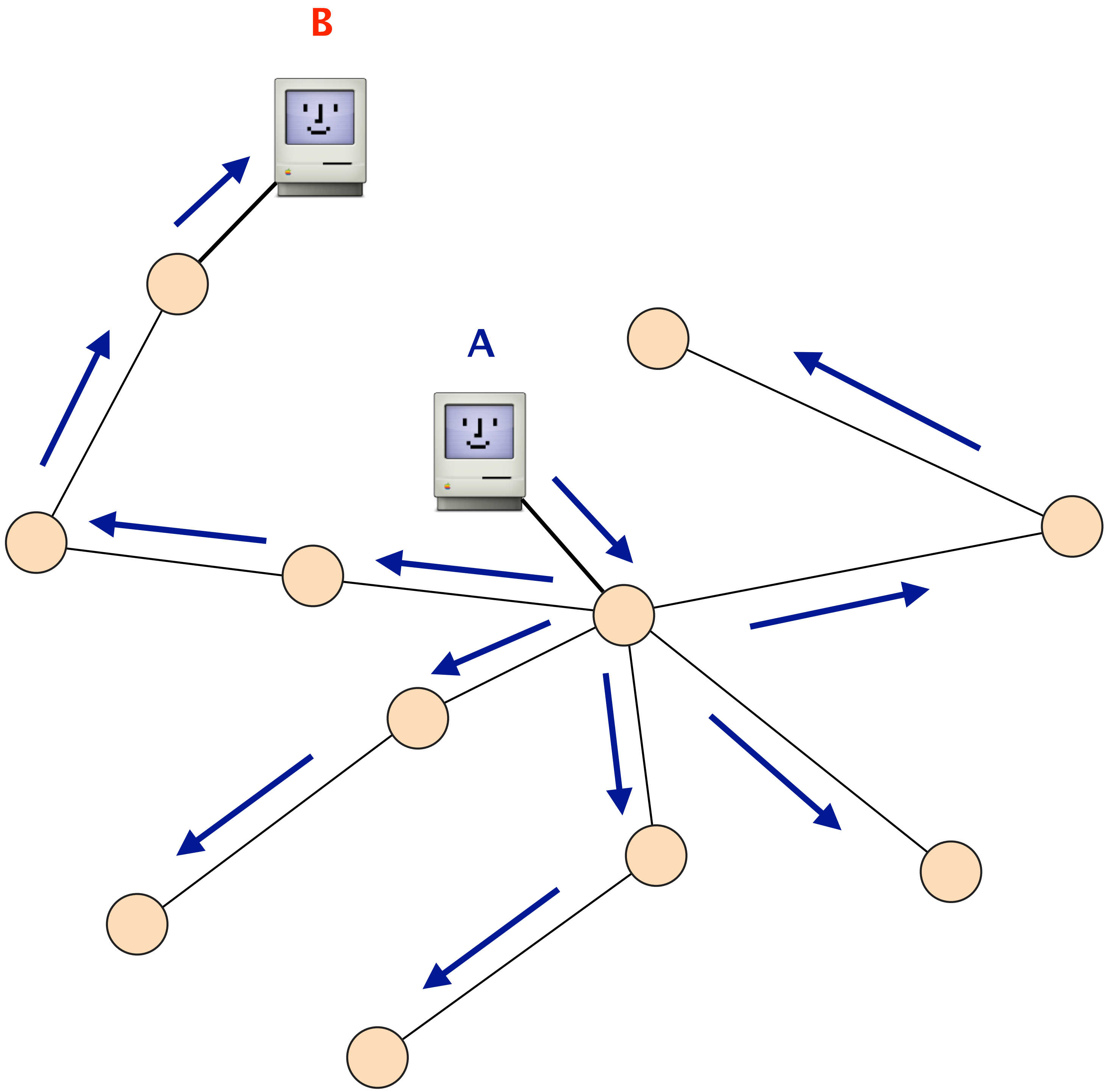
Once we have a spanning tree,

forwarding on it is easy

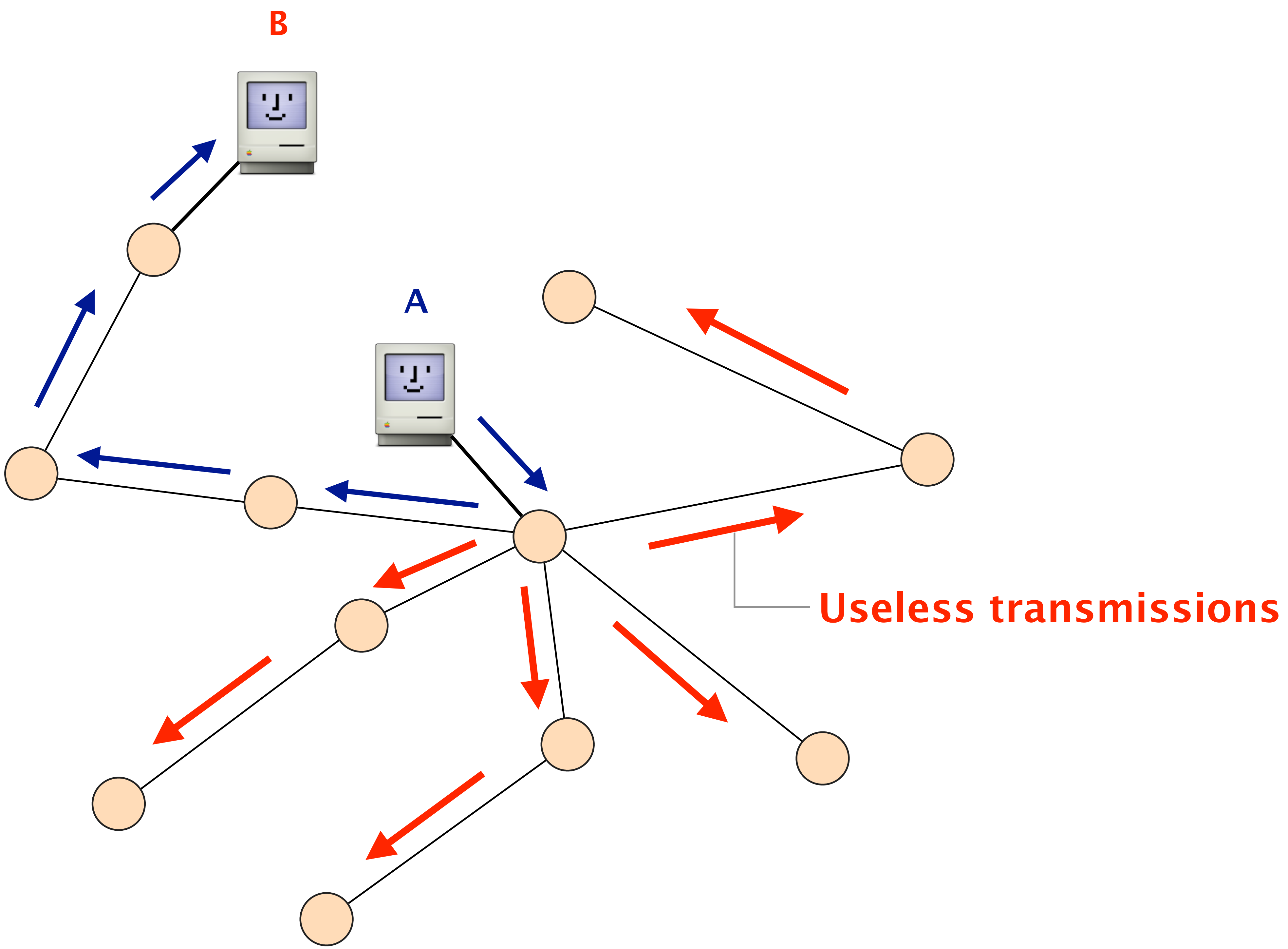
literally just flood

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

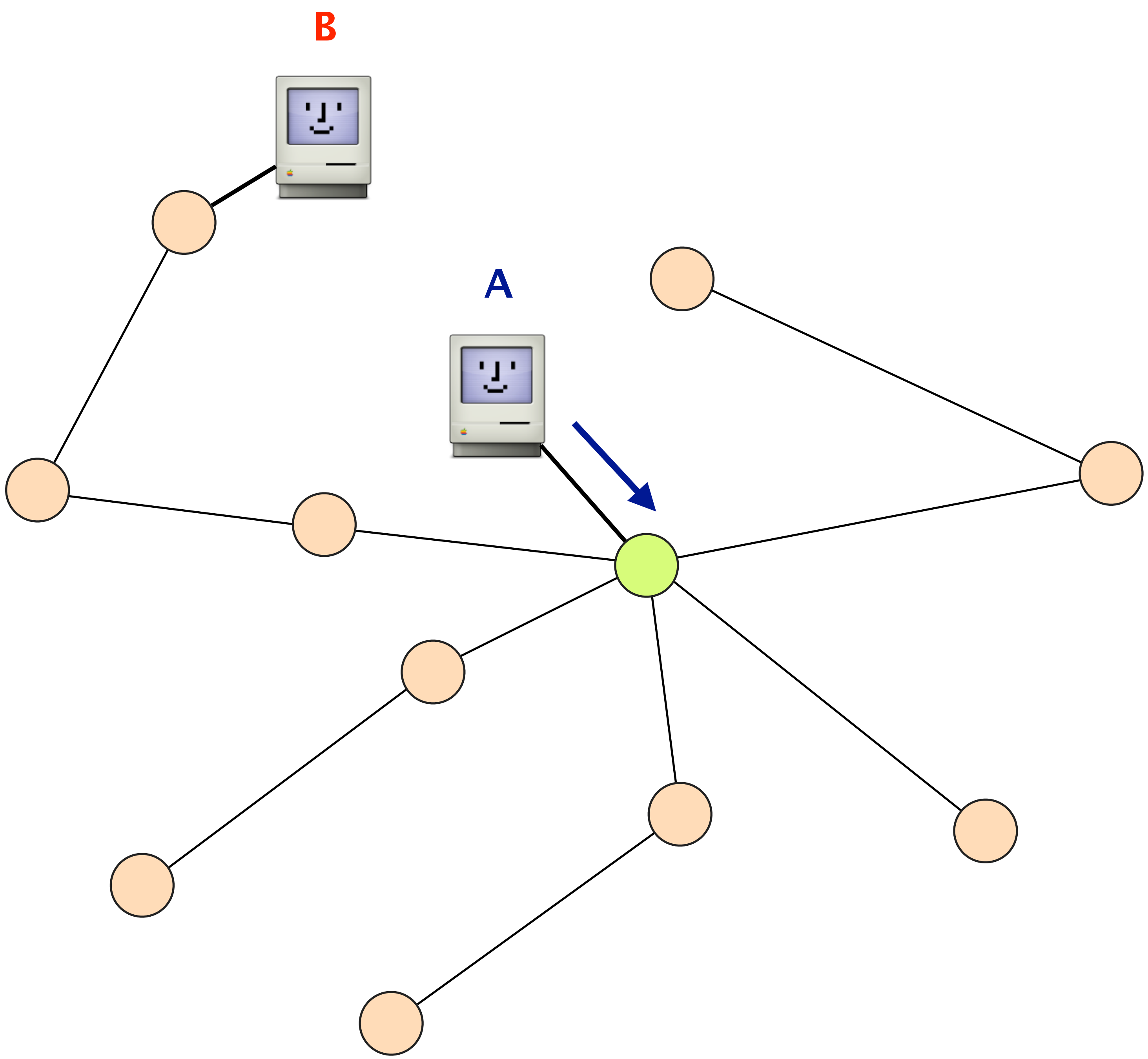
intuition

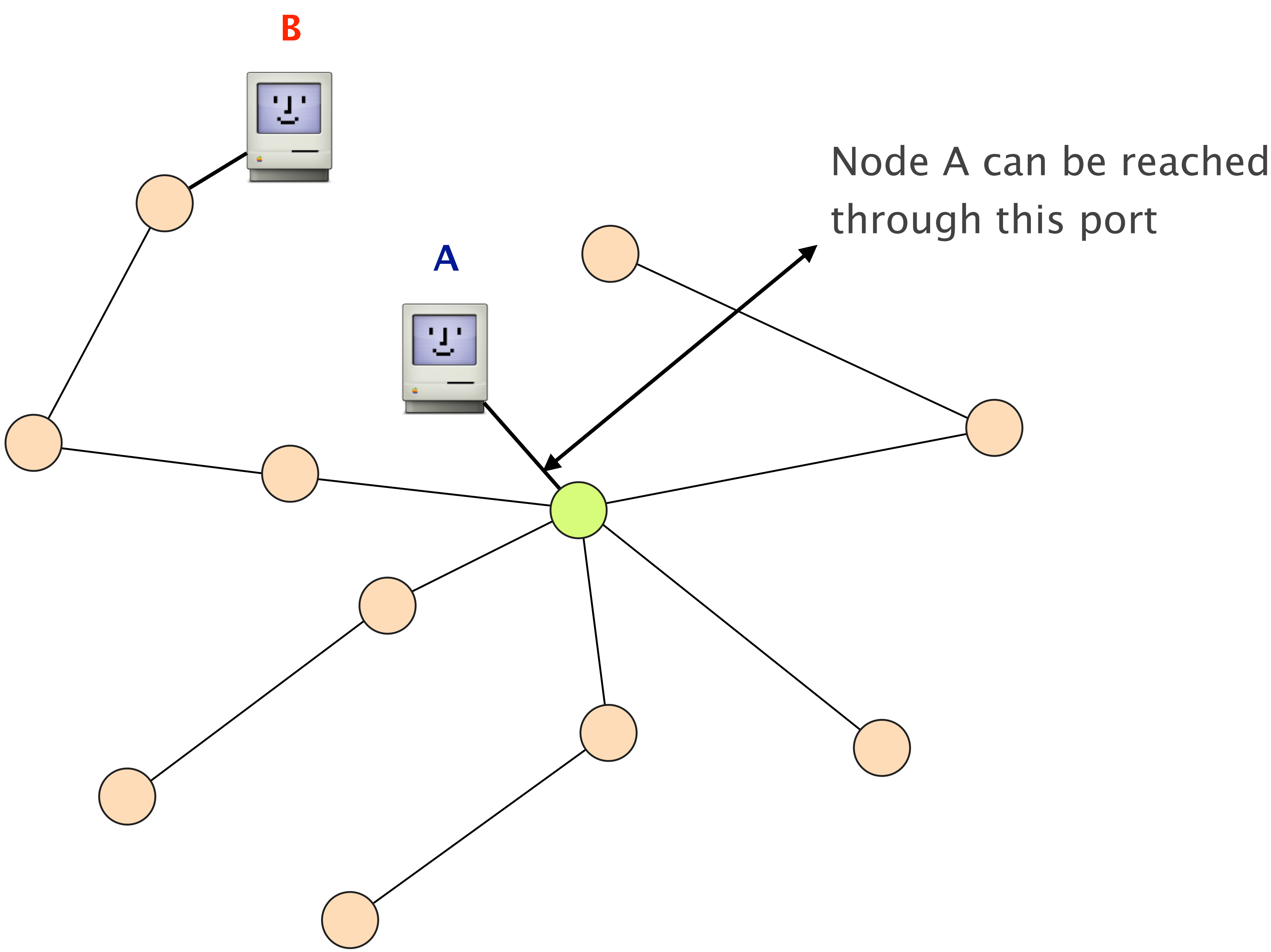
if

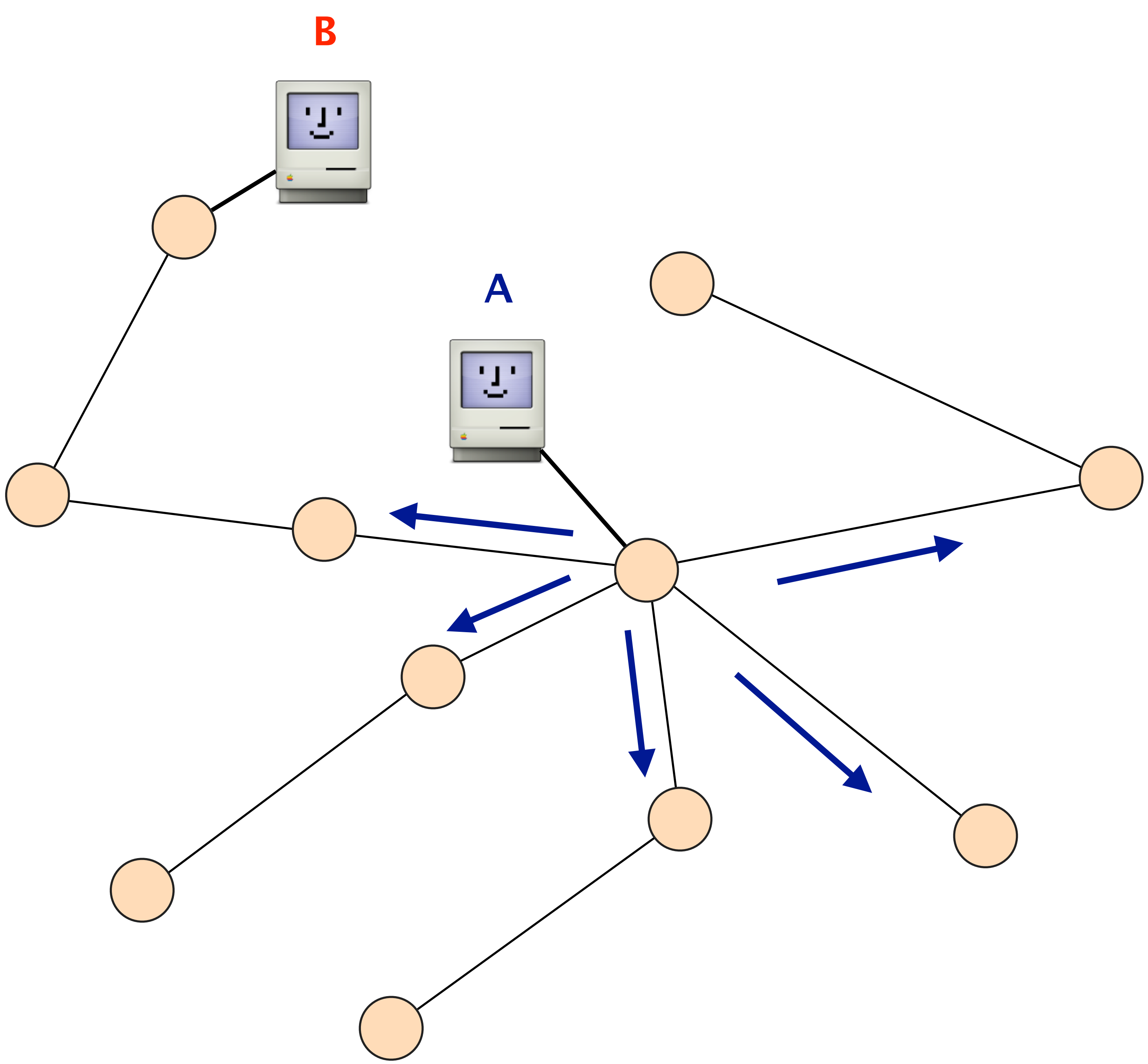
flood packet from node *A*
entered switch *X* on port *4*

then

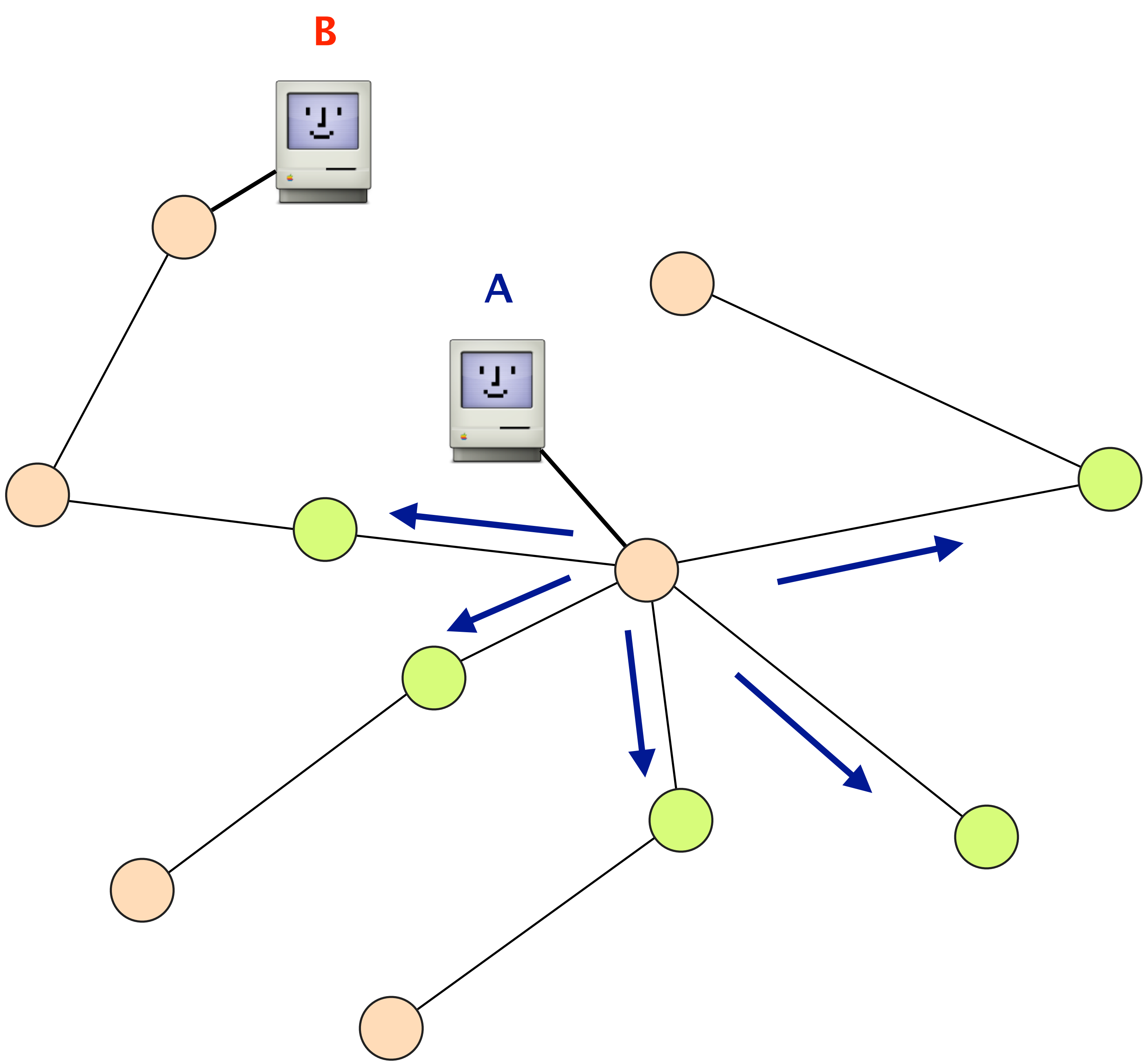
switch *X* can use port *4*
to reach node *A*


B
A

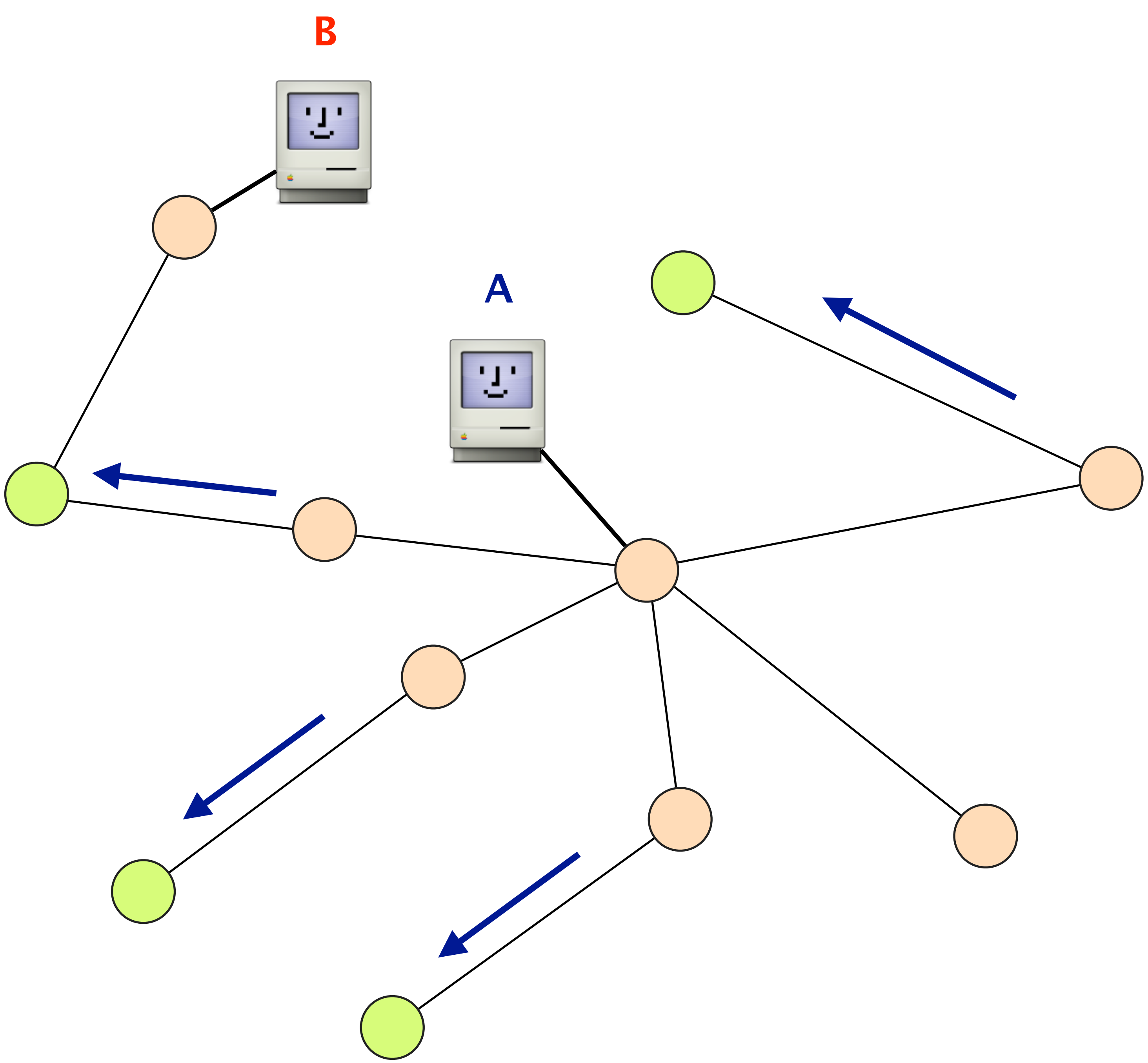

B
A
Node A can be reached
through this port


B
A

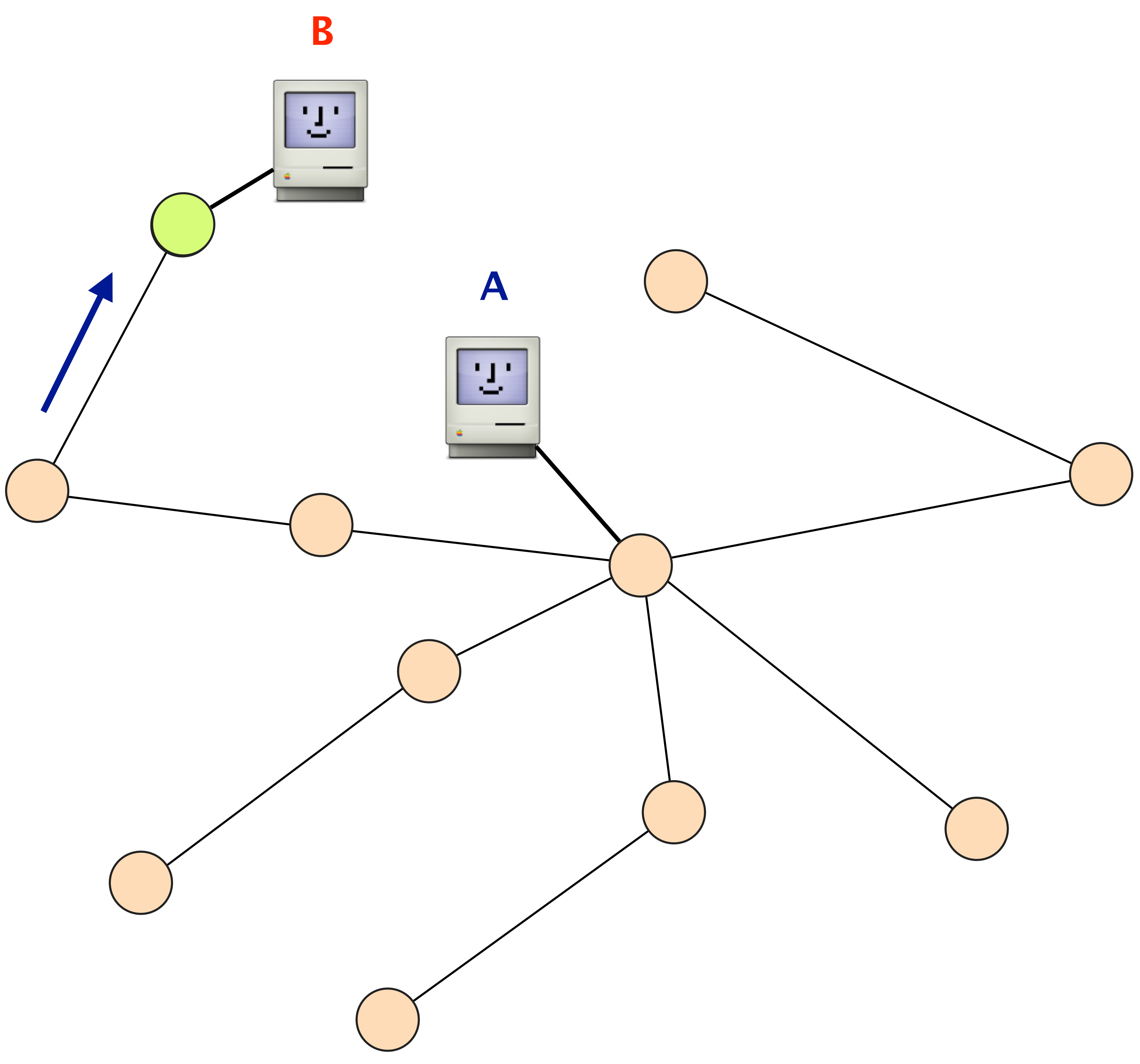
All the green nodes learn how to reach A



All the green nodes learn how to reach A

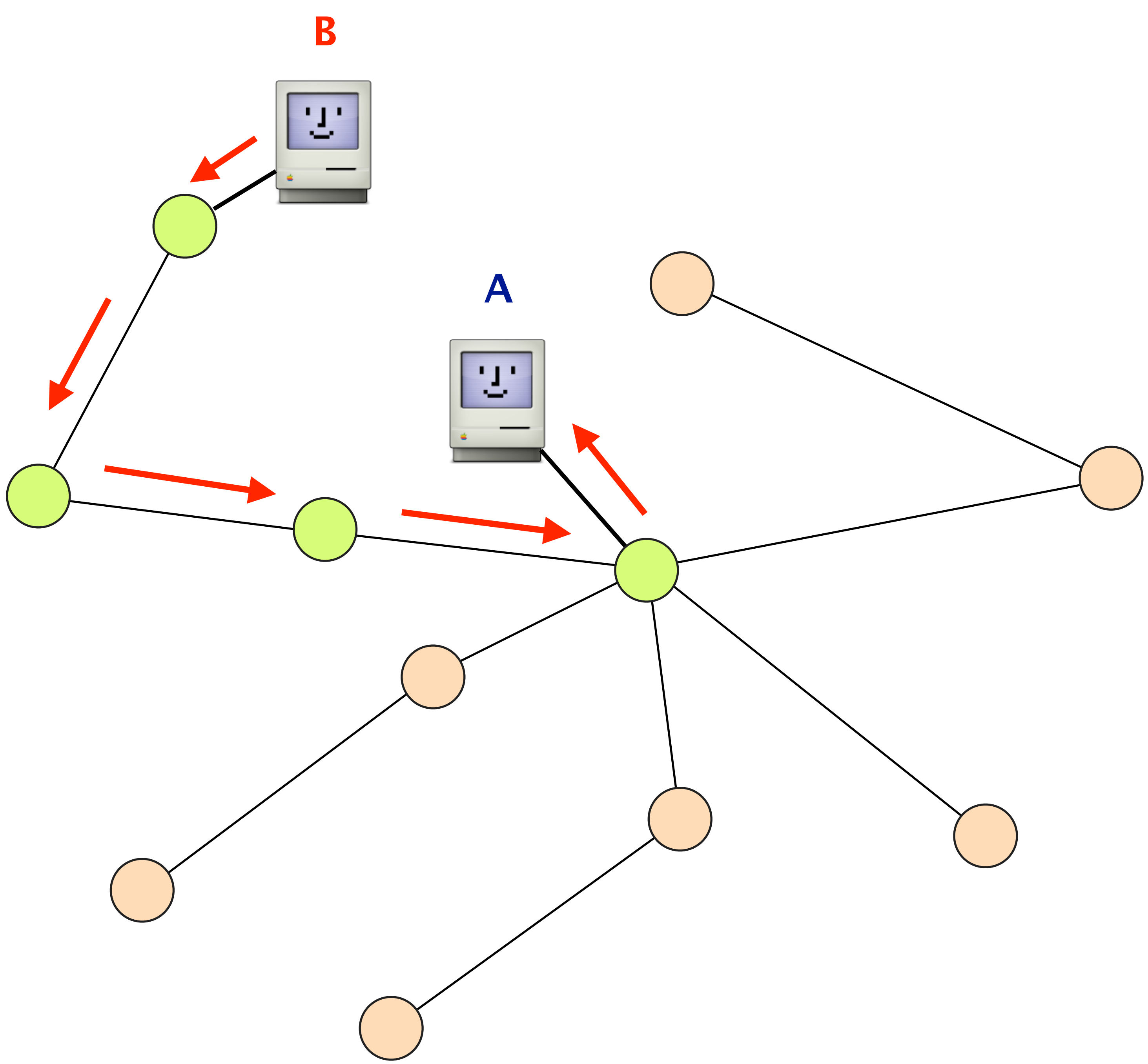


All the nodes know on which port A can be reached

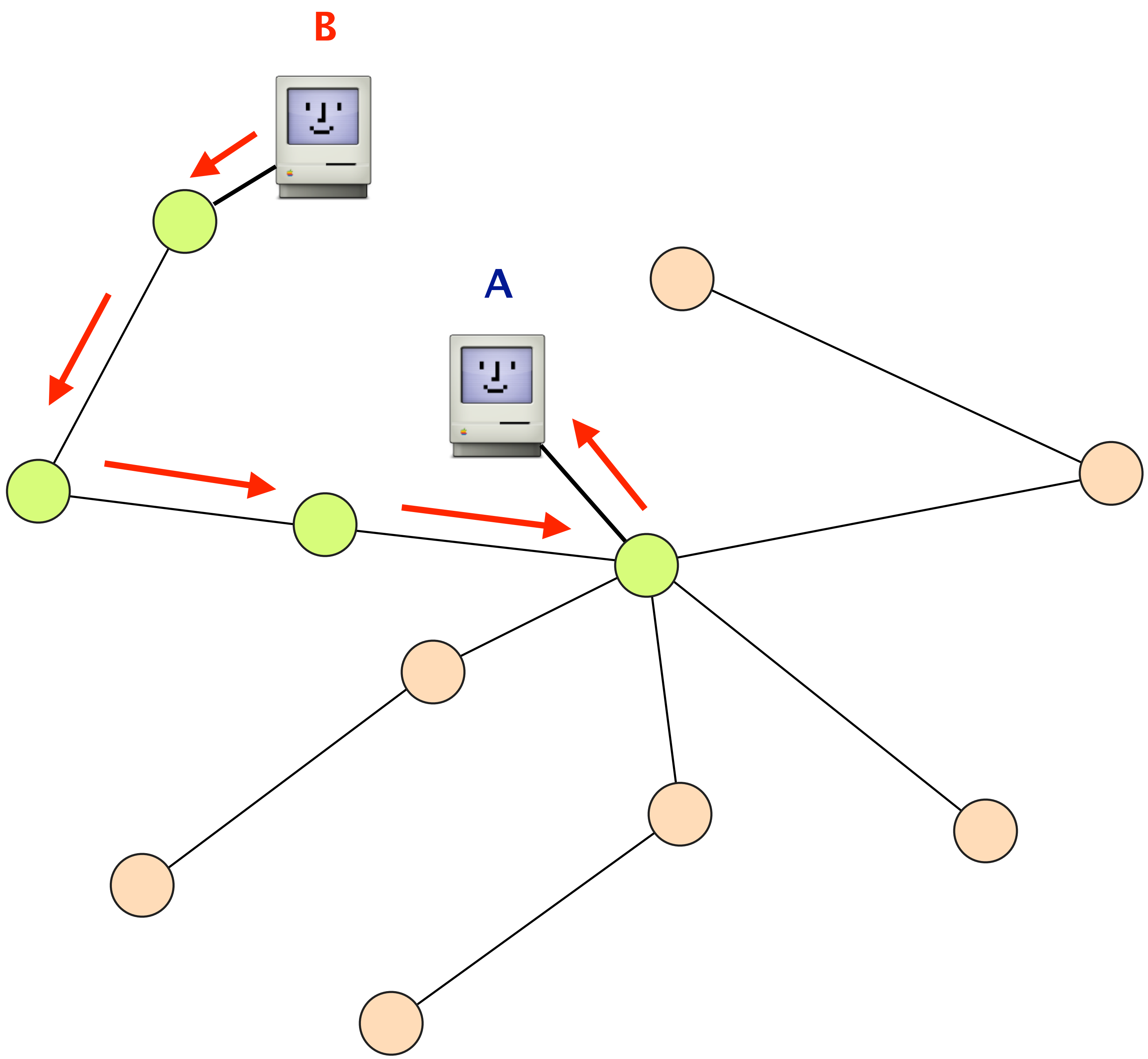


B answers back to A

enabling the green nodes to also learn where B is

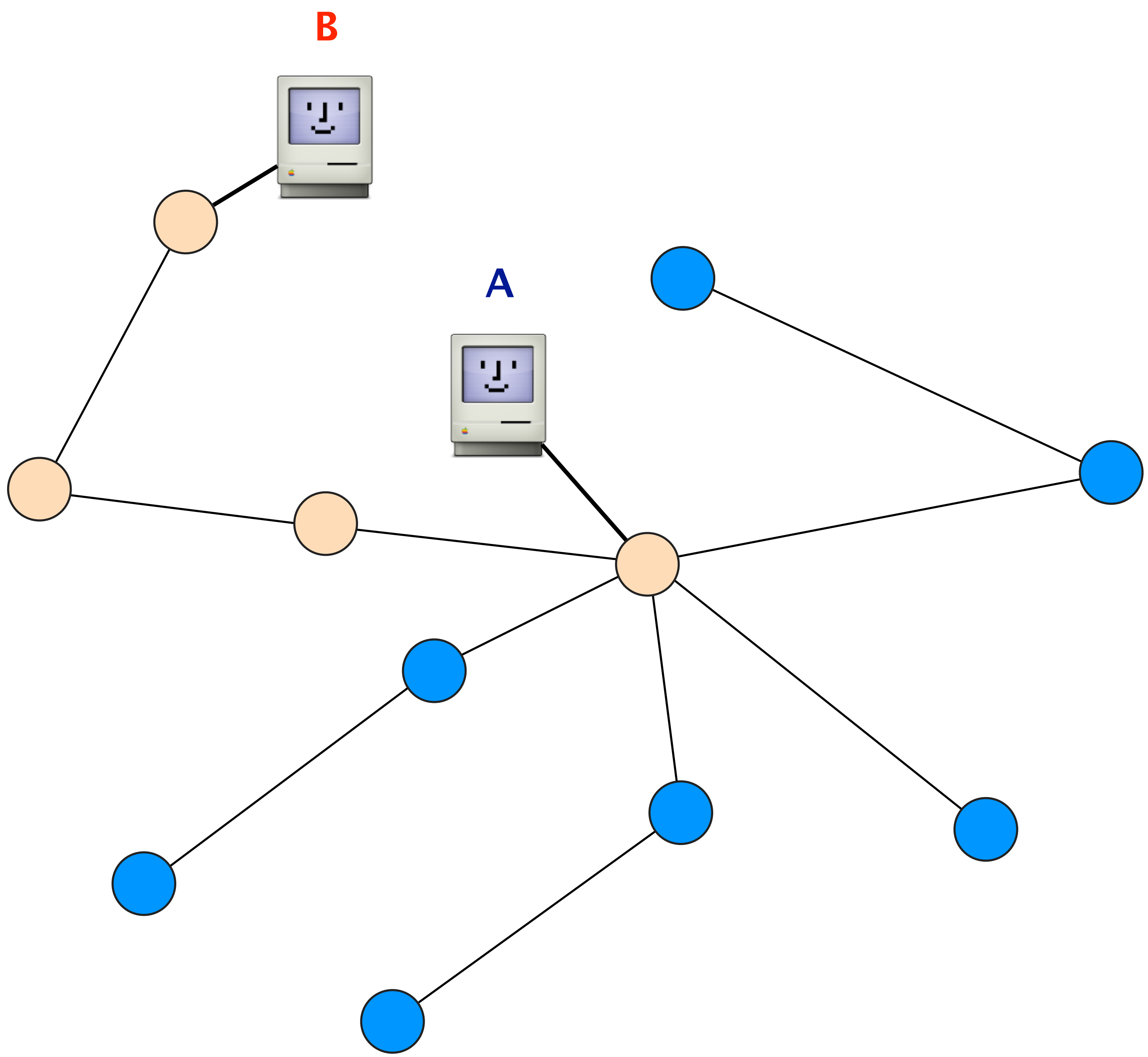


There is no need for flooding here
as the position of A is already known by everybody



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

	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

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*

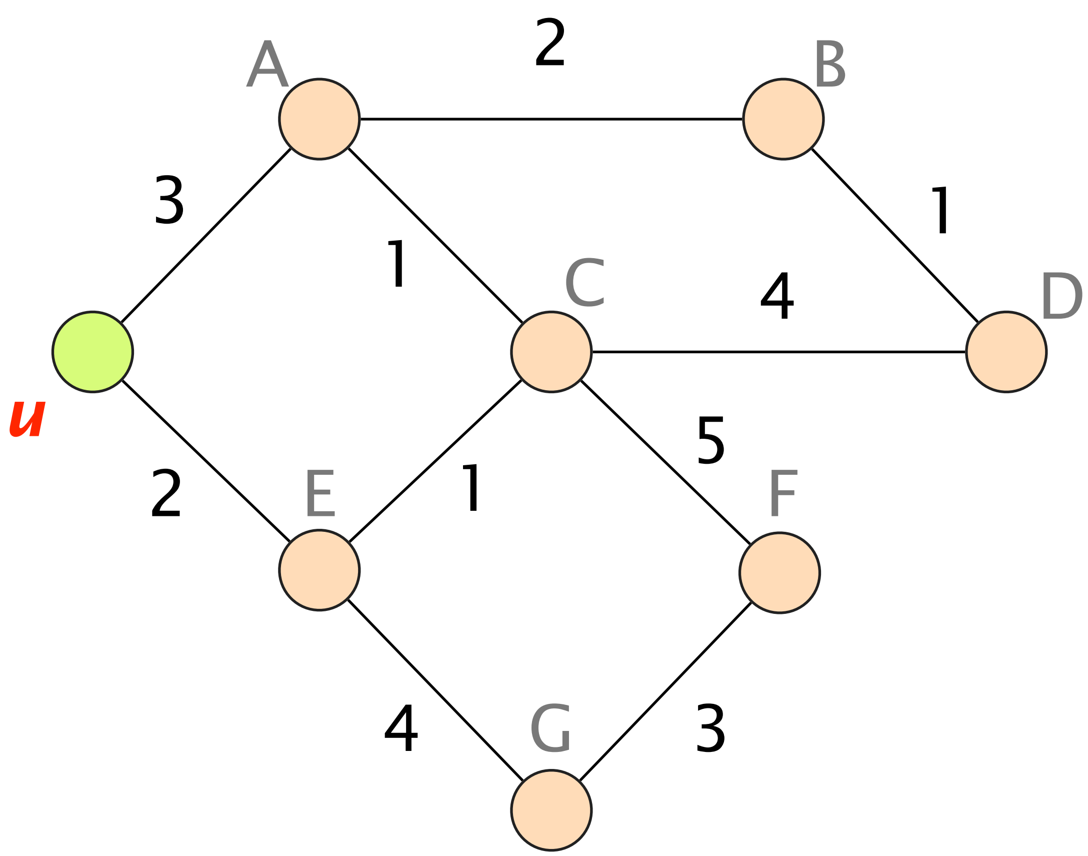
else:

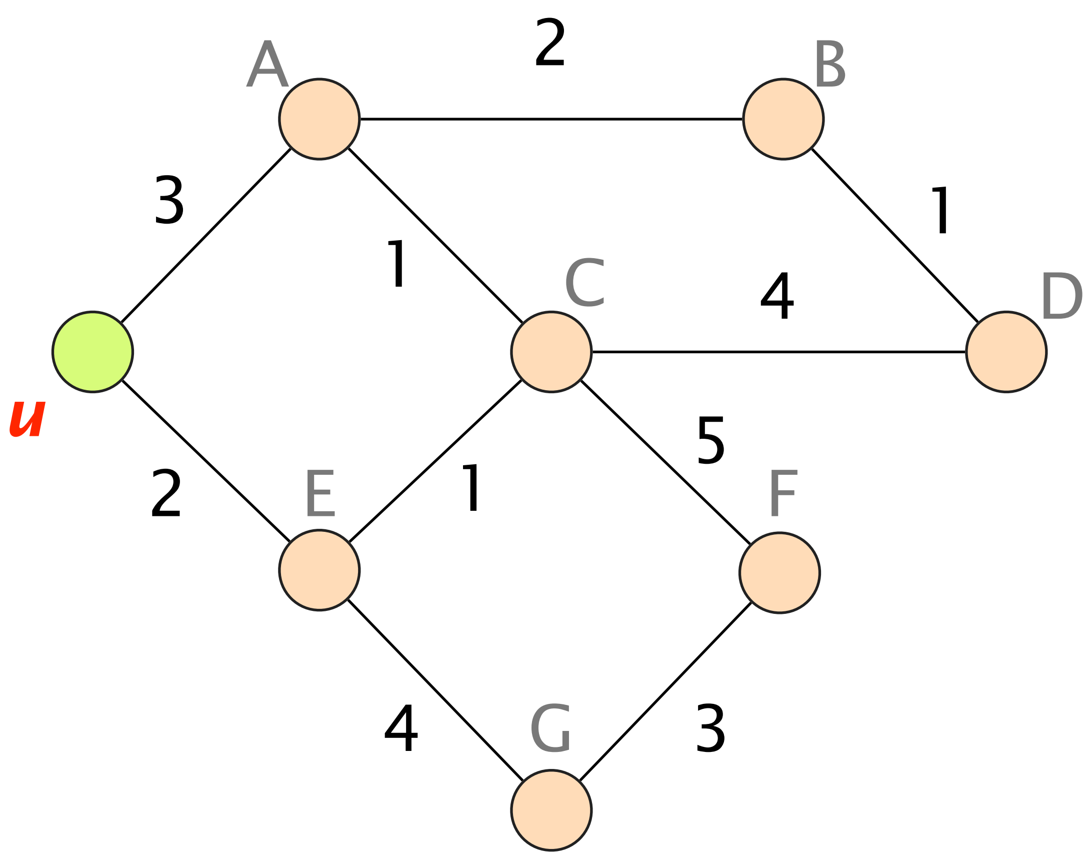
D(*v*) = ∞

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:

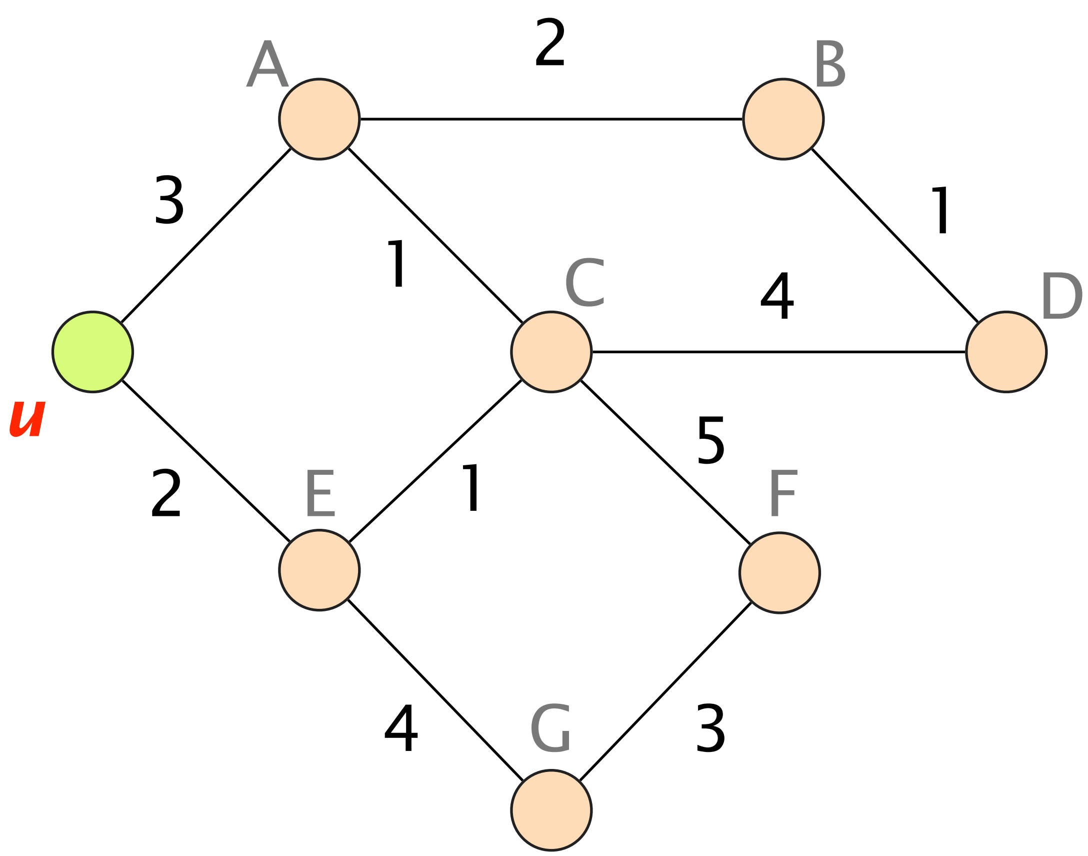
if (v is adjacent to u):

D(v) = c(u,v)

else:

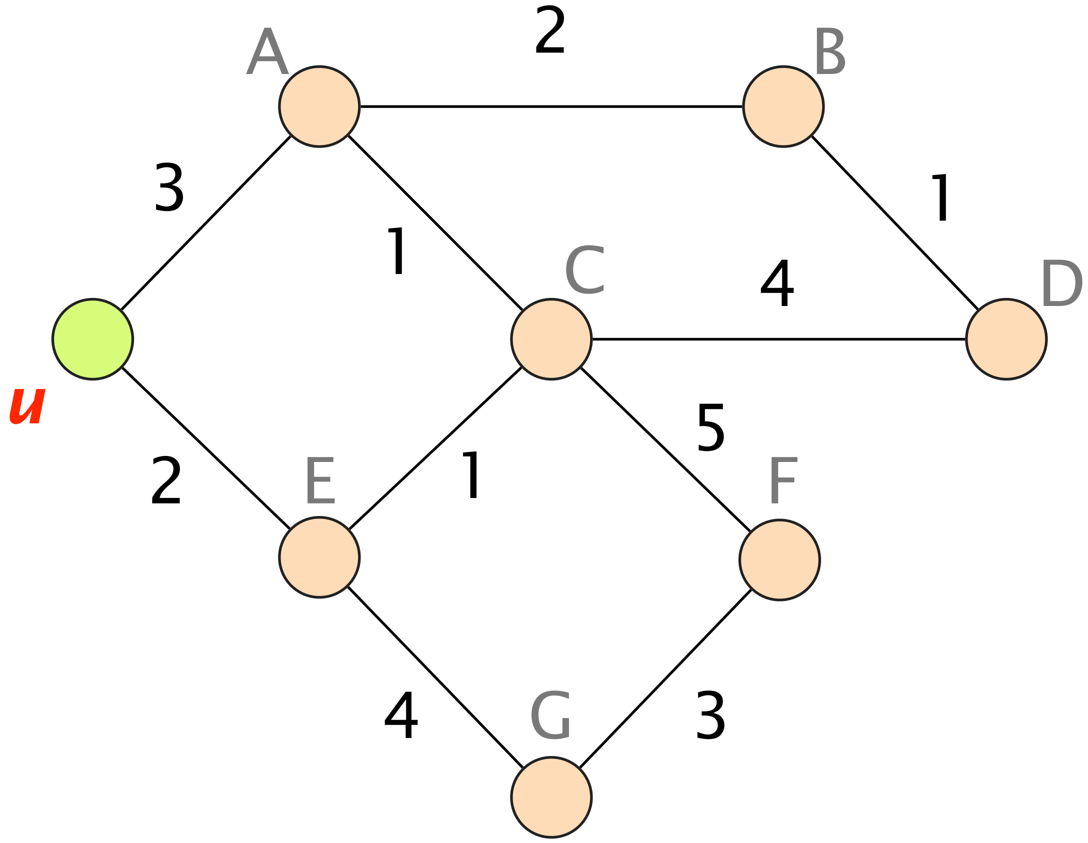
D(v) = ∞

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	∞



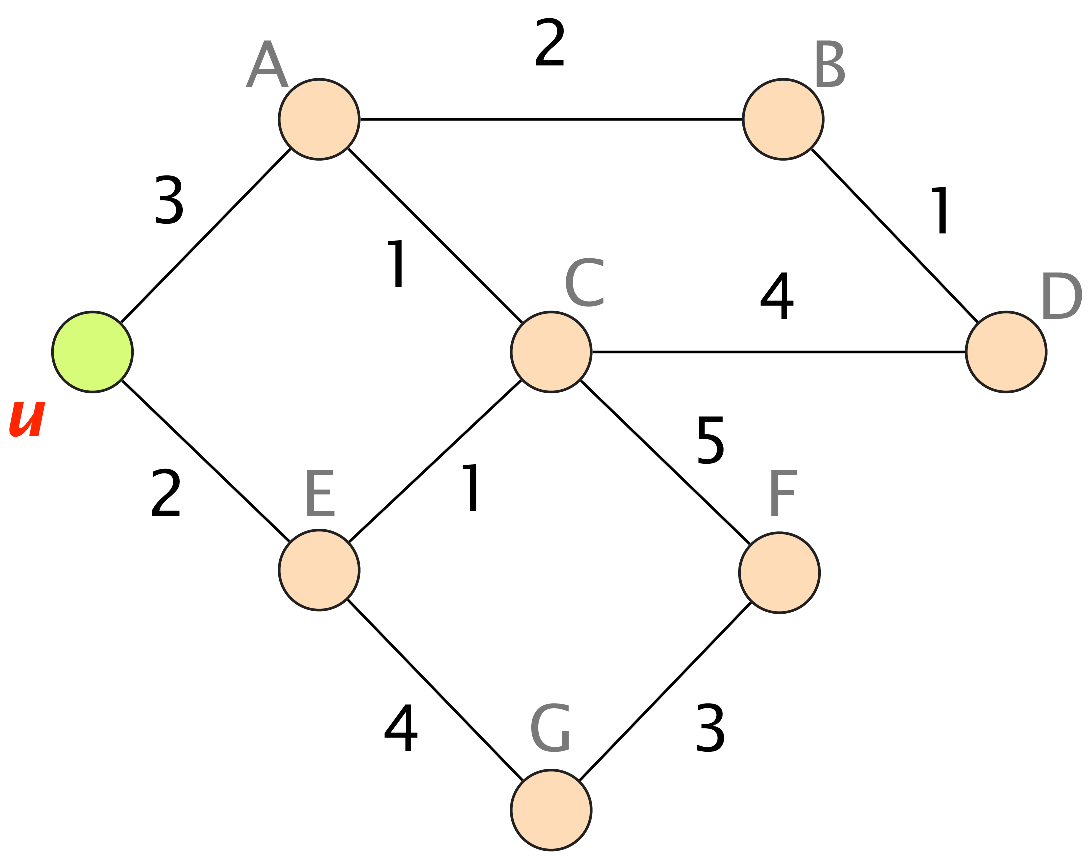
Loop

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:

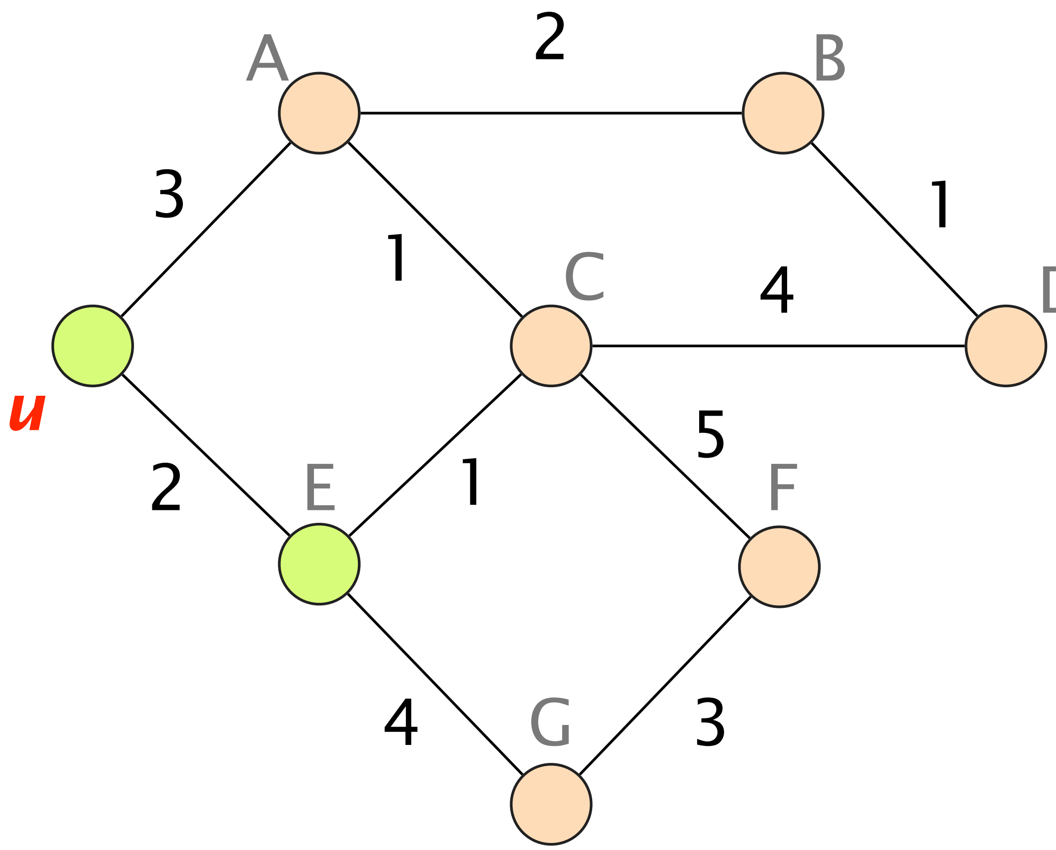
$D(v) = \min\{D(v), D(w) + c(w,v)\}$



D(.) = S = {u}

A	3
B	∞
C	∞
D	∞
E	2
F	∞
G	∞

smallest D(*w*)

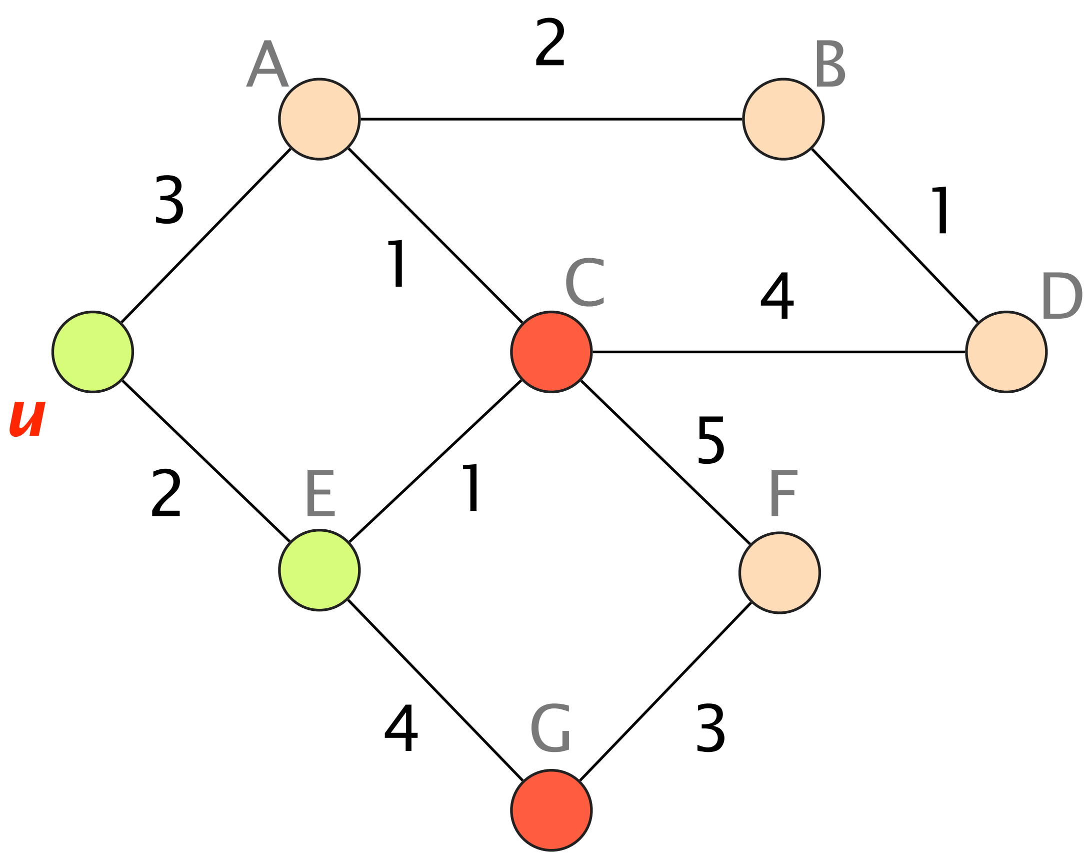


add E to S

D(.) =

S = {u, E}

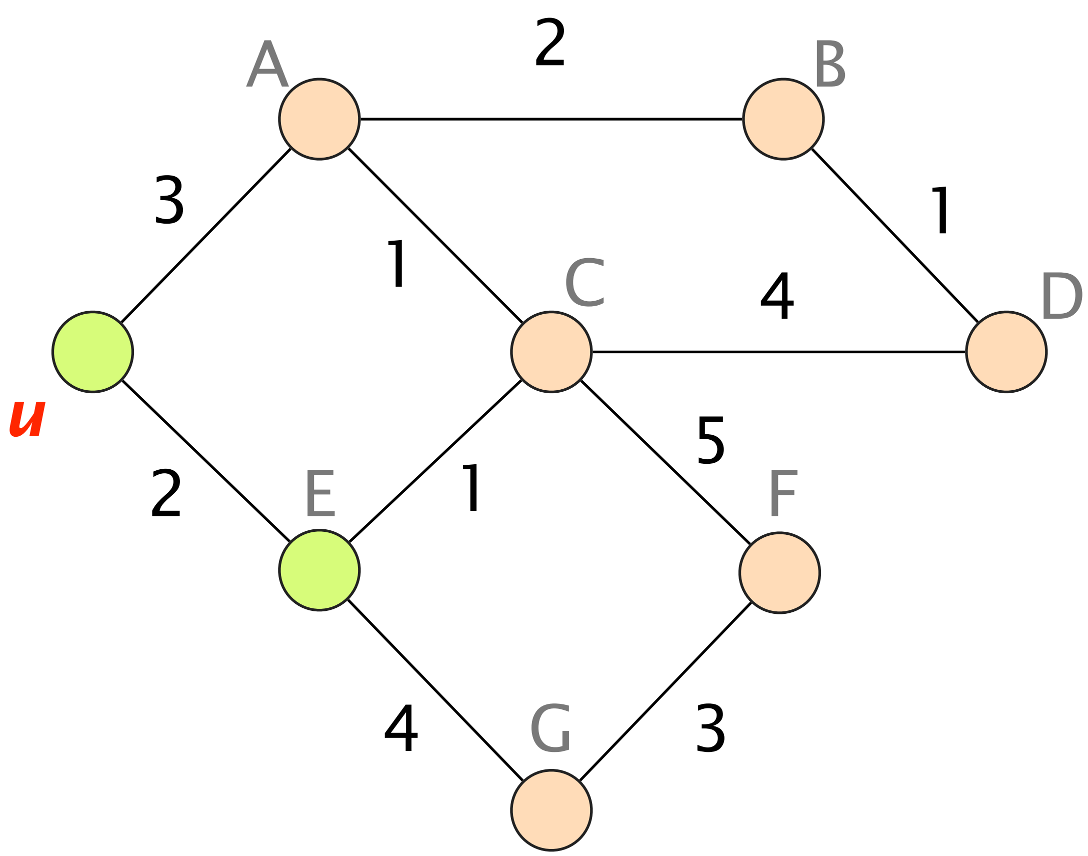
A	3
B	∞
C	∞
D	∞
E	2
F	∞
G	∞



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

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

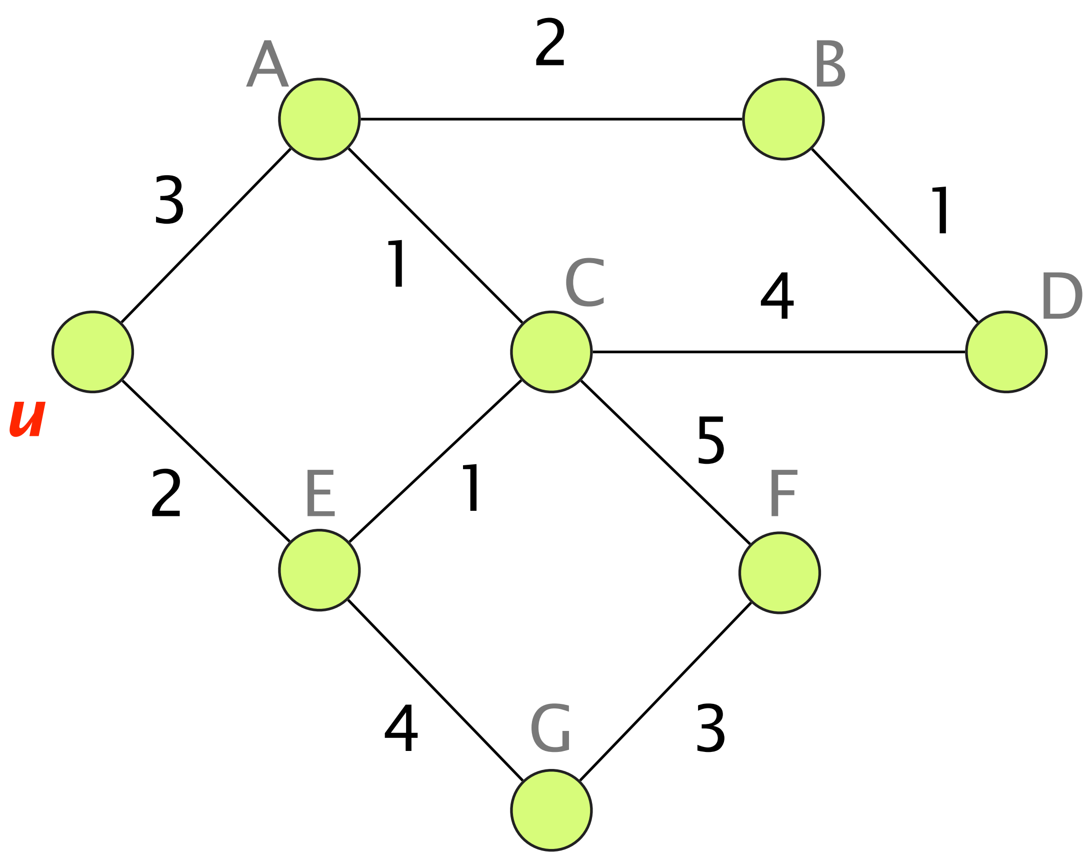
Now, do it by yourself



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

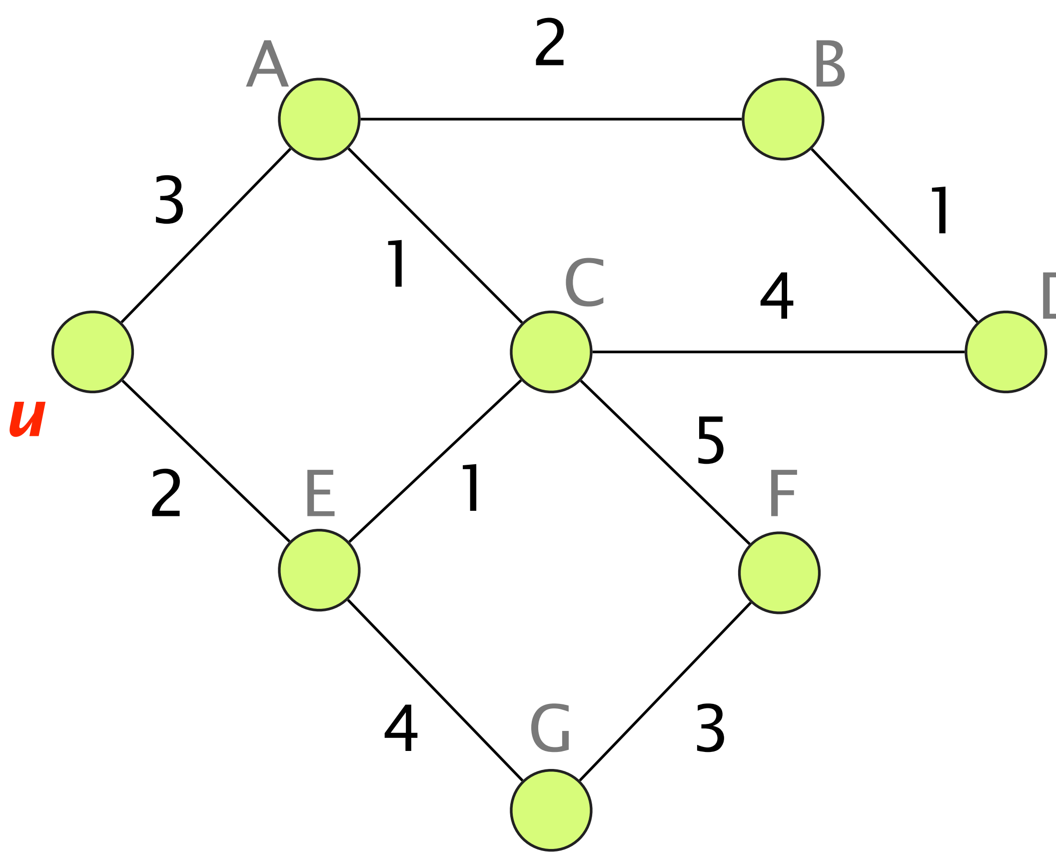
$\frac{n(n+1)}{2}$ operations => O(n^2)

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



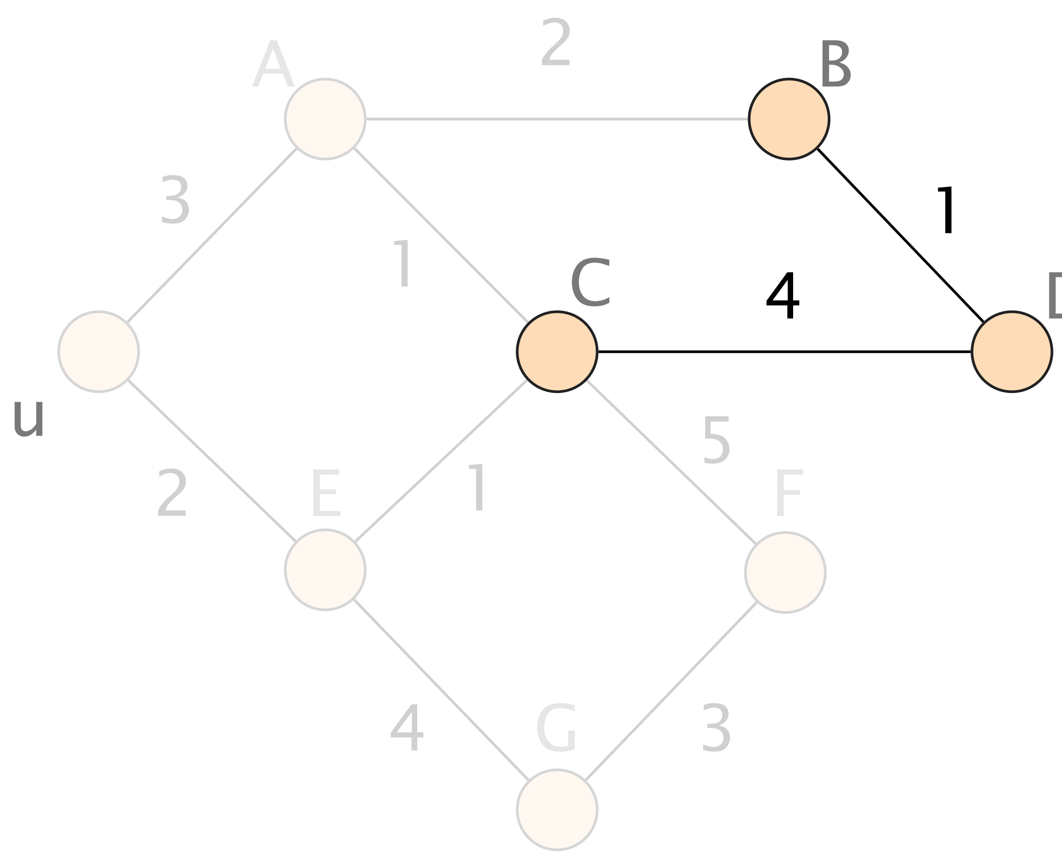
Forwarding table

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

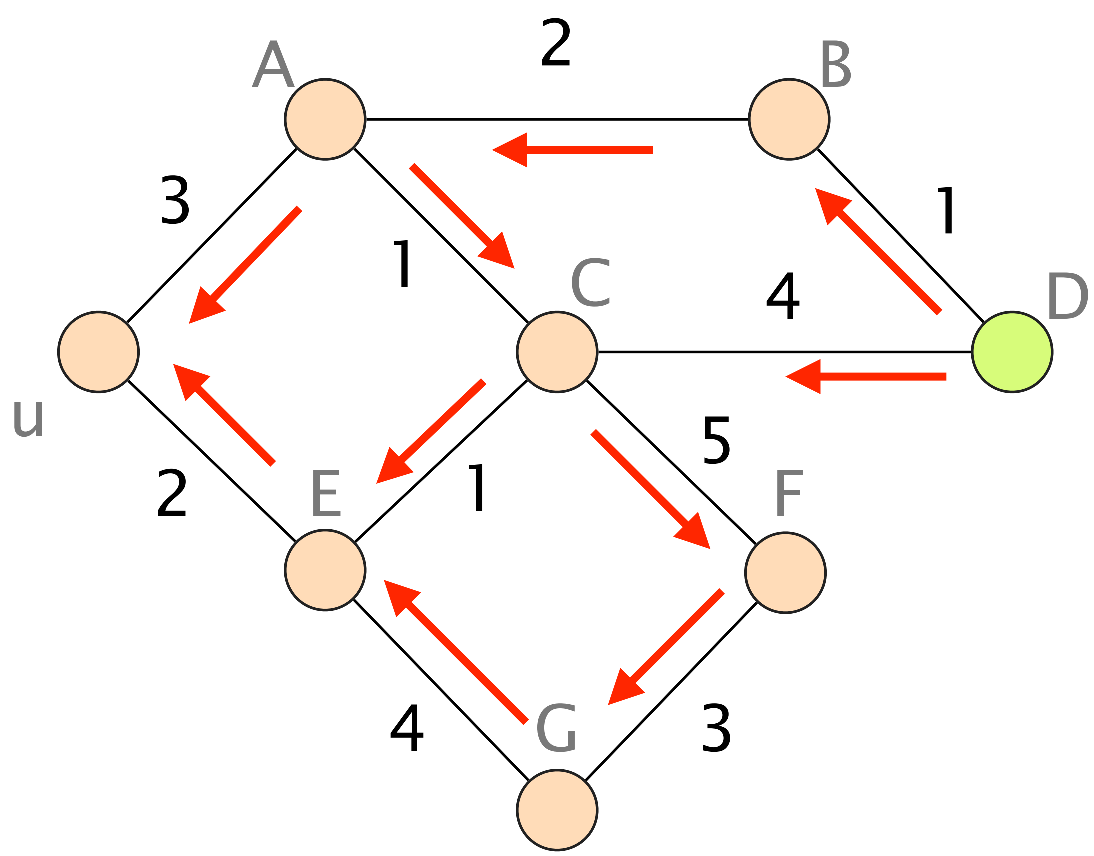
Initially,
routers only know their ID and their neighbors



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



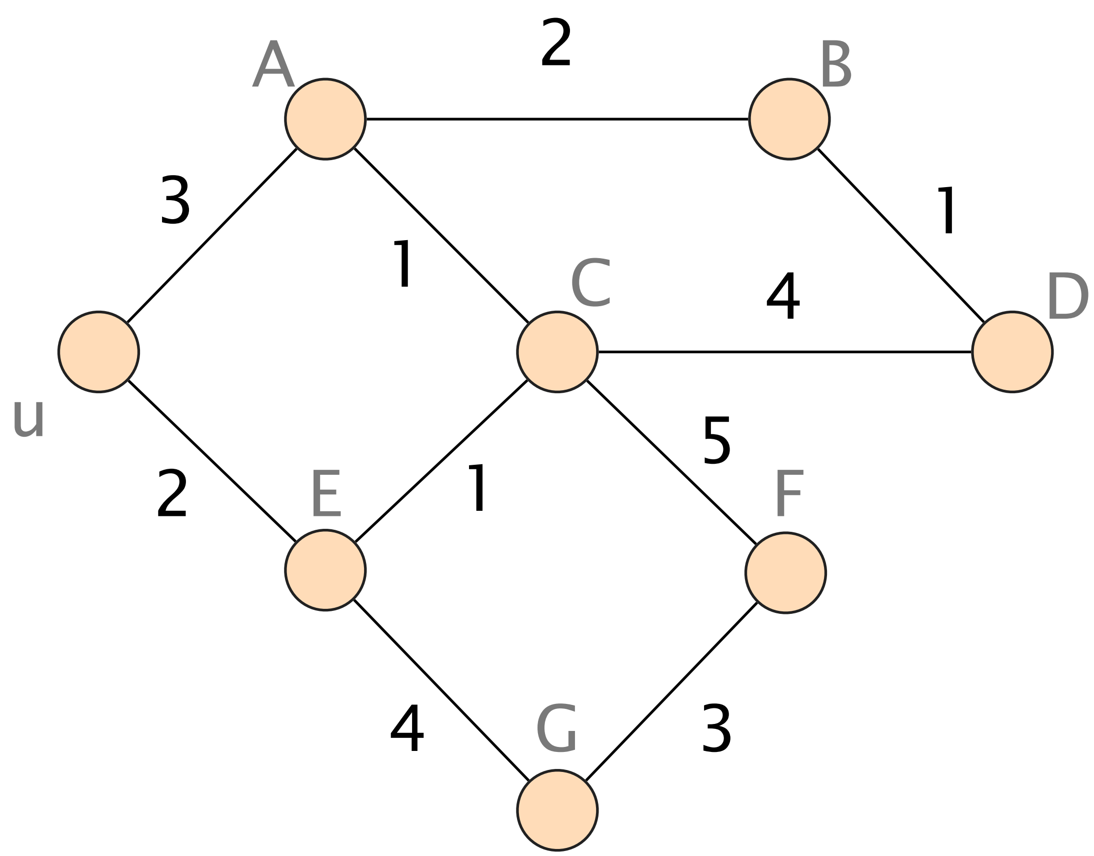
D's Advertisement

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. exercice session
for the dynamic case

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

until convergence

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

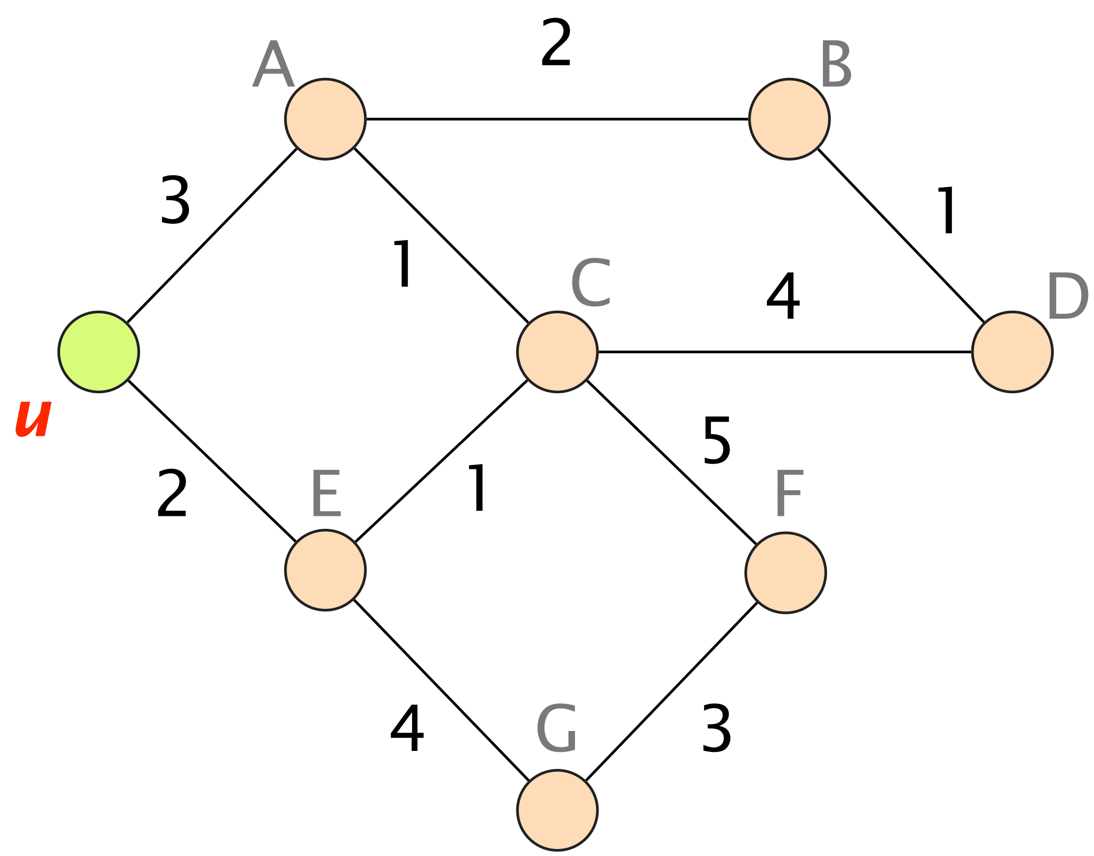
Each node bundles these distances into one message (called a vector) that it repeatedly sends to all its neighbors

until convergence

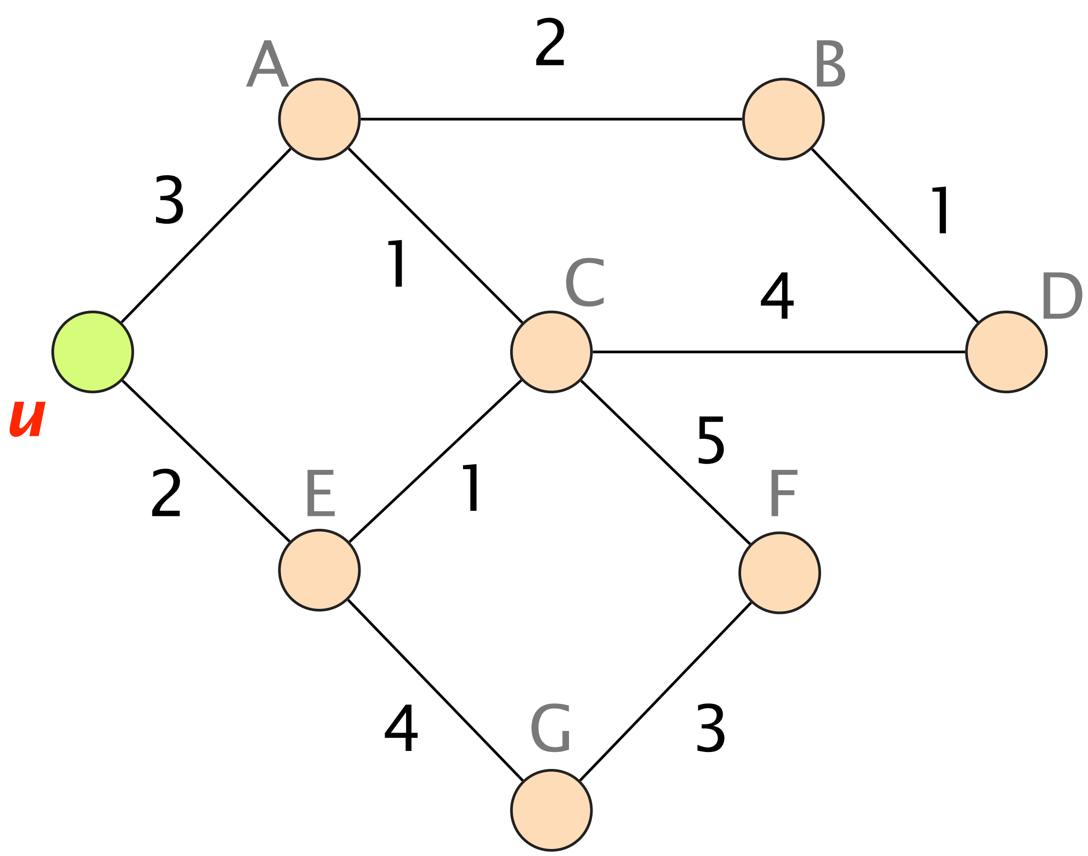
Each node updates its distances based on neighbors' vectors:

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



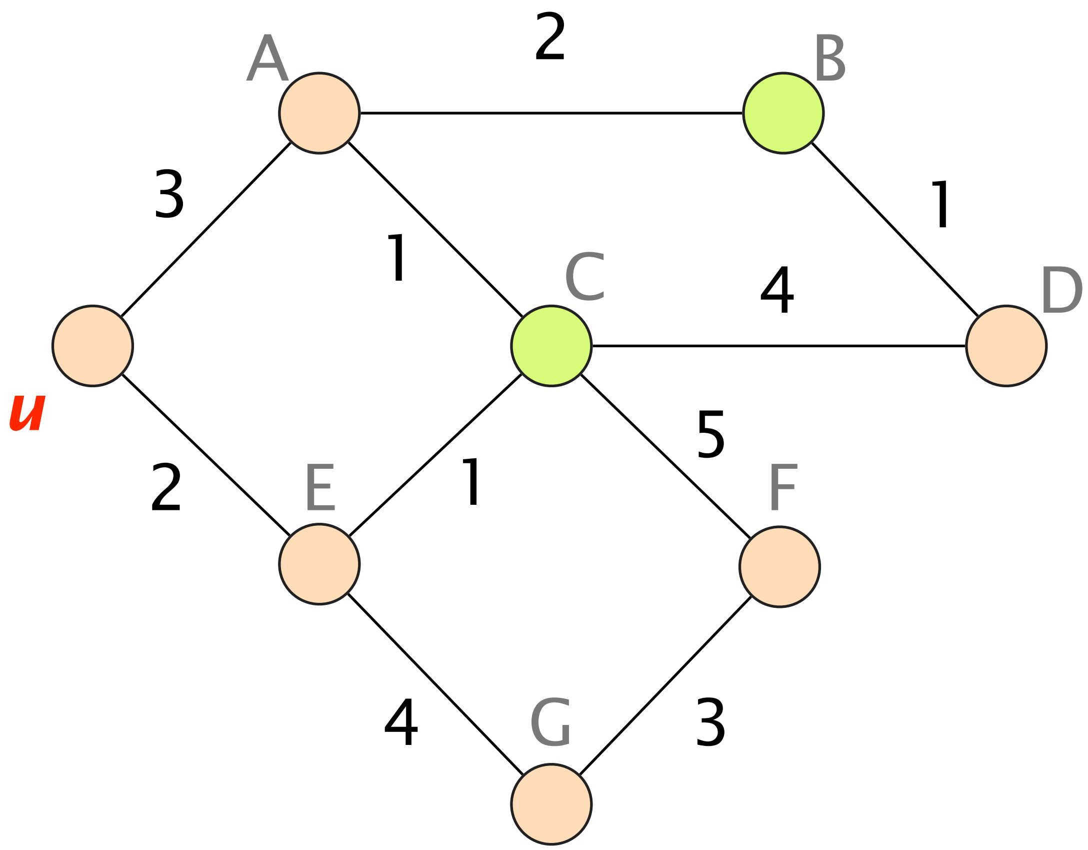
$$d_x(y) = \min\{\ c(x,v) + d_v(y)\ \}$$

over all neighbors *v*

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

To unfold the recursion,

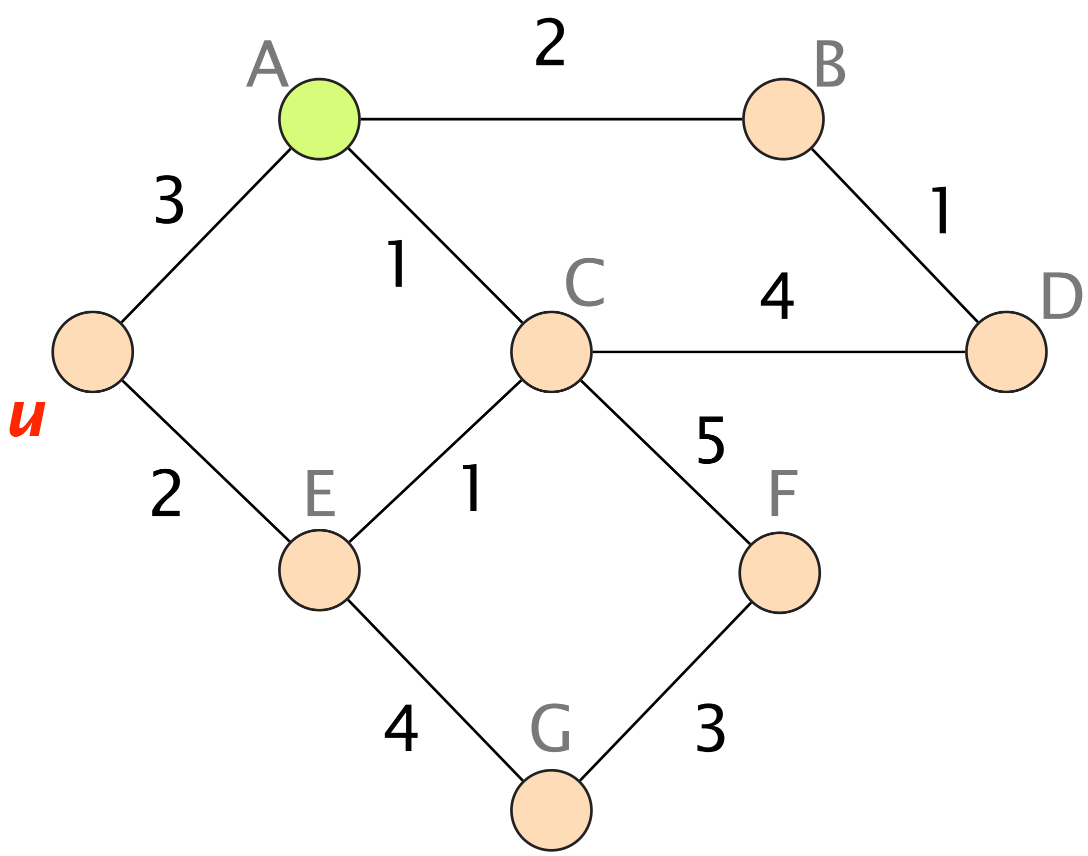
let's start with the direct neighbor of D



$d_B(D) = 1$

$d_C(D) = 4$

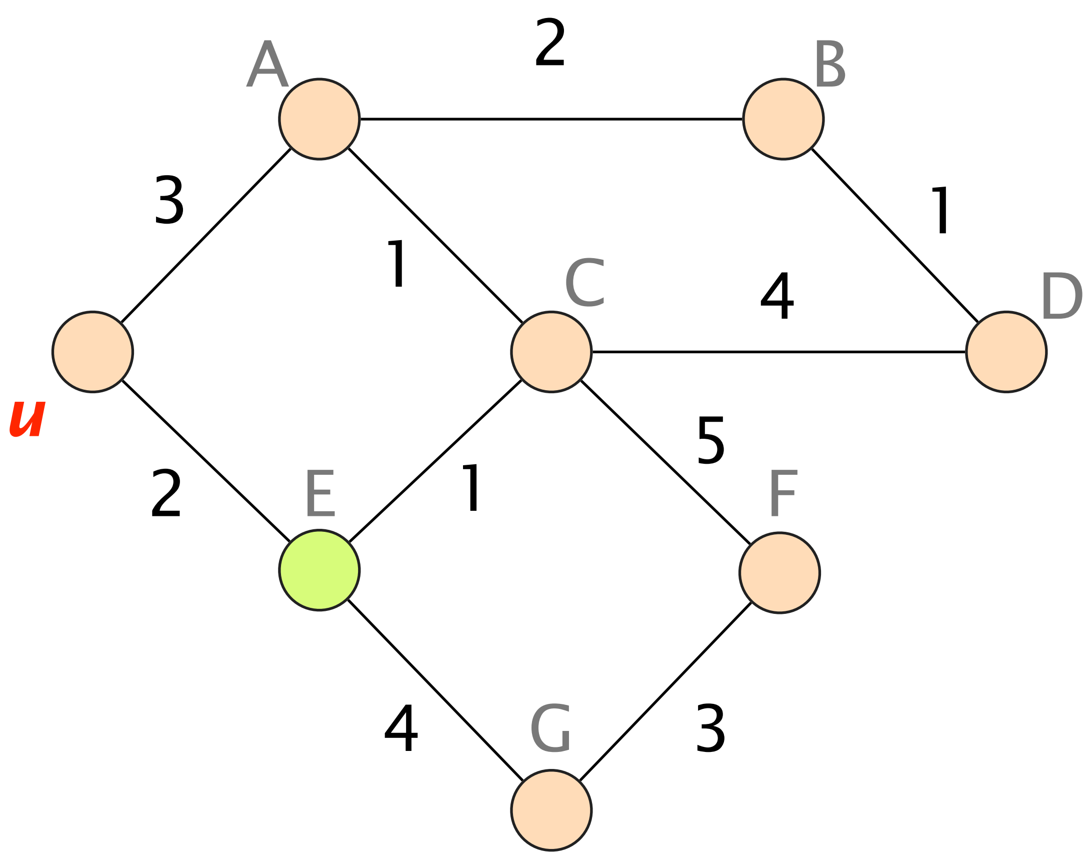
B and C announce their vector to their neighbors, enabling A to compute its shortest-path



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

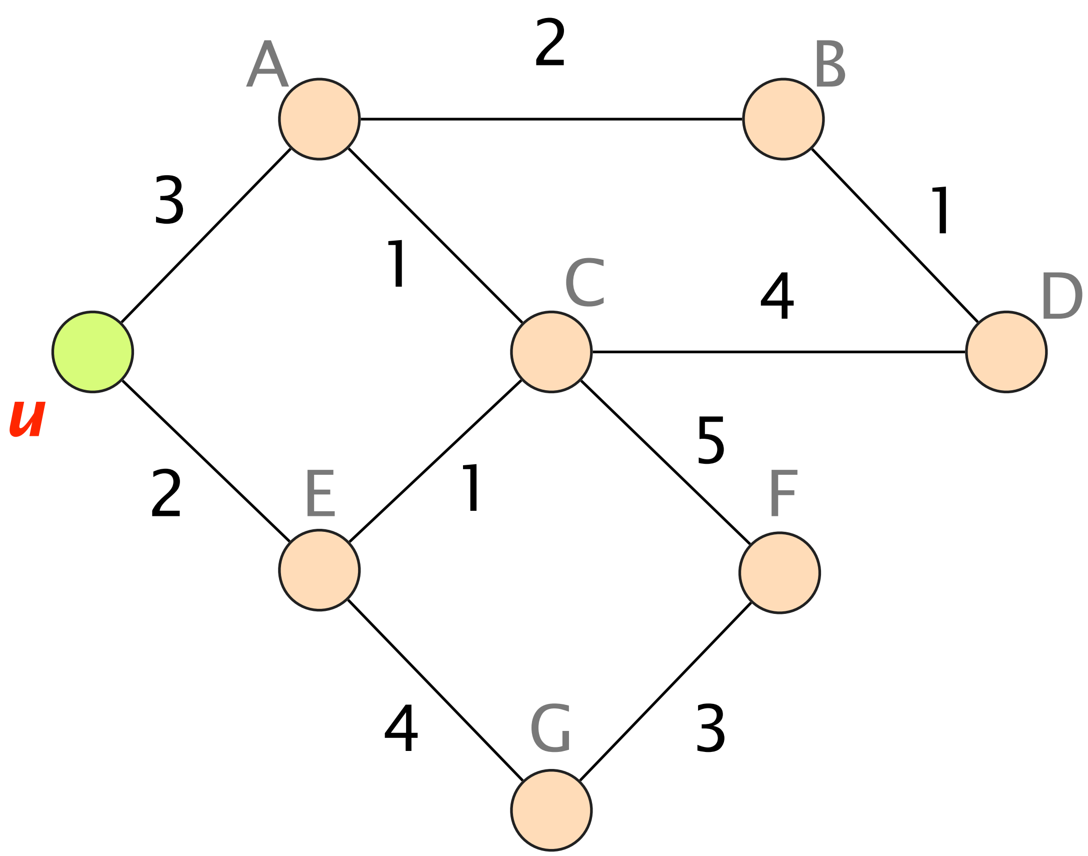
$$= 3$$

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

Evaluating the complexity of DV is harder,
we’ll get back to that in a couple of weeks

Communication Networks

Part 2: Concepts

routing

reliable delivery

Communication Networks

Part 2: Concepts

routing

reliable delivery

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

In the Internet, reliability is ensured by the end hosts, not by the network

The Internet puts reliability in L4, just above the Network layer

goals

Keep the network simple, dumb

make it relatively "easy" to build and operate a network

Keep applications as network "unaware" as possible

a developer should focus on its app, not on the network

design

Implement reliability in-between, in the networking stack

relieve the burden from both the app and the network

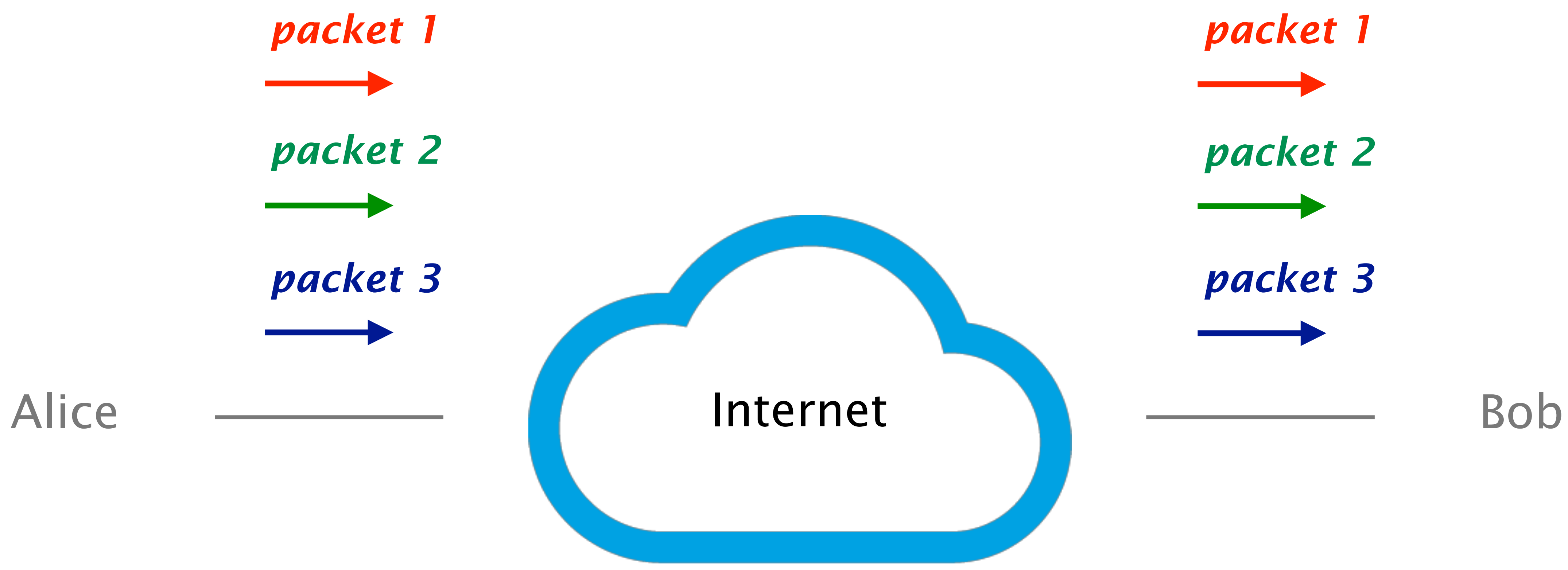
The Internet puts reliability in L4, just above the Network layer

	layer	
	Application	
L4	Transport	reliable end-to-end delivery
L3	Network	global best-effort delivery
	Link	
	Physical	

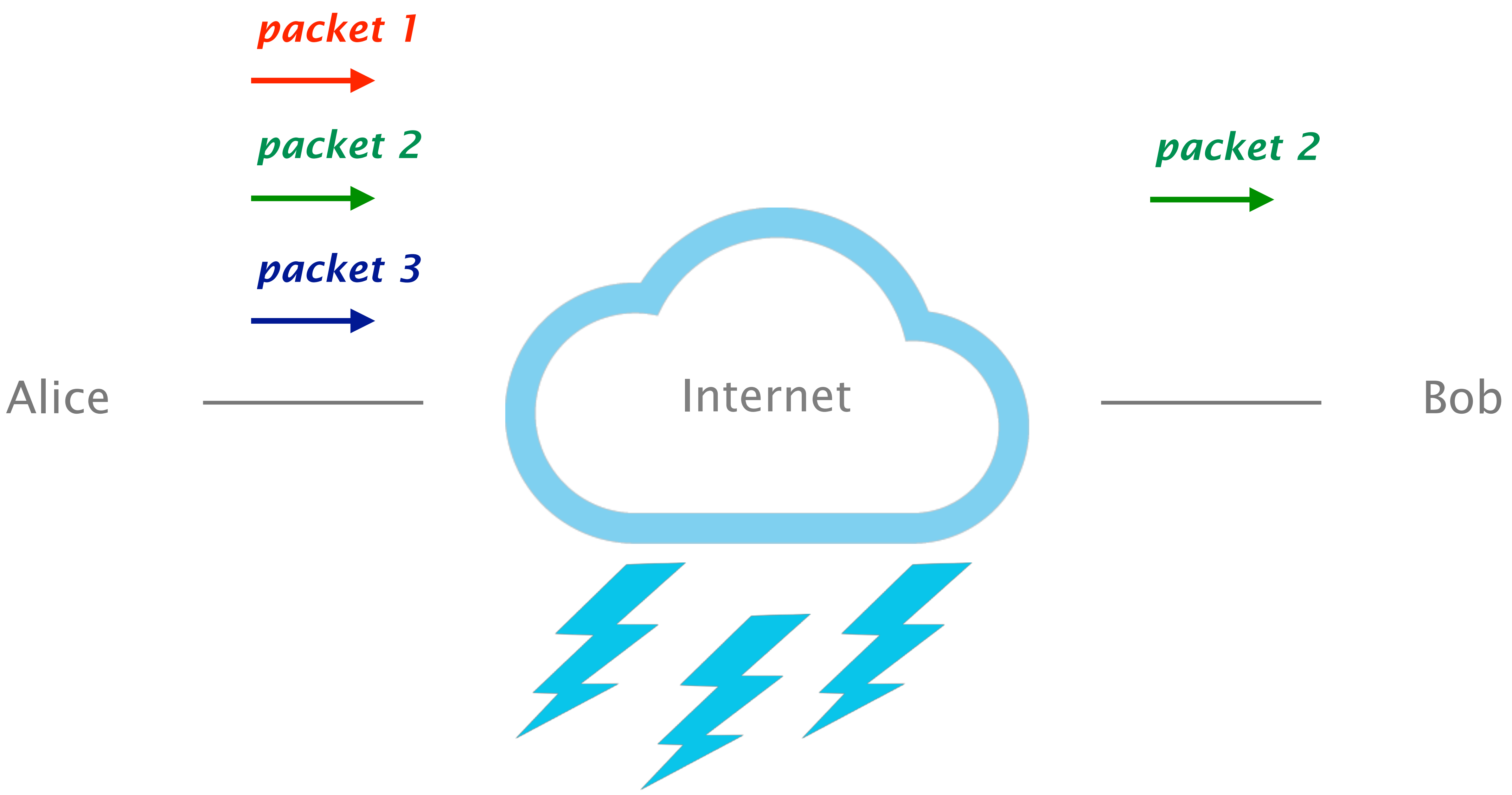
Recall that the Network provides a best-effort service, with quite poor guarantees

	layer	
	Application	
L4	Transport	reliable end-to-end delivery
L3	Network	global best-effort delivery
	Link	
	Physical	

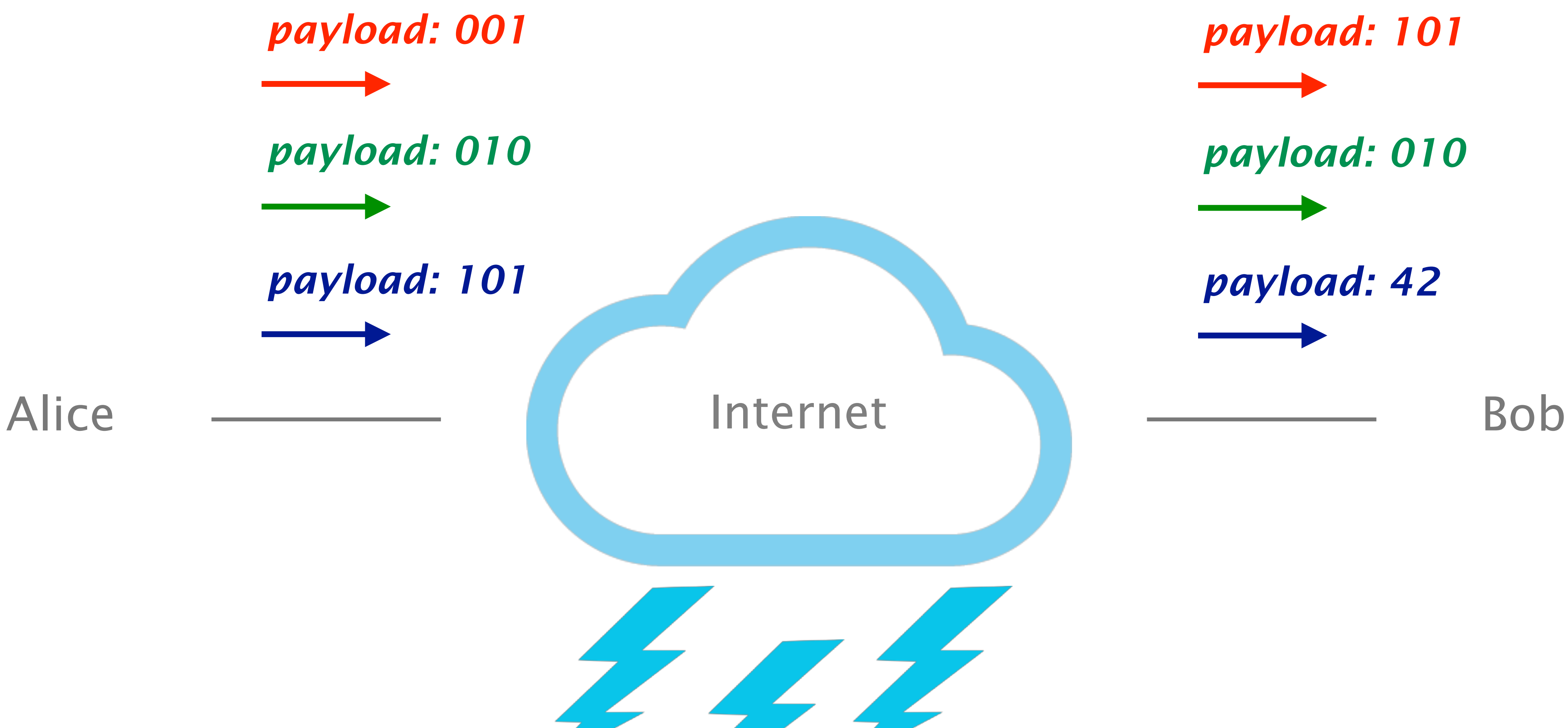
Let’s consider a simple communication between two end-points, Alice and Bob



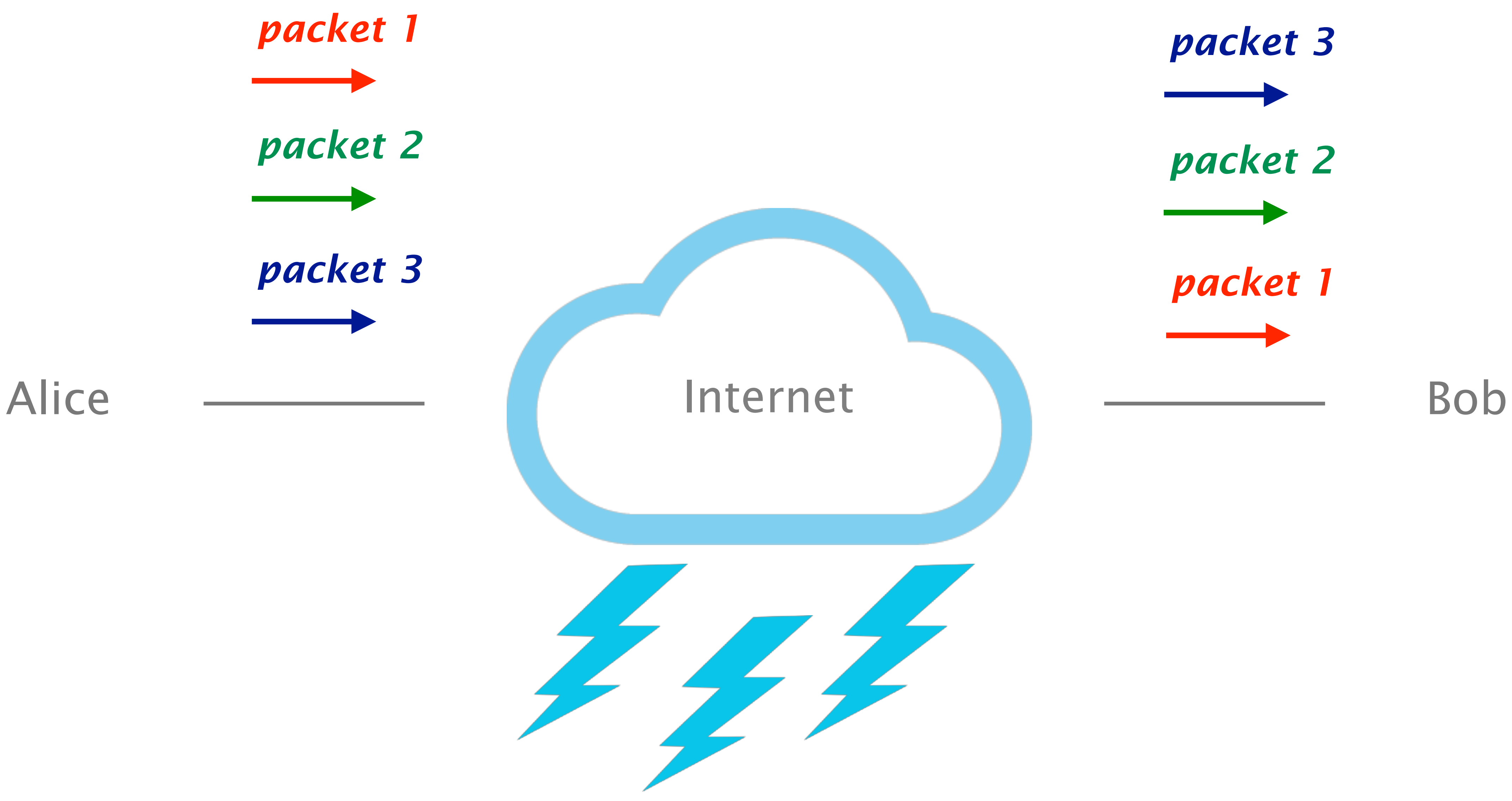
IP packets can get lost or delayed



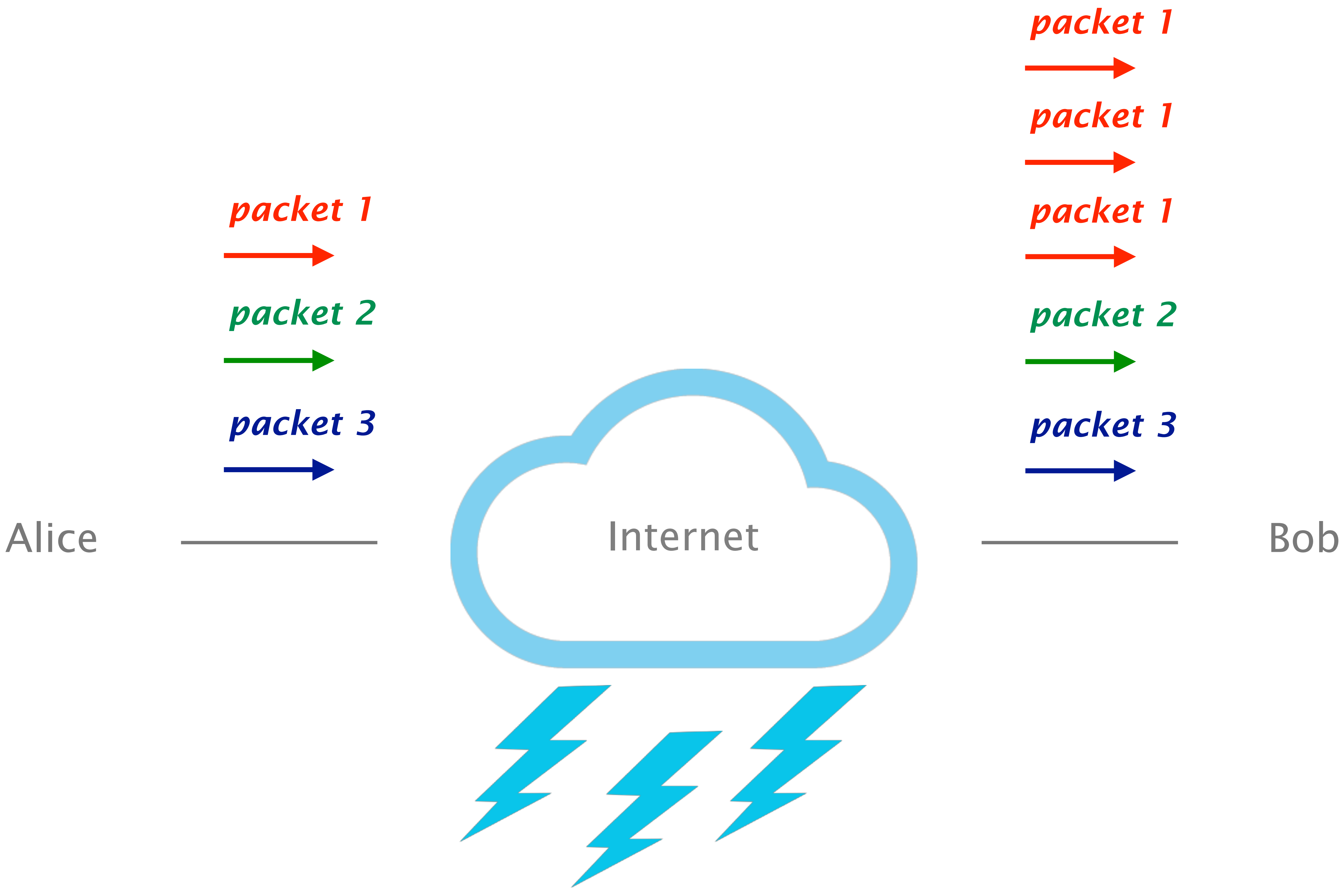
IP packets can get corrupted



IP packets can get reordered



IP packets can get duplicated



Reliable Transport

1 **Correctness condition**

if-and-only if again

2 **Design space**

timeliness *vs* efficiency *vs* …

3 **Examples**

Go-Back-N & Selective Repeat

Reliable Transport

1 **Correctness condition**

if-and-only if again

Design space

timeliness *vs* efficiency *vs* …

Examples

Go-Back-N & Selective Repeat

The four goals of reliable transfer

goals

correctness	ensure data is delivered, in order, and untouched
timeliness	minimize time until data is transferred
efficiency	optimal use of bandwidth
fairness	play well with concurrent communications

goals

correctness ensure data is delivered, in order, and untouched

Routing had a **clean sufficient and necessary** correctness condition

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

We need the same kind of “if and only if” condition for a “correct” reliable transport design

A reliable transport design is correct if…

attempt #1 packets are delivered to the receiver

Wrong Consider that the network is partitioned

We cannot say a transport design is *incorrect*
if it doesn't work in a partitioned network…

A reliable transport design is correct if…

attempt #2

packets are delivered to receiver if and only if it was possible to deliver them

Wrong

If the network is only available one instant in time, only an oracle would know when to send

We cannot say a transport design is *incorrect* if it doesn't know the unknowable

A reliable transport design is correct if…

attempt #3

It resends a packet if and only if the previous packet was lost or corrupted

Wrong

Consider two cases

- packet made it to the receiver and all packets from receiver were dropped
- packet is dropped on the way and all packets from receiver were dropped

A reliable transport design is correct if…

attempt #3

It resends a packet if and only if the previous packet was lost or corrupted

Wrong

In both case, the sender has no feedback at all

Does it resend or not?

A reliable transport design is correct if…

attempt #3

It resends a packet if and only if the previous packet was lost or corrupted

Wrong

but better as it refers to what the design does (which it can control), not whether it always succeeds (which it can't)

A reliable transport design is correct if…

attempt #4

A packet is always resent if
the previous packet was lost or corrupted

A packet may be resent at other times

Correct!

A transport mechanism is correct

if and only if it resends all dropped or corrupted packets

Sufficient "if"	algorithm will always keep trying to deliver undelivered packets
Necessary "only if"	if it ever let a packet go undelivered without resending it, it isn't reliable
Note	it is ok to give up after a while but must announce it to the application

Reliable Transport

Correctness condition

if-and-only if again

2 Design space

timeliness *vs* efficiency *vs* …

Examples

Go-Back-N & Selective Repeat

Now, that we have a correctness condition

how do we achieve it and with what tradeoffs?

Design a *correct*, *timely*, *efficient* and *fair* transport mechanism

knowing that

packets can get lost → let's focus on these aspects first

corrupted

reordered

delayed

duplicated

Alice

```
for word in list:
    send_packet(word);
    set_timer();

    upon timer going off:
        if no ACK received:
            send_packet(word);
            reset_timer();
    upon ACK:
        pass;
```

Bob

```
receive_packet(p);
if check(p.payload) == p.checksum:
    send_ack();

    if word not delivered:
        deliver_word(word);
else:
    pass;
```

There is a clear tradeoff between timeliness and efficiency in the selection of the timeout value

```
for word in list:
    send_packet(word);
    set_timer();

    upon timer going off:
        if no ACK received:
            send_packet(word);
            reset_timer();
    upon ACK:
        pass
```

```
receive_packet(p);
if check(p.payload) == p.checksum:
    send_ack();

    if word not delivered:
        deliver_word(word);
else:
    pass;
```

Timeliness argues for small timers, efficiency for large ones

timeliness

small timers

risk

unnecessary retransmissions

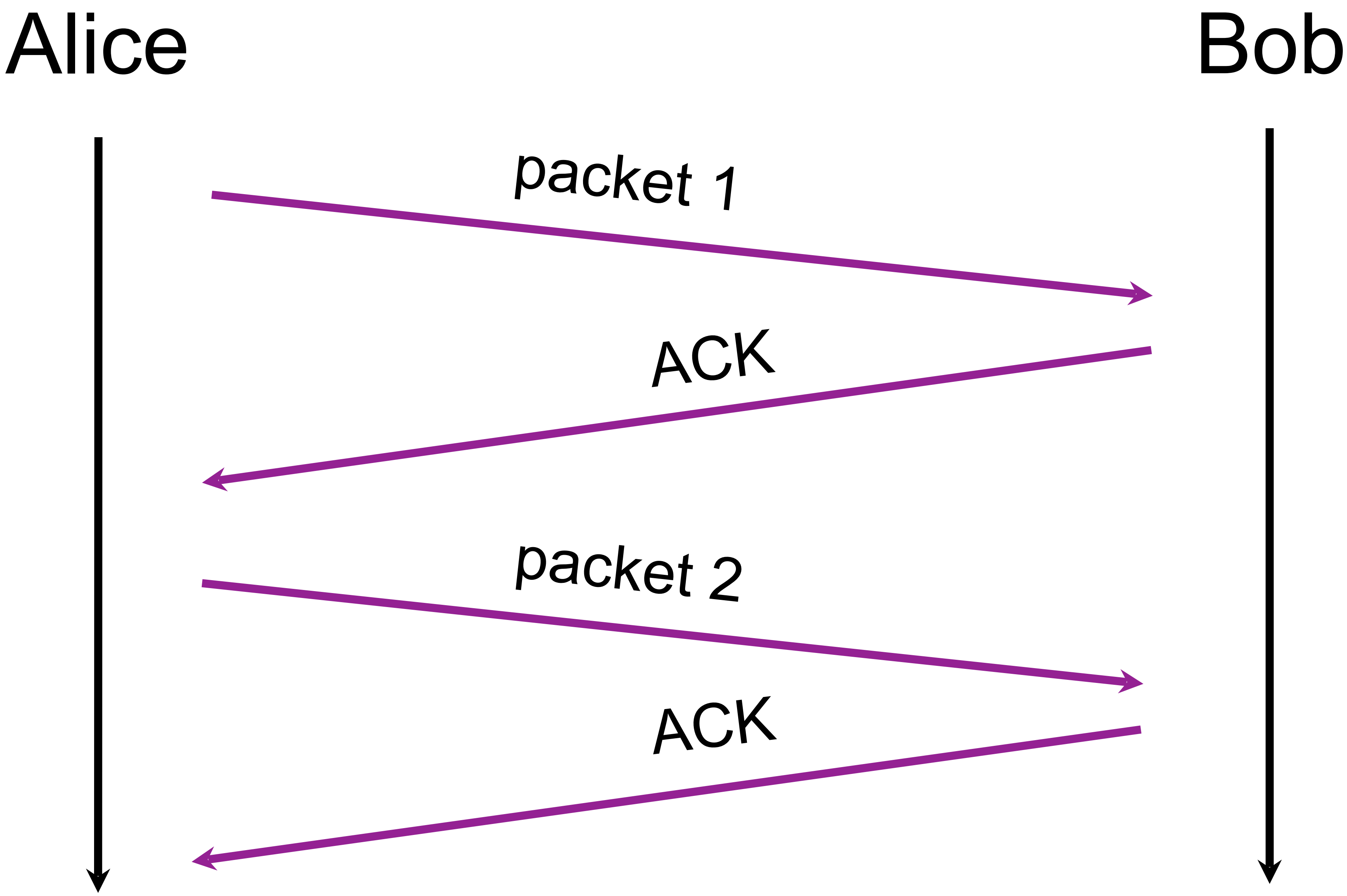
efficiency

large timers

risk

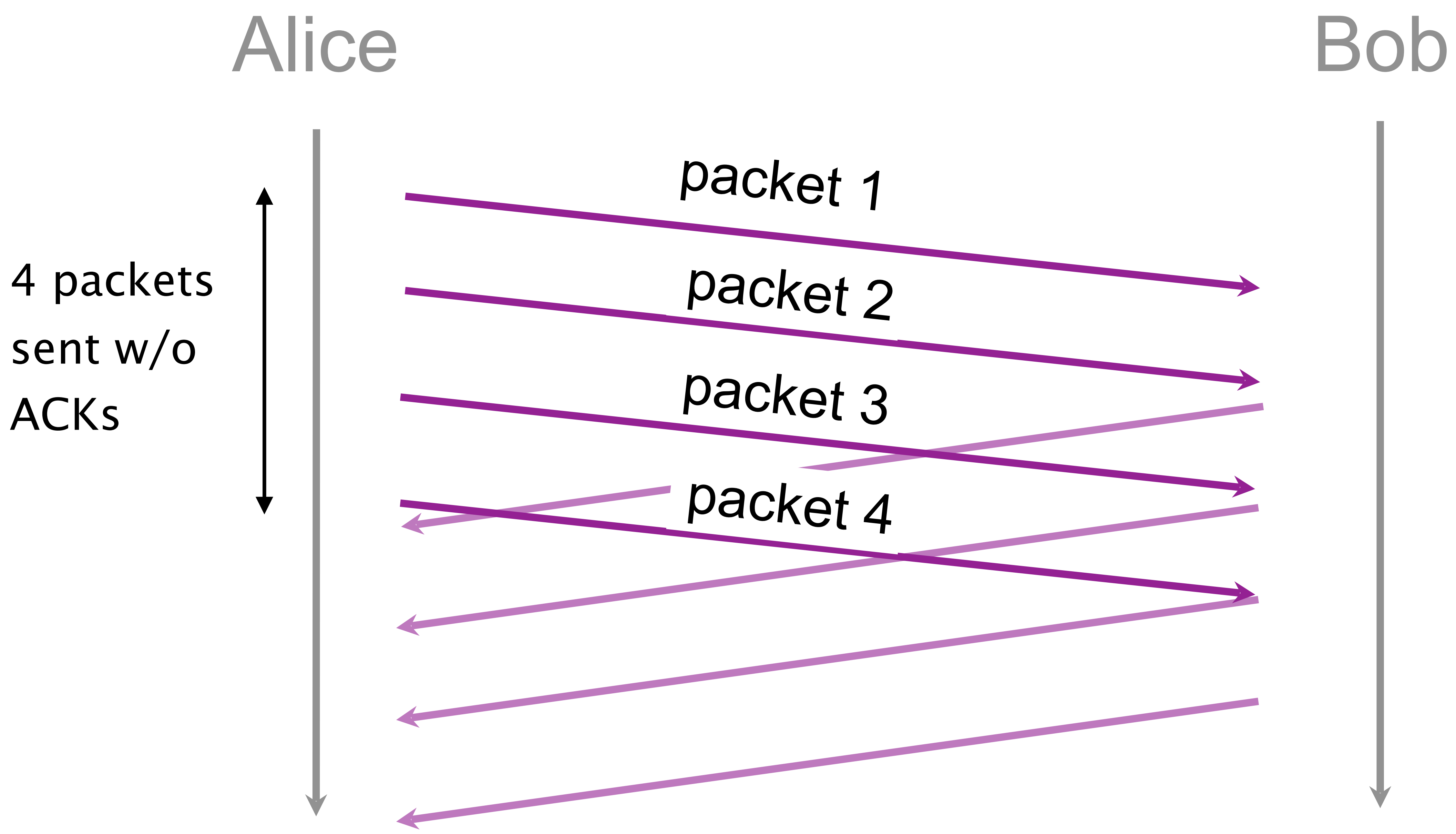
slow transmission

Even with short timers, the timeliness of our protocol is extremely poor: one packet per Round-Trip Time (RTT)

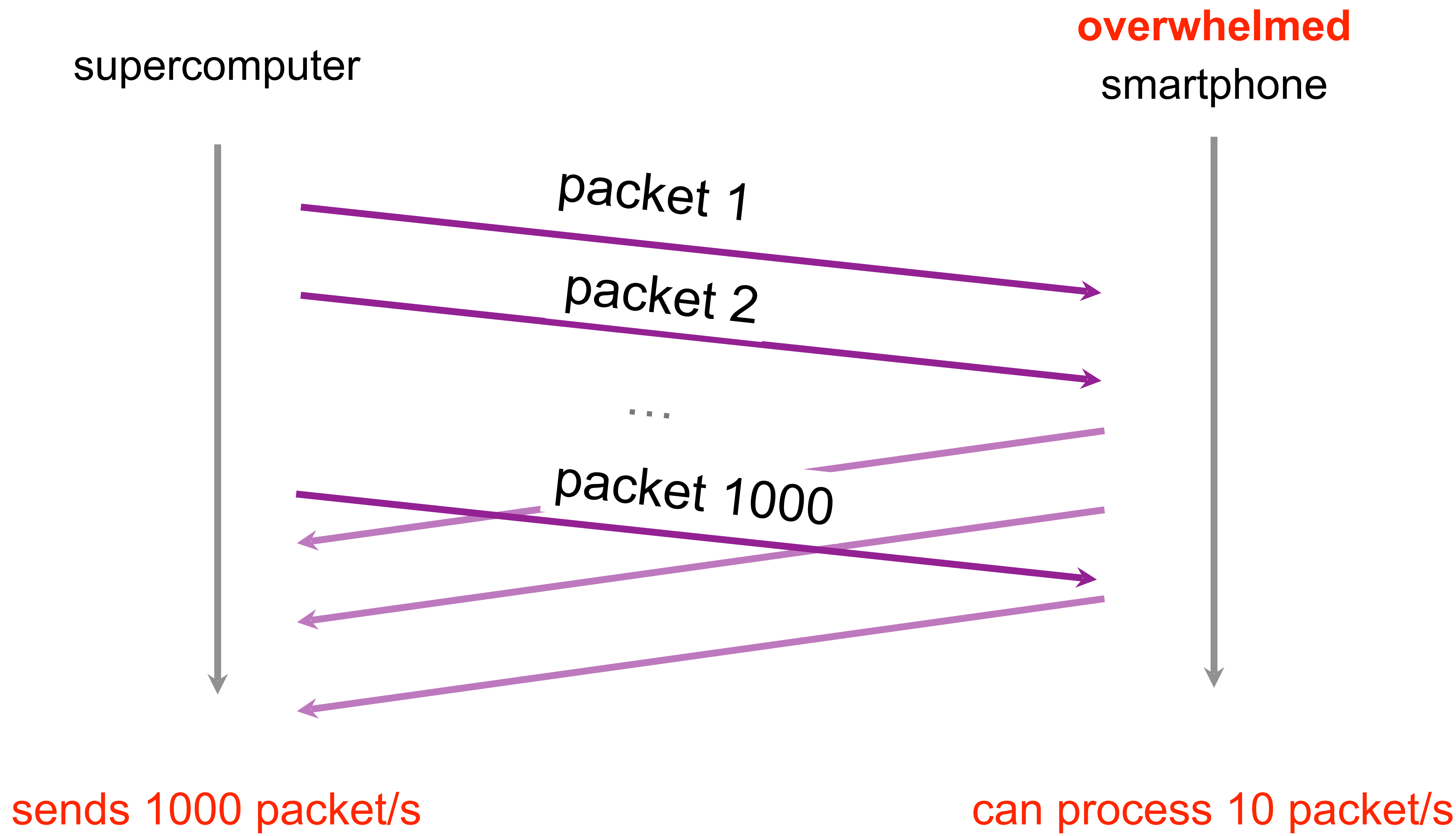


An obvious solution to improve timeliness is to send **multiple packets at the same time**

approach	add sequence number inside each packet	
	add buffers to the sender and receiver	
	sender	store packets sent & not acknowledged
	receiver	store out-of-sequence packets received


Alice
Bob
4 packets
sent w/o
ACKs
packet 1
packet 2
packet 3
packet 4

Sending multiple packets improves timeliness, but it can also **overwhelm the receiver**



To solve this issue,

we need a mechanism for flow control

Using **a sliding window** is one way to do that

Sender keeps a list of the sequence # it can send

known as the *sending window*

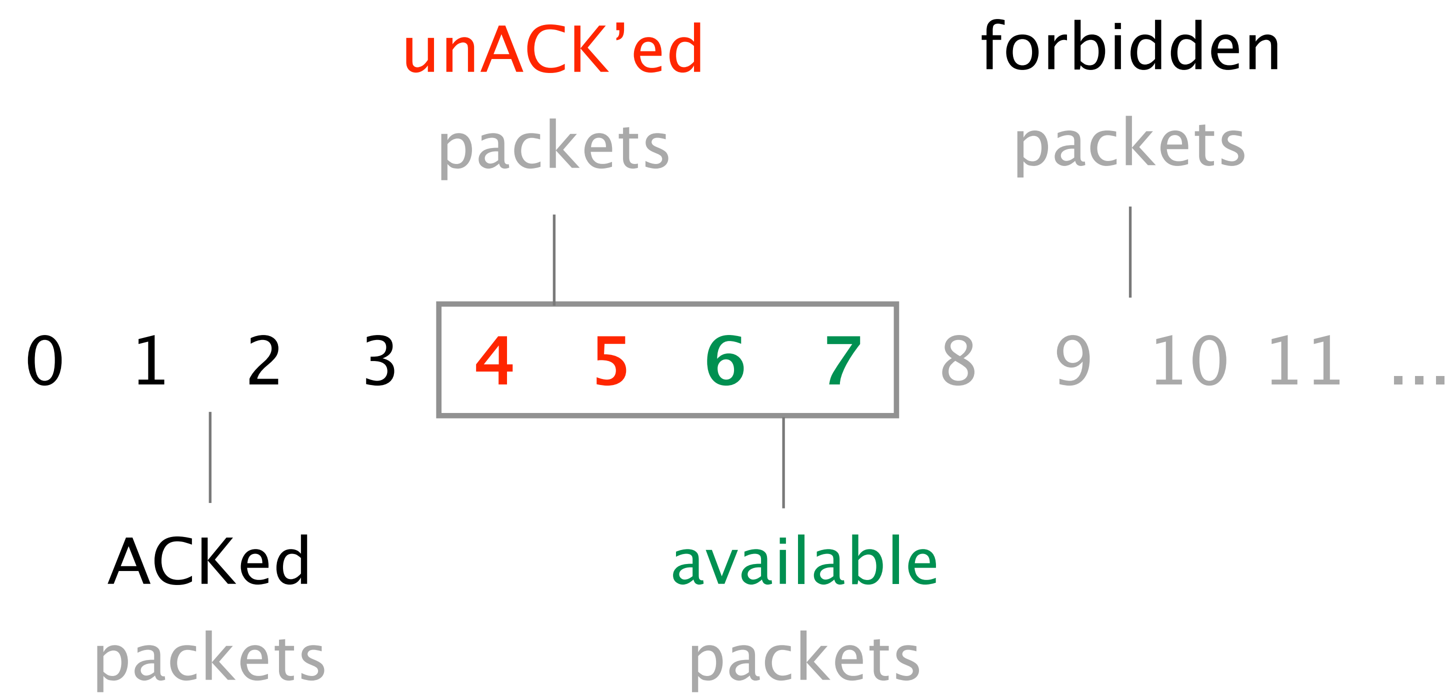
Receiver also keeps a list of the acceptable sequence #

known as the *receiving window*

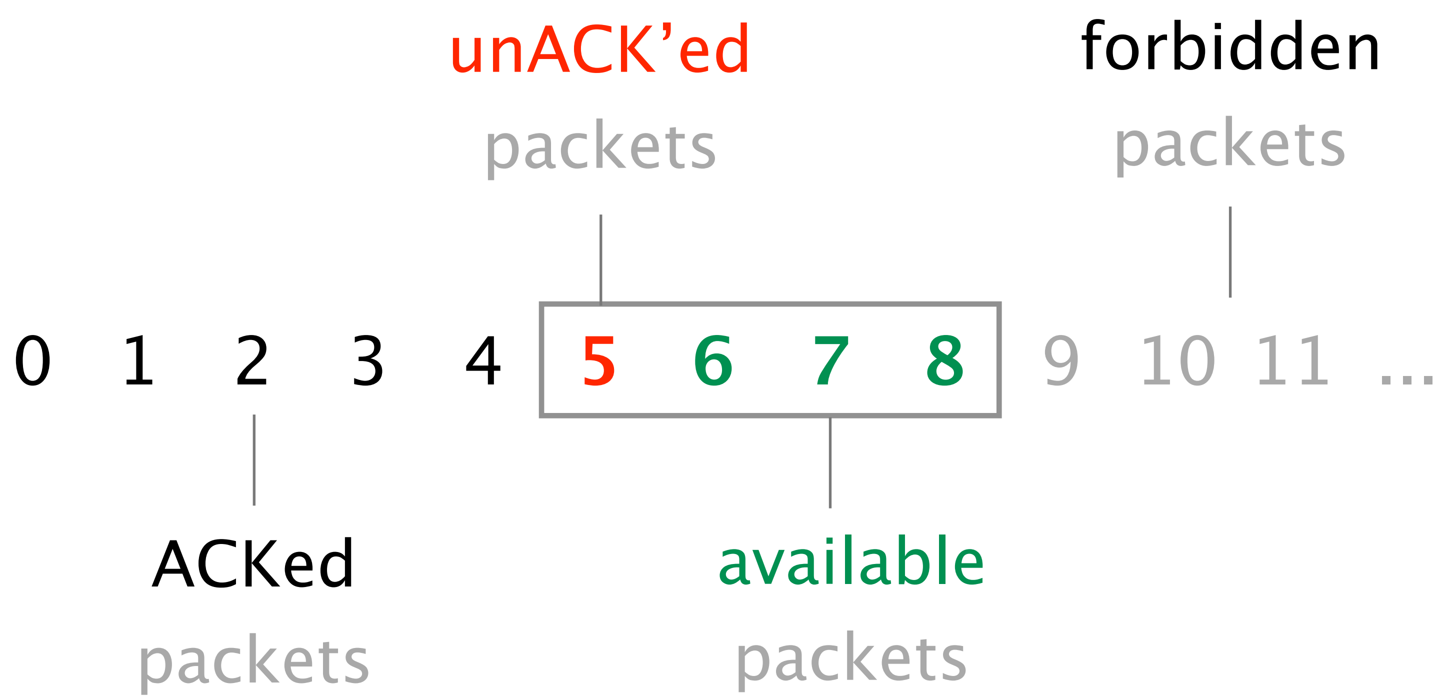
Sender and receiver negotiate the window size

sending window <= receiving window

Example with a window composed of 4 packets



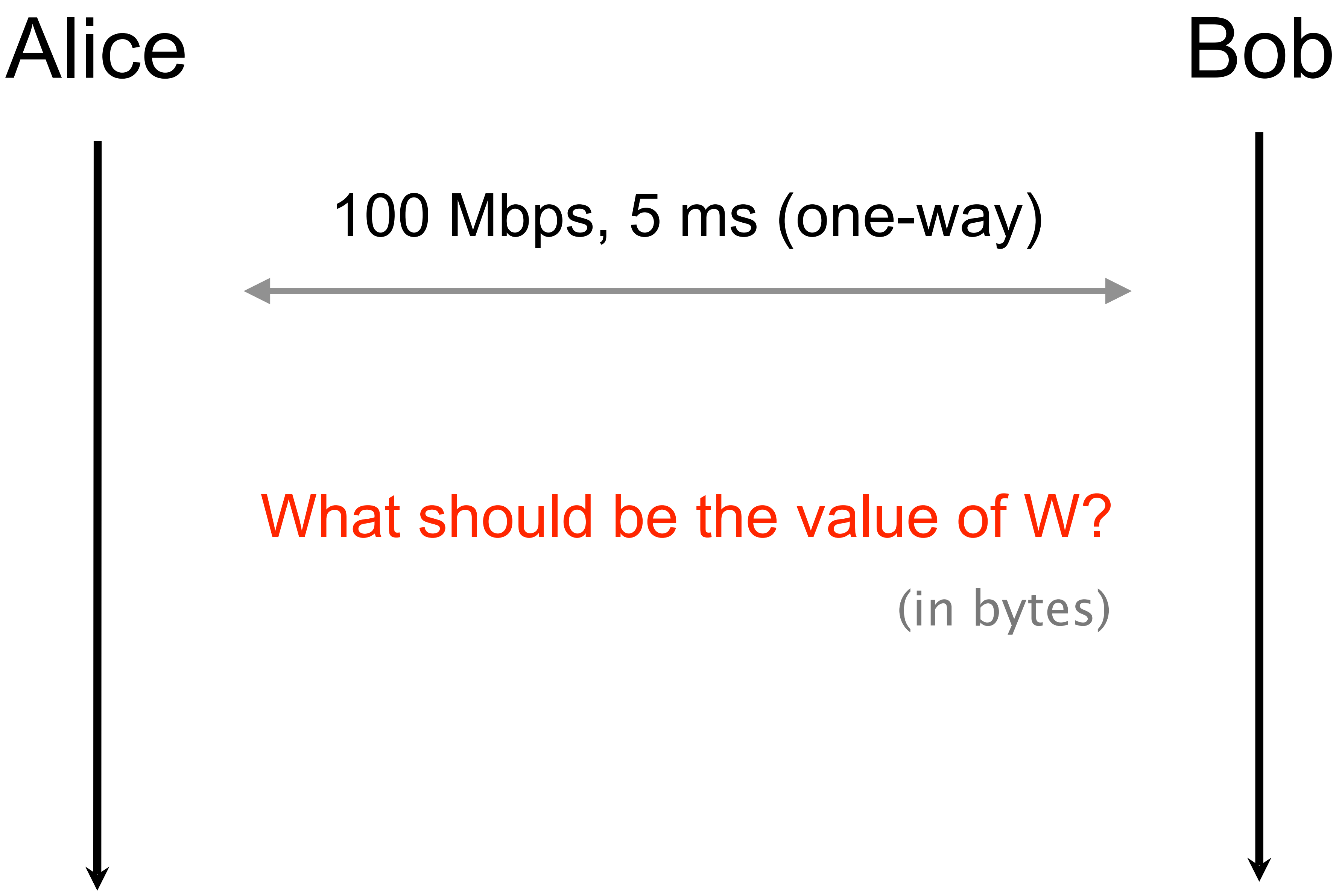
Window after sender receives ACK 4



Timeliness of the window protocol depends on

the size of the sending window

Assuming infinite buffers,
how **big** should the window be to **maximize timeliness?**



Timeliness matters,

but what about efficiency?

The efficiency of our protocol essentially depends on two factors

receiver feedback

behavior upon losses

How much information does the sender get?

How does the sender detect and react to losses?

The efficiency of our protocol essentially depends on two factors

receiver feedback

behavior upon losses

How much information does the sender get?

ACKing individual packets provides detailed feedback, but triggers unnecessary retransmission upon losses

advantages	disadvantages
know fate of each packet	loss of an ACK packet requires a retransmission
simple window algorithm W single-packet algorithms	causes unnecessary retransmission
not sensitive to reordering	

Cumulative ACKs enables to recover from lost ACKs, but provides coarse-grained information to the sender

approach	ACK the highest sequence number for which all the previous packets have been received
advantages	recover from lost ACKs
disadvantages	confused by reordering incomplete information about which packets have arrived causes unnecessary retransmission

Full Information Feedback prevents unnecessary retransmission, but can induce a sizable overhead

approach	List all packets that have been received highest cumulative ACK, plus any additional packets
advantages	complete information resilient form of individual ACKs
disadvantages	overhead (hence lowering efficiency) *e.g.*, when large gaps between received packets

We see that Internet design is

all about balancing tradeoffs (again)

The efficiency of our protocol essentially depends on two factors

receiver
feedback

behavior
upon losses

How does the sender
detect and react to losses?

As of now, we detect loss by using timers.

That's only one way though

Losses can also be detected by relying on ACKs

With individual ACKs, missing packets (gaps) are implicit

Assume packet 5 is lost

but no other

ACK stream

1

2

3

4

6

7

...

sender can infer that 5 is missing

and resend 5 after *k* subsequent packets

With **full information**,
missing packets (gaps) are **explicit**

Assume packet 5 is lost

but no other

ACK stream

up to 1

up to 2

up to 3

up to 4

up to 4, plus 6 — sender learns that 5 is missing

up to 4, plus 6—7 retransmits after *k* packets

...

With **cumulative ACKs**, missing packets are harder to know

Assume packet 5 is lost

but no other

ACK stream

1

2

3

4

4 sent when 6 arrives

4 sent when 7 arrives

...

Duplicated ACKs are a sign of isolated losses.
Dealing with them is trickier though.

situation

Lack of ACK progress means that 5 hasn't made it

Stream of ACKs means that (some) packets are delivered

Sender could trigger resend
upon receiving *k* duplicates ACKs

but *what* do you resend?

only 5 or 5 and everything after?

What about fairness?

Design a *correct*, *timely*, *efficient* and *fair* transport mechanism

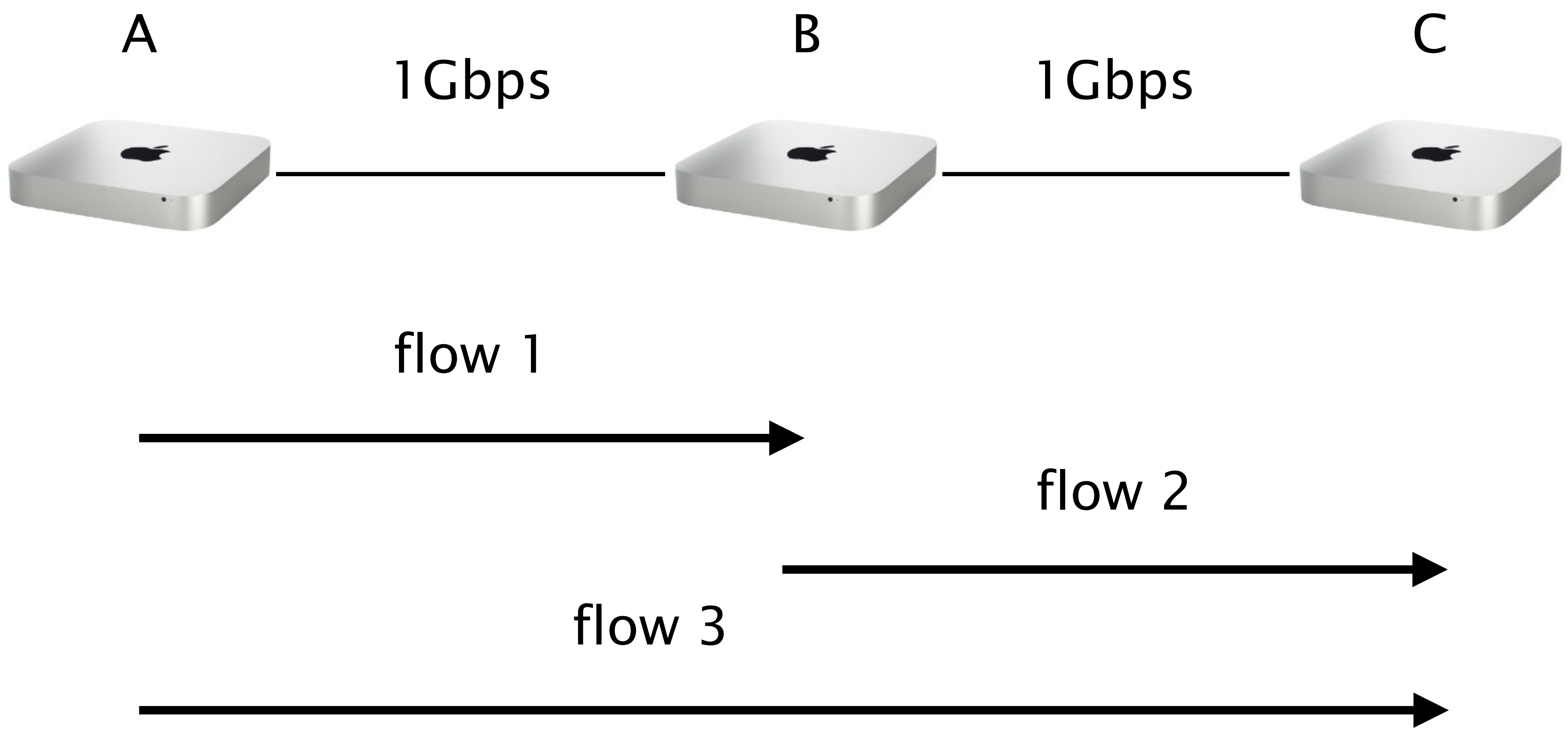
knowing that

packets can get lost
corrupted
reordered
delayed
duplicated

When *n* entities are using our transport mechanism,
we want a fair allocation of the available bandwidth

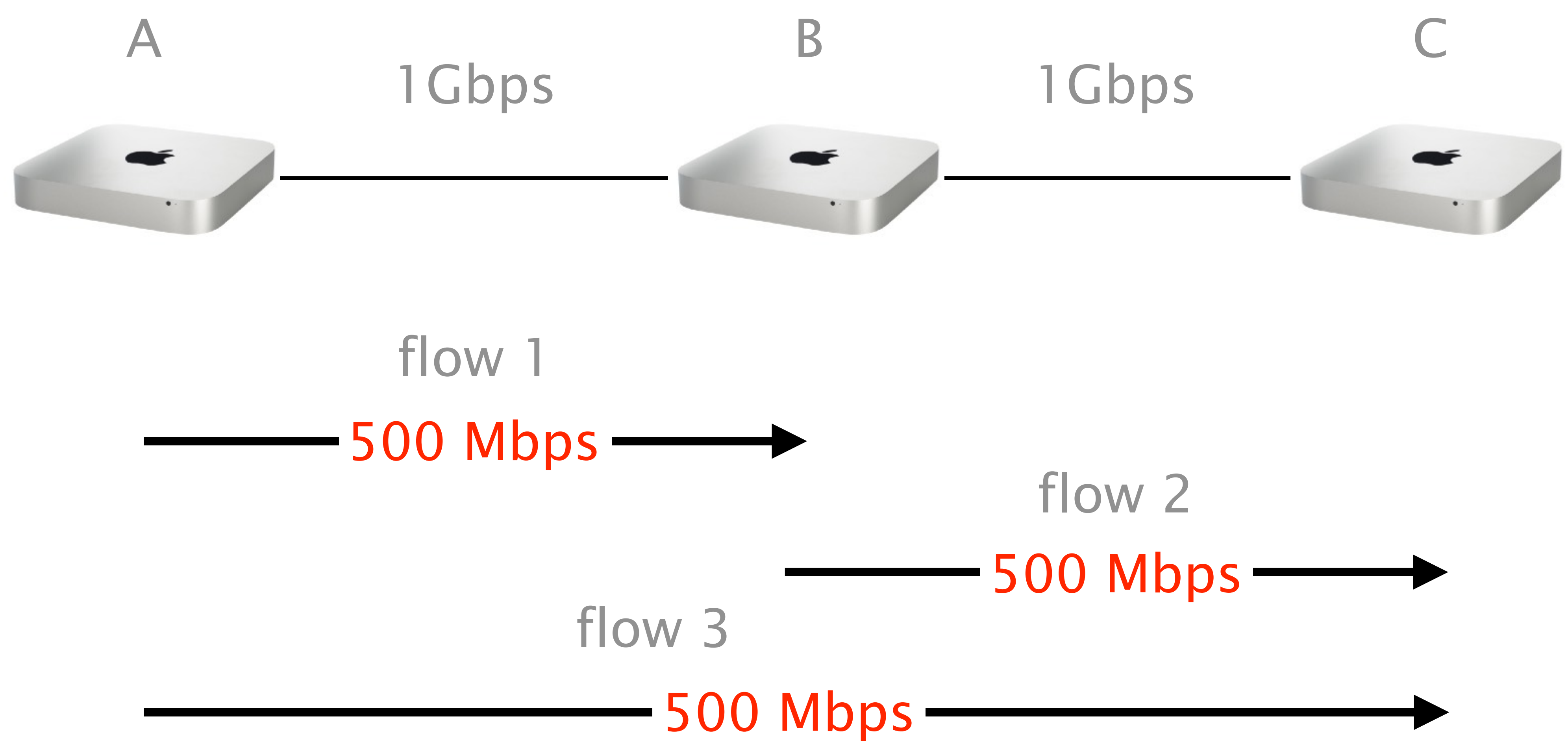
Consider this simple network

in which **three hosts are sharing two links**



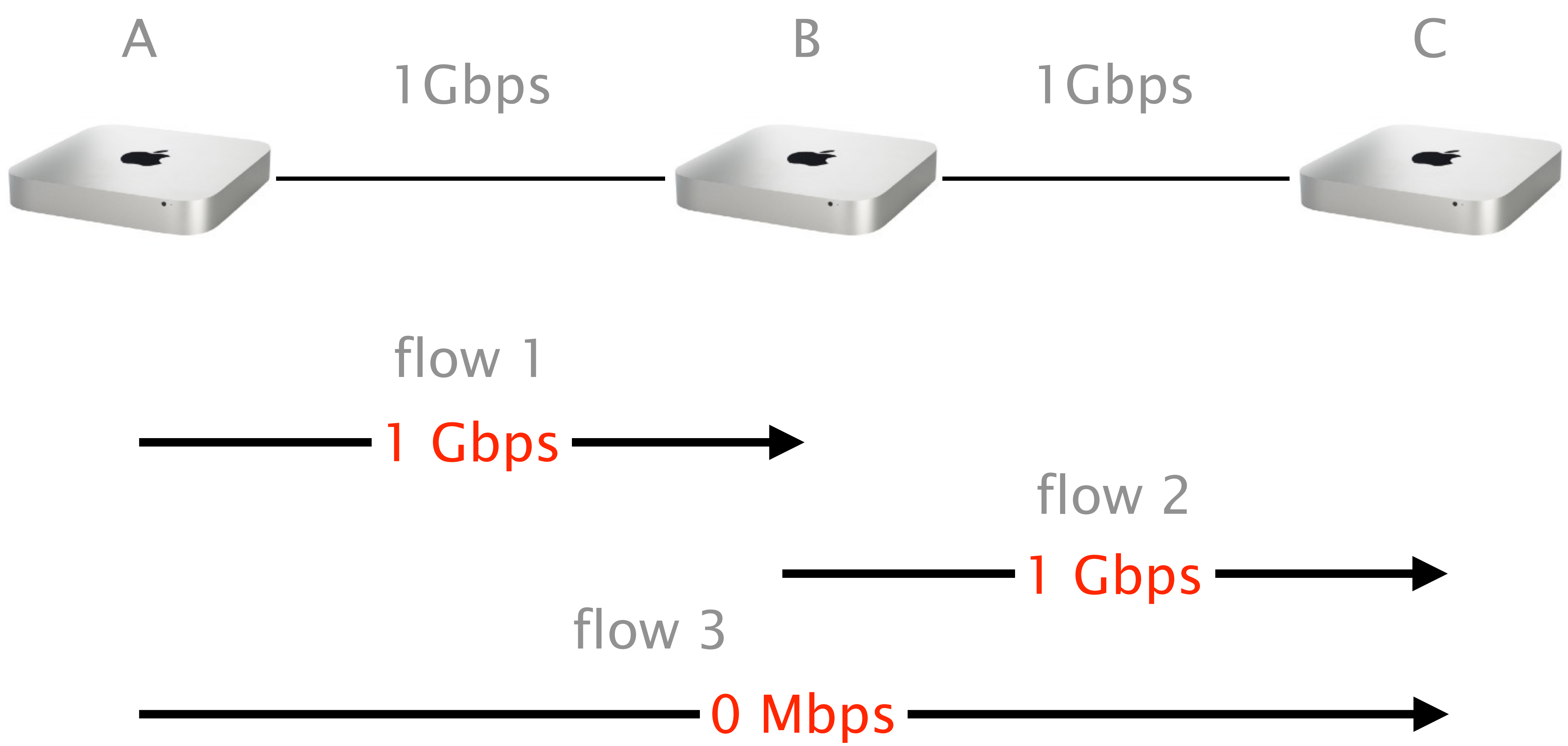
What is a fair allocation for the 3 flows?

An equal allocation is certainly "fair",
but what about the efficiency of the network?



Total traffic is 1.5 Gbps

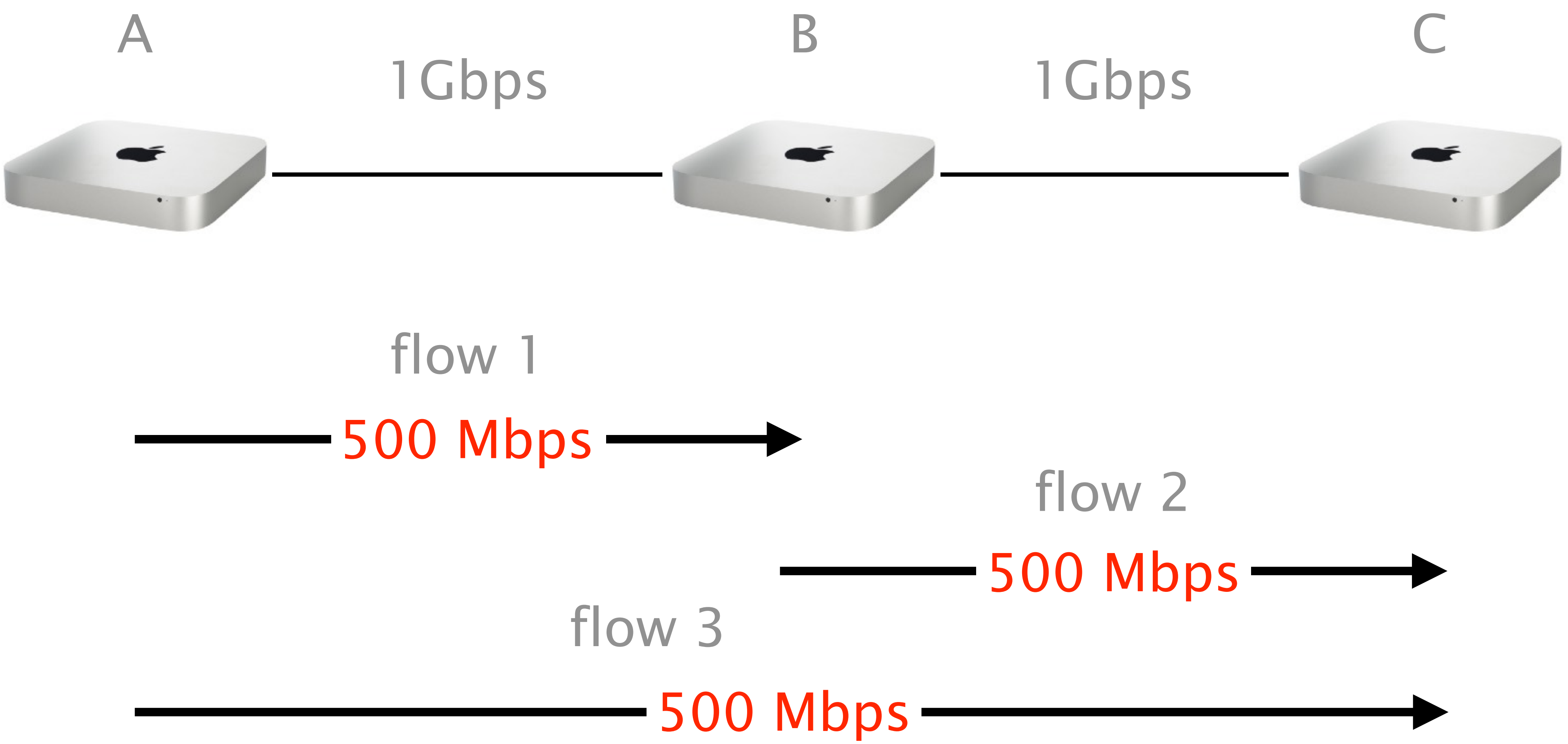
Fairness and efficiency don't always play along, here an unfair allocation ends up *more efficient*



Total traffic is 2 Gbps!

What is fair anyway?

Equal-per-flow isn't really fair as (A,C) crosses two links: it uses *more* resources



Total traffic is 1.5 Gbps

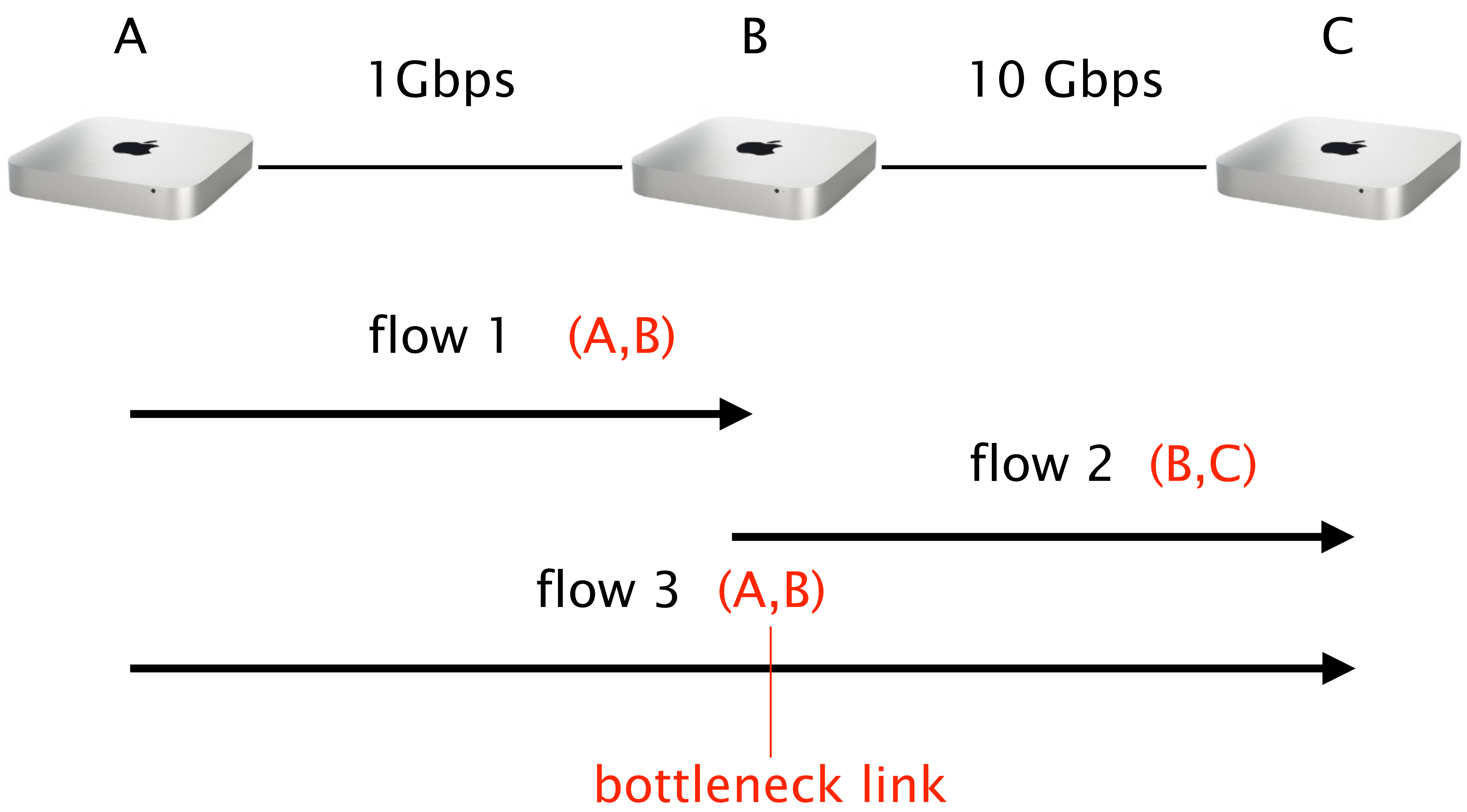
With equal-per-flow, A ends up with 1 Gbps because it sends 2 flows, while B ends up with 500 Mbps

Is it fair?

Seeking an exact notion of fairness is not productive.
What matters is to avoid starvation.

equal-per-flow is good enough for this

Simply dividing the available bandwidth doesn't work in practice since flows can see different bottleneck



Intuitively, we want to give users with "small" demands what they want, and evenly distribute the rest

Max-min fair allocation is such that

the lowest demand is maximized

after the lowest demand has been satisfied,
the second lowest demand is maximized

after the second lowest demand has been satisfied,
the third lowest demand is maximized

and so on…

Max-min fair allocation can easily be computed

step 1	Start with all flows at rate 0
step 2	Increase the flows until there is a new bottleneck in the network
step 3	Hold the fixed rate of the flows that are bottlenecked
step 4	Go to step 2 for the remaining flows

Done!

Max-min fair allocation can be approximated by slowly increasing *W* until a loss is detected

Intuition	Progressively increase the sending window size	max=receiving window
	Whenever a loss is detected, decrease the window size	signal of congestion
	Repeat	

Design a *correct*, *timely*, *efficient* and *fair* transport mechanism

knowing that

packets can get lost

corrupted

reordered

delayed

duplicated

Dealing with corruption is easy:

Rely on a checksum, treat corrupted packets as lost

The effect of reordering depends on the type of ACKing mechanism used

individual ACKs	no problem
full feedback	no problem
cumm. ACKs	create duplicate ACKs why is it a problem?

Long delays can create useless timeouts,
for all designs

Packets duplicates can lead to duplicate ACKs whose effects will depend on the ACKing mechanism used

individual ACKs	no problem
full feedback	no problem
cumm. ACKs	problematic

Design a *correct*, *timely*, *efficient* and *fair* transport mechanism

knowing that

packets can get lost

corrupted

reordered

delayed

duplicated

Here is one correct, timely, efficient and fair transport mechanism

ACKing	full information ACK
retransmission	after timeout
	after *k* subsequent ACKs
window management	additive increase upon successful delivery
	multiple decrease when timeouts

We'll come back to this when we see TCP

Reliable Transport

Correctness condition

if-and-only if again

Design space

timeliness *vs* efficiency *vs* …

3 **Examples**

Go-Back-N & Selective Repeat

Let’s see how it works in practice

visually

http://www.ccs-labs.org/teaching/rn/animations/gbn_sr/

Reliable Transport

Correctness condition

if-and-only if again

Design space

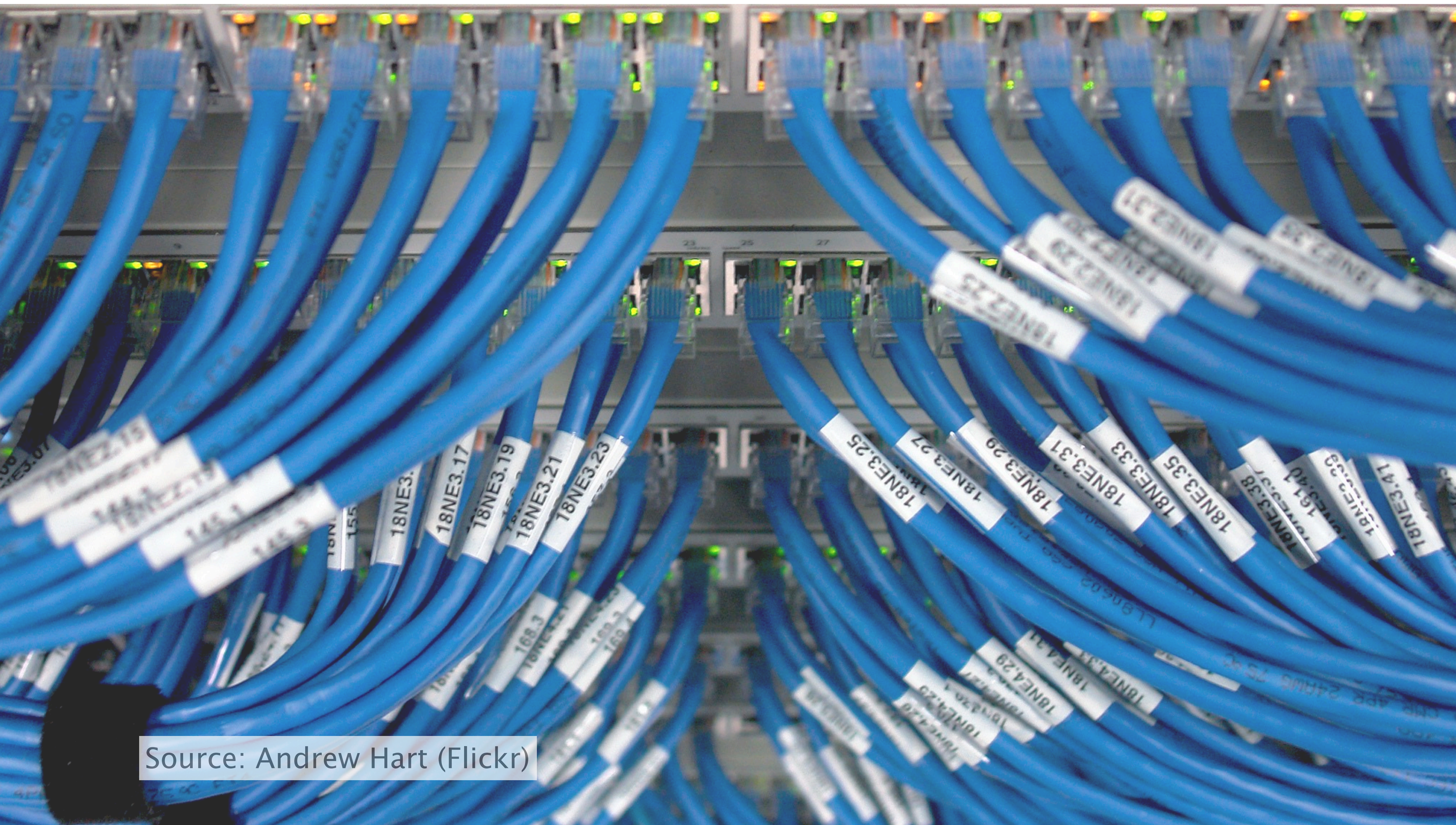
timeliness *vs* efficiency *vs* …

Examples

Go-Back-N & Selective Repeat

Next week on Communication Networks

Ethernet and Switching



Source: Andrew Hart (Flickr)

Communication Networks

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