# Communication Networks

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## Communication Networks

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Materials inspired from Scott Shenker & Jennifer Rexford

## Communication Networks

Part 2: Concepts

routing

reliable delivery

## 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?

---

routing

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

reliable delivery

---

Think of IP packets as envelopes

Packet

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Like an envelope,
packets have a header

Header

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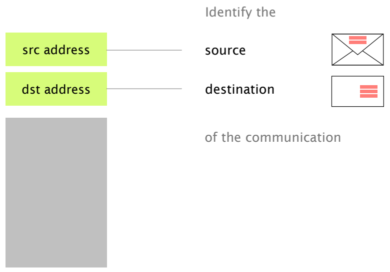
Like an envelope,
packets have a payload

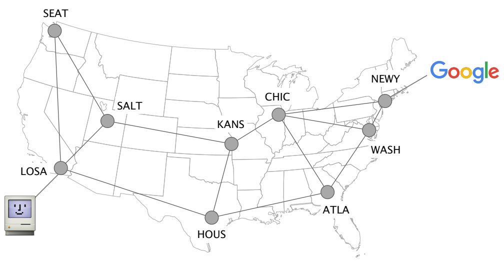
Payload

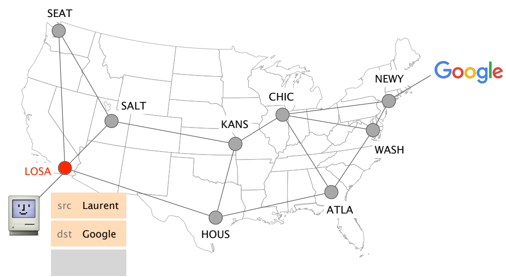
The header contains the metadata needed to forward the packet

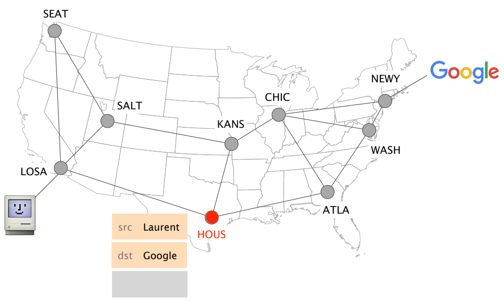


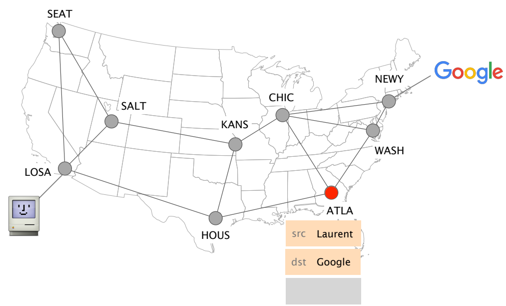

The payload contains the data to be delivered

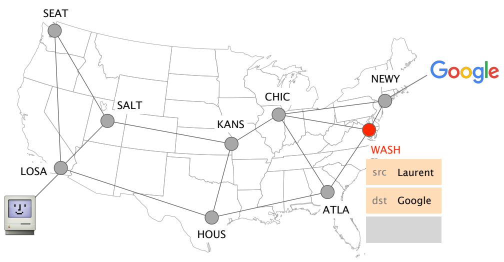

Routers forward IP packets hop-by-hop towards their destination

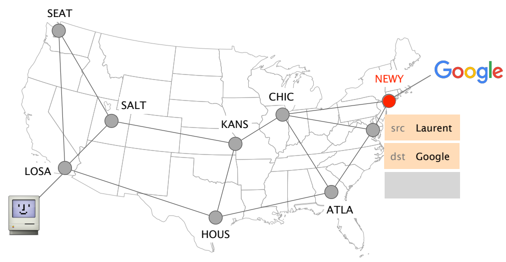


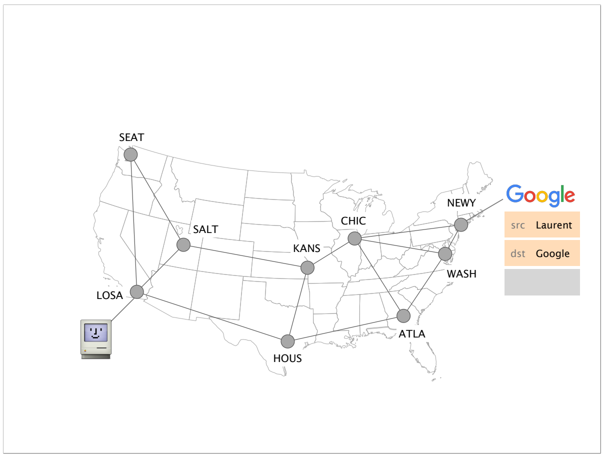



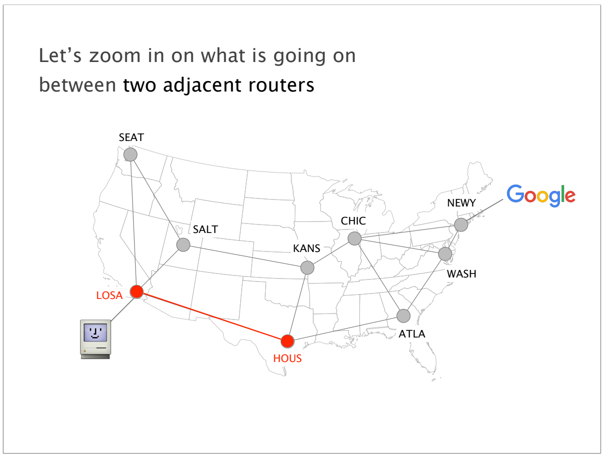



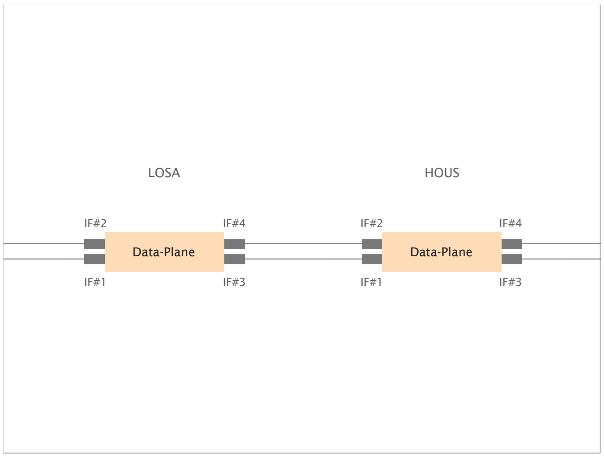



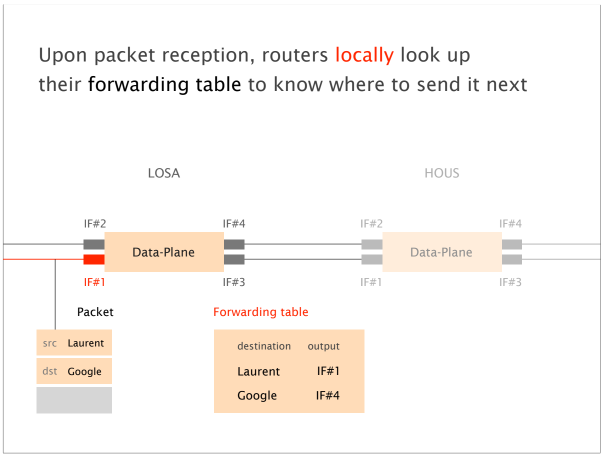



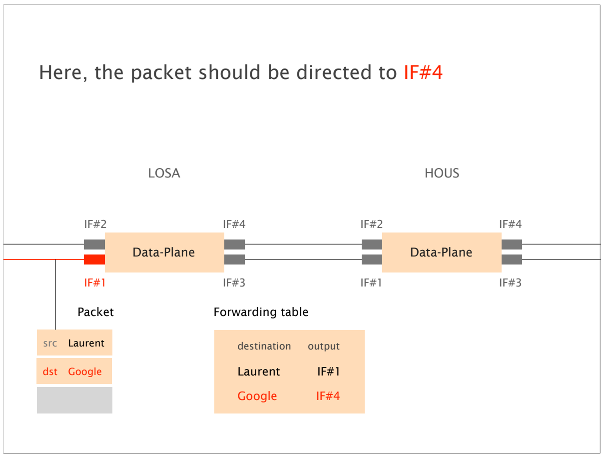



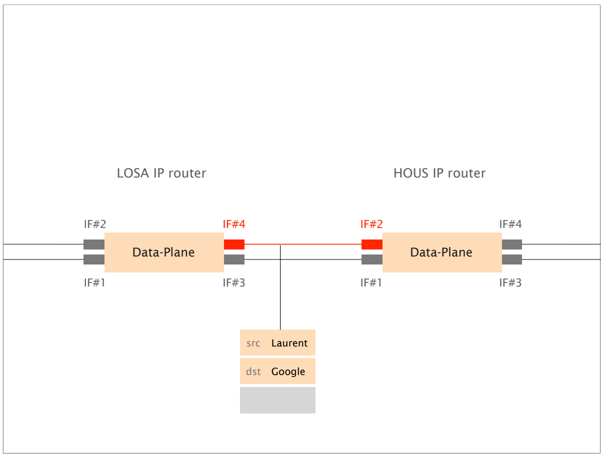

SEAT
SALT
KANS
CHIC
NEWY
WASH
LOSA
HOUS
ATLA
Google
src Laurent
dst Google

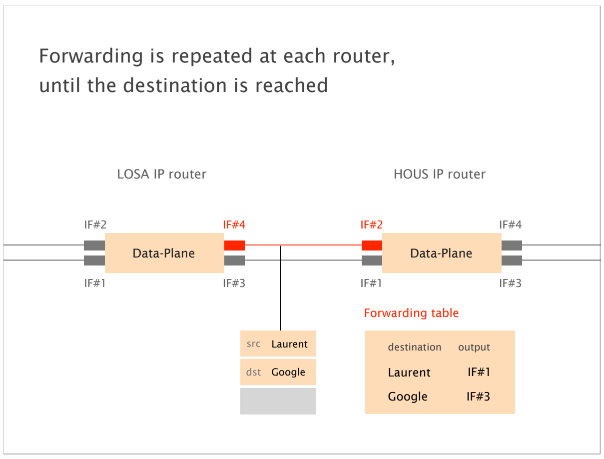

Let’s zoom in on what is going on
between two adjacent routers
SEAT
SALT
KANS
CHIC
NEWY
WASH
LOSA
HOUS
ATLA
Google

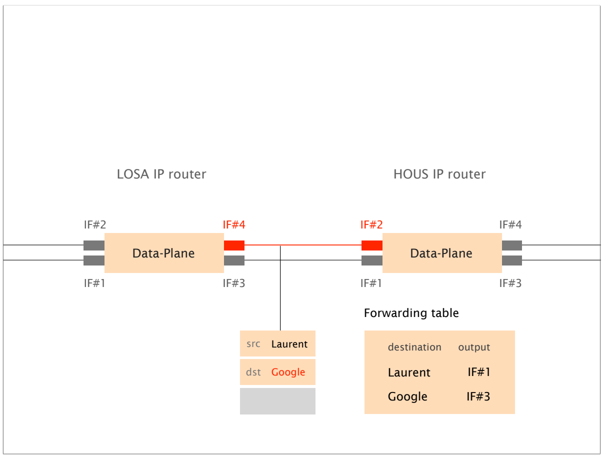

LOSA
HOUS
IF#2
IF#4
Data-Plane
IF#1
IF#3
IF#2
IF#4
Data-Plane
IF#1
IF#3

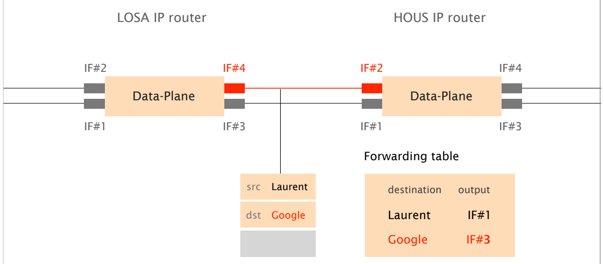

Upon packet reception, routers locally look up
their forwarding table to know where to send it next
LOSA
HOUS
Data-Plane
Data-Plane
Packet
src Laurent
dst Google
Forwarding table
destination output
Laurent IF#1
Google IF#4

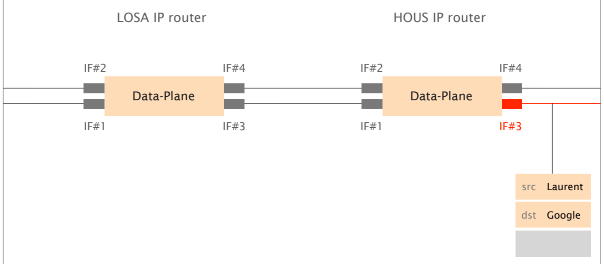

Here, the packet should be directed to IF#4
LOSA
HOUS
Data-Plane
Data-Plane
Packet
src Laurent
dst Google
Forwarding table
destination output
Laurent IF#1
Google IF#4


LOSA IP router
HOUS IP router
Data-Plane
Data-Plane
src Laurent
dst Google


Forwarding is repeated at each router,
until the destination is reached
LOSA IP router
HOUS IP router
Data-Plane
Data-Plane
src Laurent
dst Google
Forwarding table
destination output
Laurent IF#1
Google IF#3


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




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

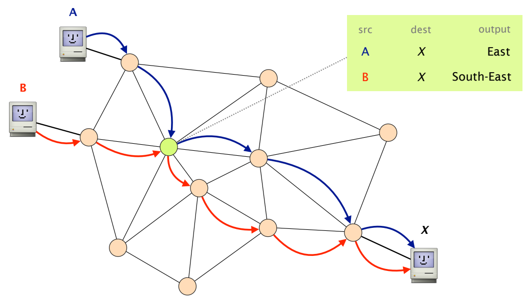
| criteria | | |
|---|---|---|
| | destination | mandatory (why?) |
| | source | requires $n^2$ state |
| | input port | traffic engineering |
| | +any other header | |

destination

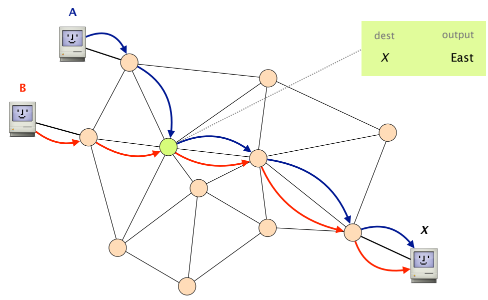
source

Let's compare these two

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




With **destination-based routing**,
paths from different source coincide once they overlap

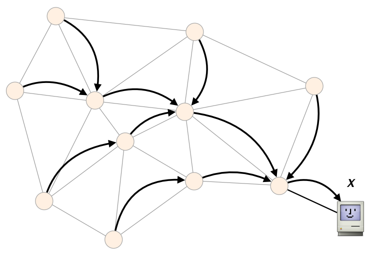



Once path to destination meet,
they will *never* split

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

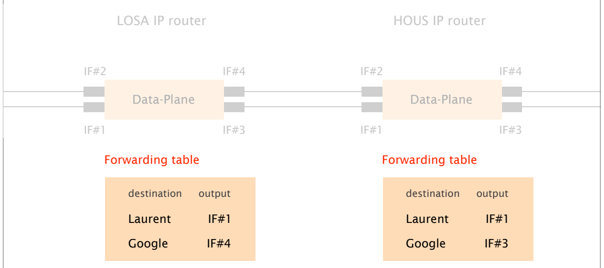
Here is an example of a spanning tree
for destination *X*

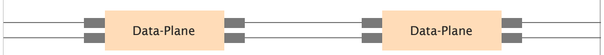


In the rest of the lecture,
we'll consider destination-based routing

the default in the Internet

Where are these forwarding tables coming from?



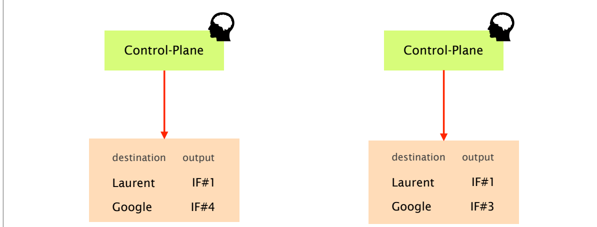




In addition to **a data-plane**,
routers are also equipped with **a control-plane**


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

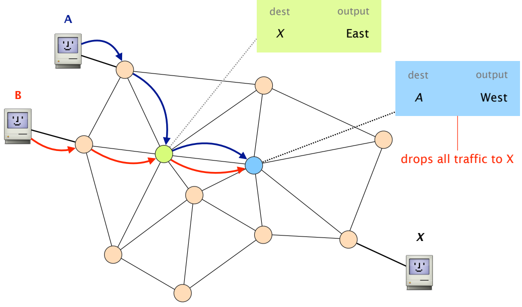
it always delivers packets
to the correct destination

sufficient and necessary condition

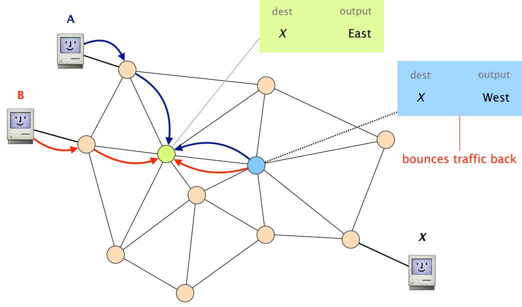
Theorem a global forwarding state is valid if and only if

- 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




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

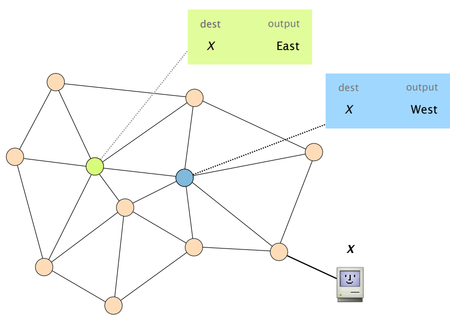
simple algorithm
for one destination

Mark all outgoing ports with an arrow

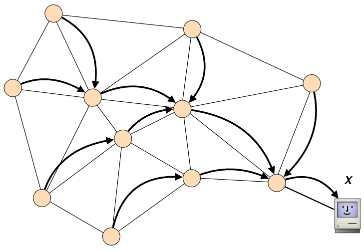
Eliminate all links with no arrow

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

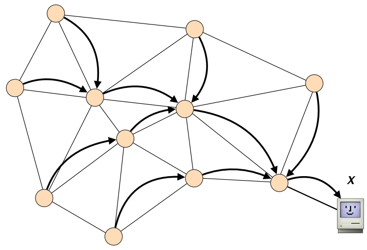
Given a graph with the corresponding forwarding state

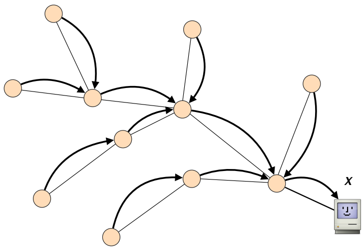


Mark all outgoing ports with an arrow

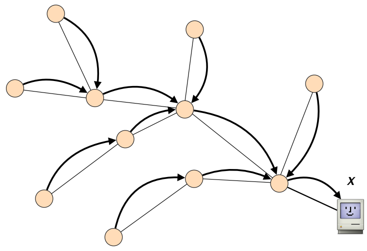



Eliminate all links with no arrow

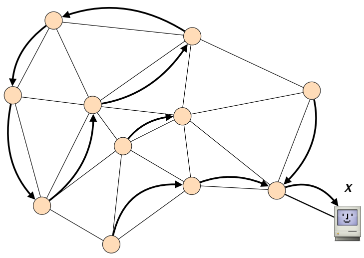


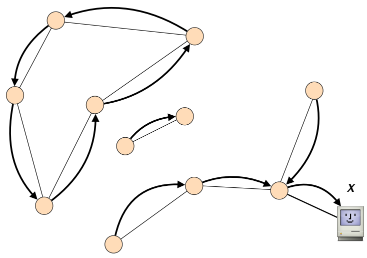

The result is a spanning tree.
This is a valid routing state



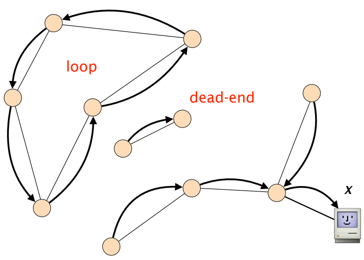

Mark all outgoing ports with an arrow




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

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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<br>SDN |
| #3 | Rely on distributed computation | Distance-Vector<br>BGP |

---

Essentially,
there are three ways to compute valid routing state

| | | |
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| #1 | Use tree-like topologies | Spanning-tree |
| | Rely on a global network view | Link-State<br>SDN |
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---

The easiest way to **avoid loops** is to route traffic
on a loop-free topology

| | |
|---|---|
| simple algorithm | Take an arbitrary topology<br><br>Build a spanning tree and ignore all other links<br><br>Done! |
| Why does it work? | Spanning-trees have only one path between any two nodes |

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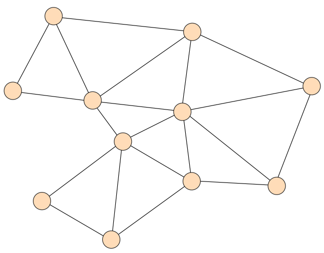
In practice,
there can be ***many*** spanning-trees for a given topology



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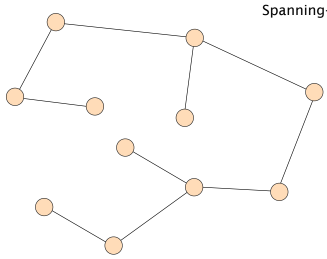
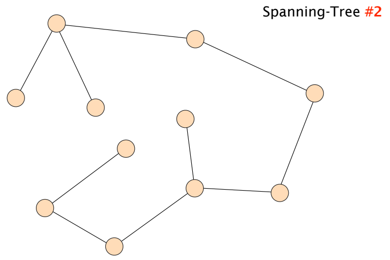
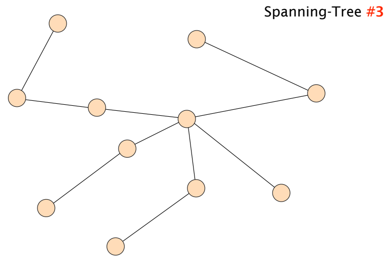
Spanning-Tree #1



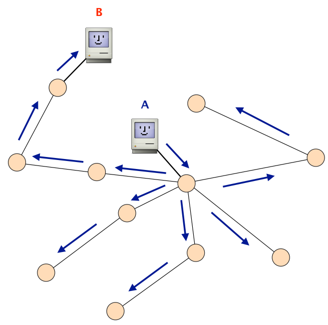


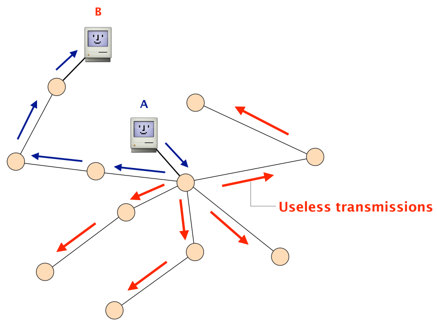

Once we have a spanning tree,
forwarding on it is easy

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

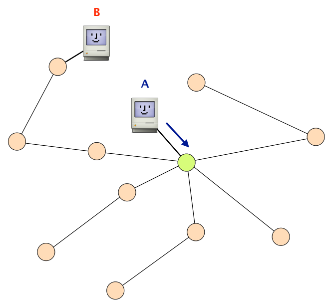
intuition

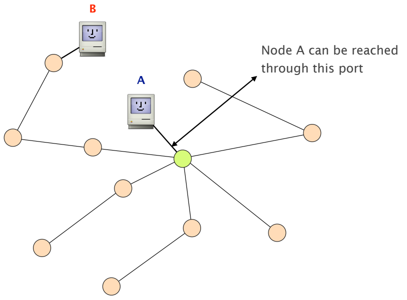
if

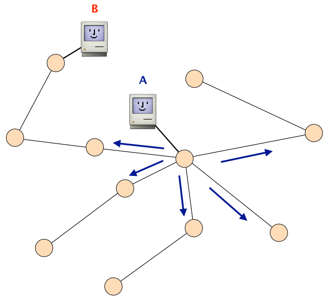
flood packet from node *A*
entered switch *X* on port *4*

then

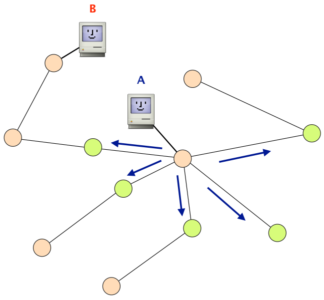
switch *X* can use port *4*
to reach node *A*



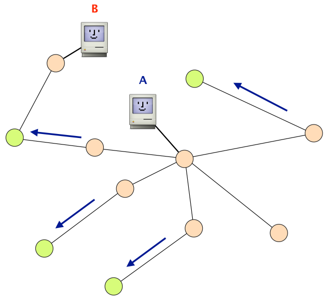


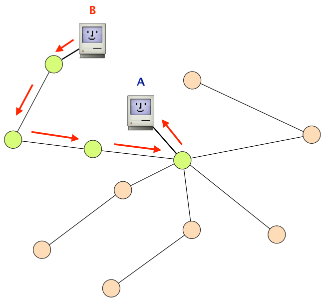

All the green nodes learn how to reach A



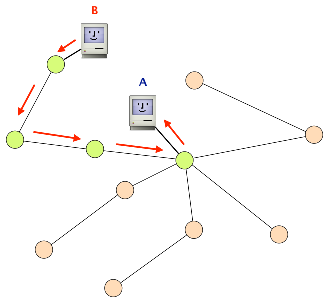

All the green nodes learn how to reach A



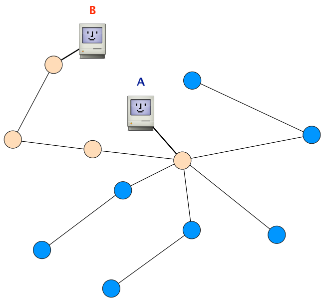

B answers back to A
enabling the green nodes to also learn where B is




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 | disadvantages |
|---|---|
| plug-and-play<br>configuration-free | mandate a spanning-tree<br>eliminate many links from the topology |
| automatically adapts<br>to moving host | slow to react to failures<br>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<br>SDN |
| | Rely on distributed computation | Distance-Vector<br>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*)}

## Dijkstra maintains two data structures:
*S* and *D*

**S**
successors
the set of vertices whose shortest path is known

**D(v)**
distances
the current estimate of the shortest path cost towards vertex v

## The initialization phase defines
the original data structures content

*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*) = ∞

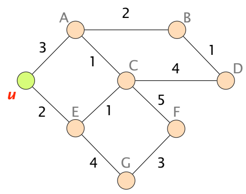
D(*v*) is the smallest distance currently known by *u* to reach *v*

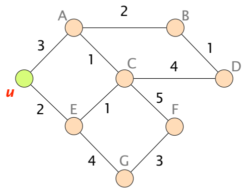
## Each iteration Dijkstra adds 1 node to S (the closest one)
before updating the distances to reach the others nodes

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*)}

## Let's compute the shortest-paths
from *u*



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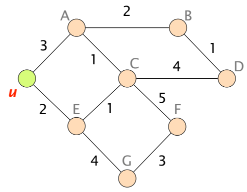
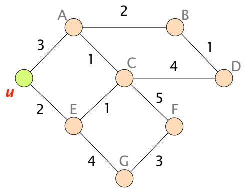
S only contains u itself and
D is initialized based on u's weight

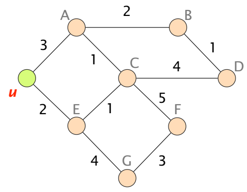



| D(.) = | | S = {u} |
|---|---|---|
| A | 3 | |
| B | ∞ | |
| C | ∞ | |
| D | ∞ | |
| E | 2 | |
| F | ∞ | |
| G | ∞ | |

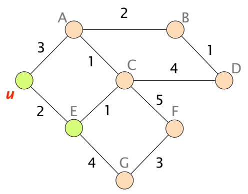



Loop

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*)}

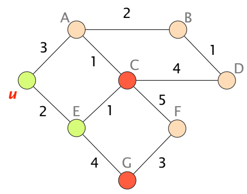



| D(.) = | | S = {u} |
|---|---|---|
| A | 3 | |
| B | ∞ | |
| C | ∞ | |
| D | ∞ | |
| E | 2 | smallest D(*w*) |
| F | ∞ | |
| G | ∞ | |



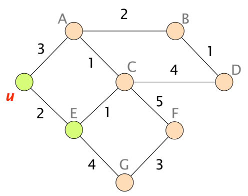

add E to S

| D(.) = | | S = {u, E} |
|---|---|---|
| A | 3 | |
| B | ∞ | |
| C | ∞ | |
| D | ∞ | |
| E | 2 | |
| F | ∞ | |
| G | ∞ | |



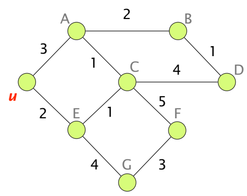

| D(.) = | | S = {u, E} |
|---|---|---|
| A | 3 | |
| B | ∞ | |
| C | 3 | D(*v*) = min{∞, 2 + 1} |
| D | ∞ | |
| E | 2 | |
| F | ∞ | |
| G | 6 | D(*v*) = min{∞, 2 + 4} |

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(.) = | | S = {u, A, B, C, D, E, F,G} |
|---|---|---|
| A | 3 | |
| B | 5 | |
| C | 3 | |
| D | 6 | |
| E | 2 | |
| F | 8 | |
| G | 6 | |

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

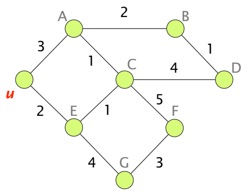
| | |
|---|---|
| iteration #1 | search for minimum through $n$ nodes |
| iteration #2 | search for minimum through $n$-1 nodes |
| iteration $n$ | search for minimum through 1 node |

$\frac{n(n+1)}{2}$ 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

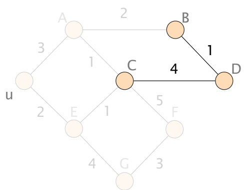



Forwarding table

| *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

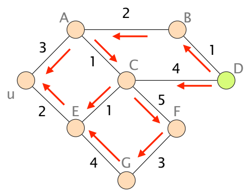
Initially,
routers only know their ID and their neighbors




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

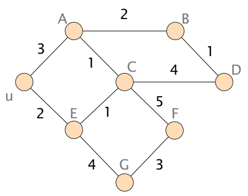



D's Advertisement

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<br>SDN |
| #3 | Rely on distributed computation | Distance-Vector<br>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 $y$

Let $d_x(y)$ be the cost of the least-cost path
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 $y$

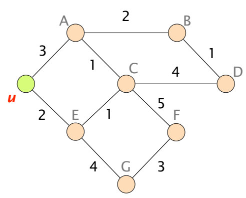
until convergence

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

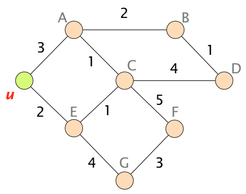
Each node updates its distances
based on neighbors' vectors:

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

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



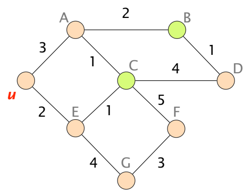

The values computed by a node *u*
depends on what it learns from its neighbors (A and E)




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

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

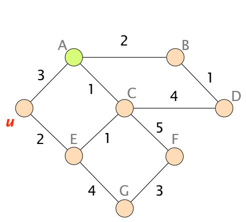
To unfold the recursion,
let's start with the direct neighbor of D




$d_B(D) = 1$

$d_C(D) = 4$

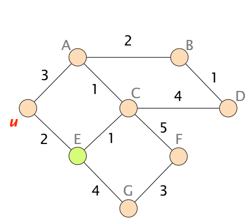
B and C announce their vector to their neighbors,
enabling A to compute its shortest-path




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

$$= 3$$

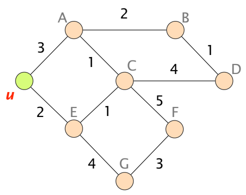
As soon as a distance vector changes,
each node propagates it to its neighbor




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

$$= 5$$

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

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