# Communication Networks

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## Communication Networks

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Material inspired from Scott Shenker & Jennifer Rexford

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Last week on

Communication Networks

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## Communication Networks

Part 1: General overview

#1 What is a network made of?

#2 How is it shared?

#3 How is it organized?

#4 How does communication happen?

#5 How do we characterize it?

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

| | layer |
|---|---|
| L5 | Application |
| L4 | Transport |
| L3 | Network |
| L2 | Link |
| L1 | Physical |

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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 |

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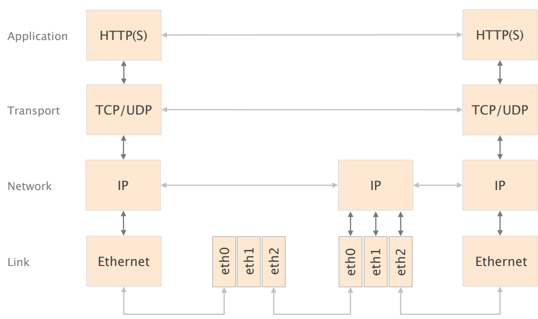
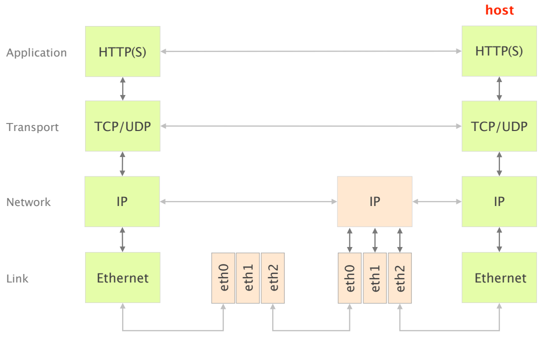
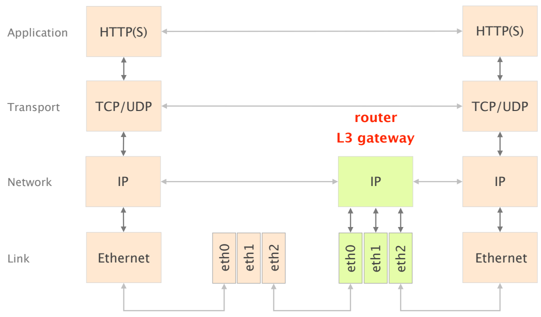
In practice, layers are distributed on every network device



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




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




## Communication Networks

Part 1: General overview

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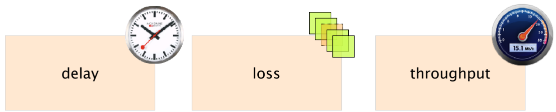
#5 How do we characterize it?

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




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

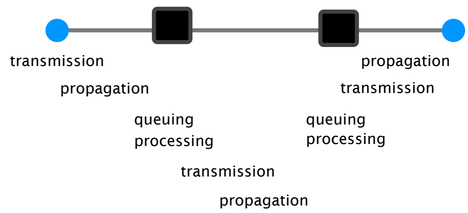
What fraction of packets sent to a destination are dropped?

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

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

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

= total delay

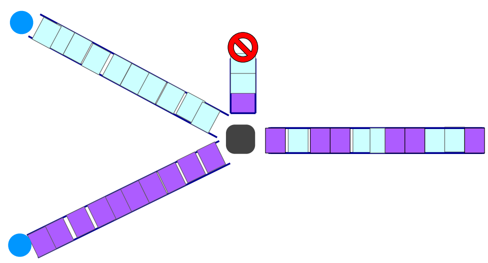



The queuing delay is the amount of time a packet waits (in a buffer) to be transmitted on a link

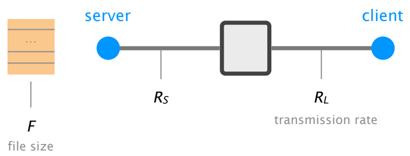
Queuing delay is the hardest to evaluate
as it varies from packet to packet

It is characterized with statistical measures
*e.g.*, average delay & variance, probability of exceeding *x*

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



To compute throughput, one has to consider the bottleneck link




Average throughput $\min(R_S, R_L)$

= transmission rate of the bottleneck link

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This week on

Communication Networks

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We will dive into two fundamental networking challenges

routing

reliable delivery

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routing

reliable delivery

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

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

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This week

Next week

routing

reliable delivery

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

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Think of IP packets as envelopes

Packet

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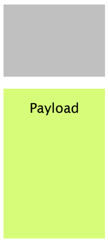
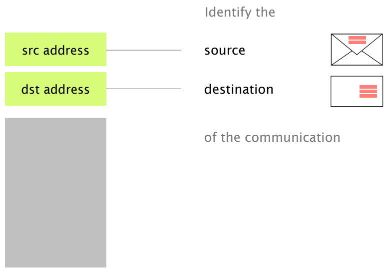
Like an envelope, packets have a header

Header

Like an envelope,
packets have a payload

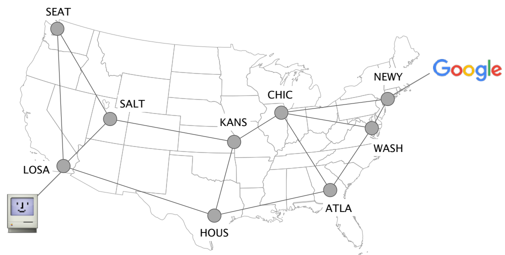


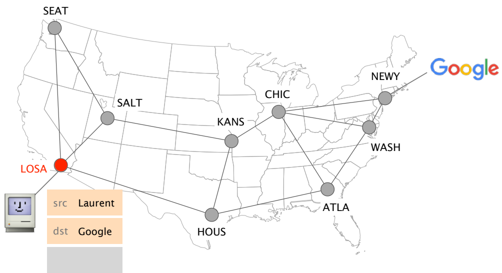

The header contains the metadata
needed to forward the packet

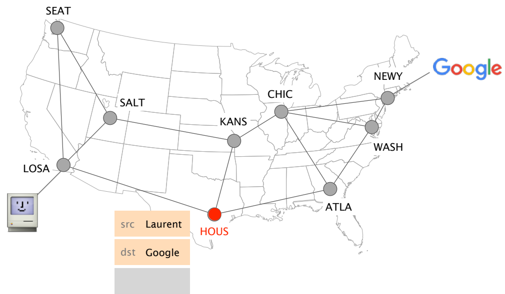


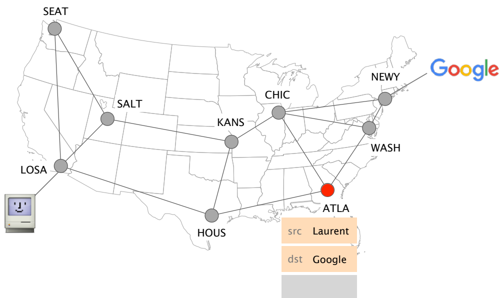

The payload contains
the data to be delivered

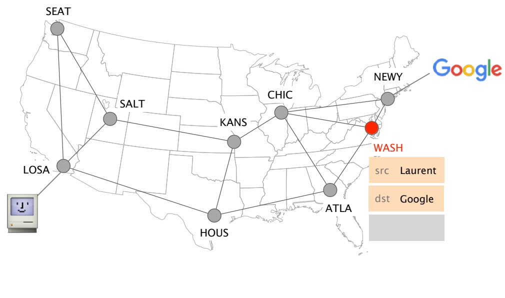

Routers forward IP packets hop-by-hop
towards their destination

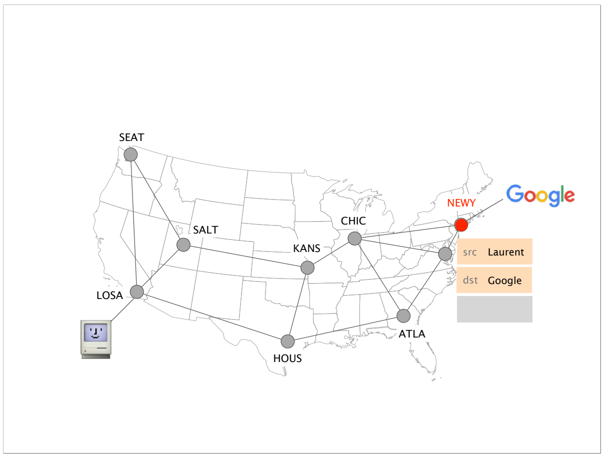


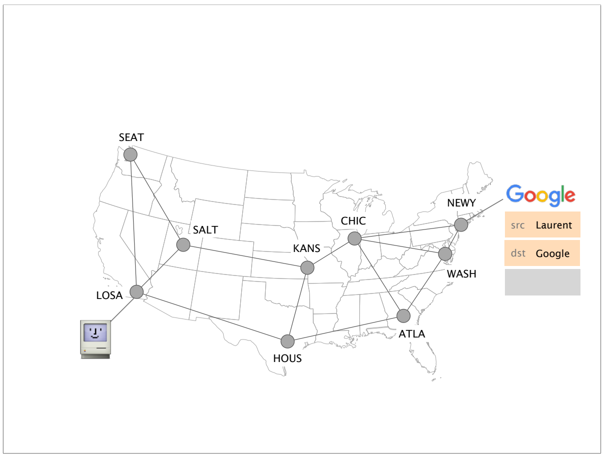



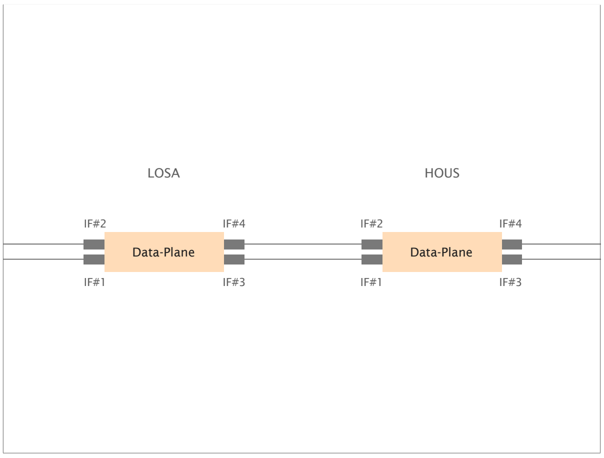



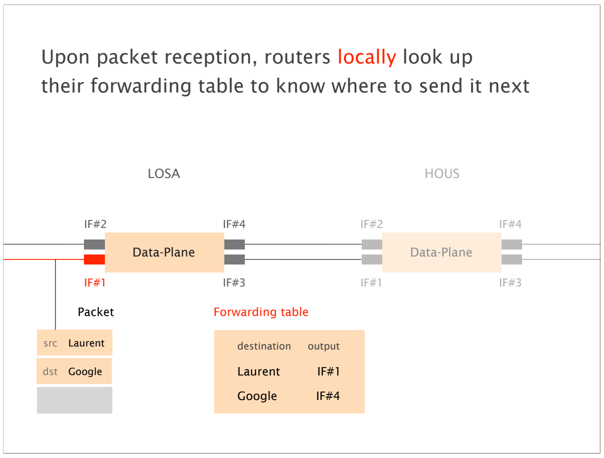



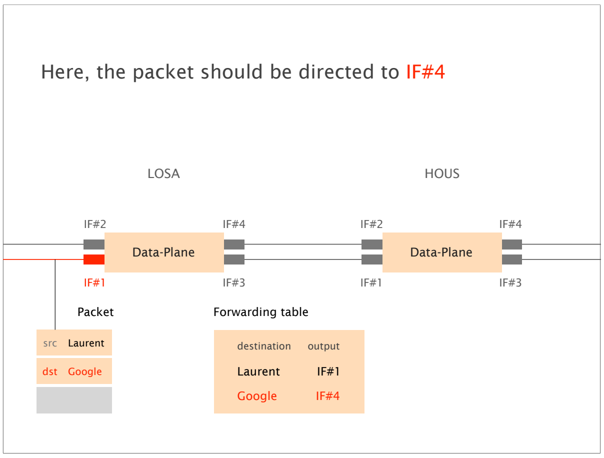

SEAT
SALT
LOSA
KANS
CHIC
NEWY
HOUS
ATLA
Google
src Laurent
dst Google

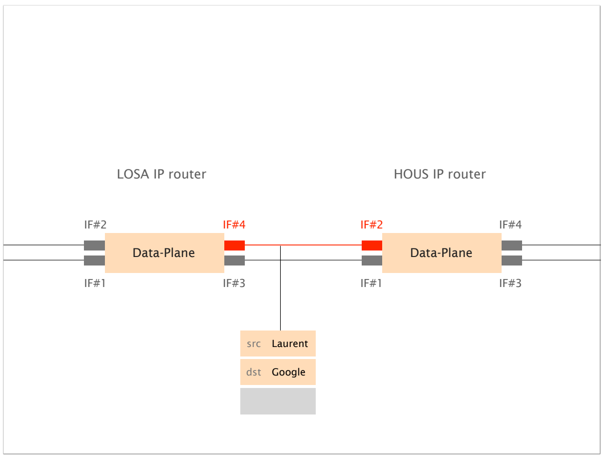

SEAT
SALT
LOSA
KANS
CHIC
NEWY
WASH
HOUS
ATLA
Google
src Laurent
dst Google

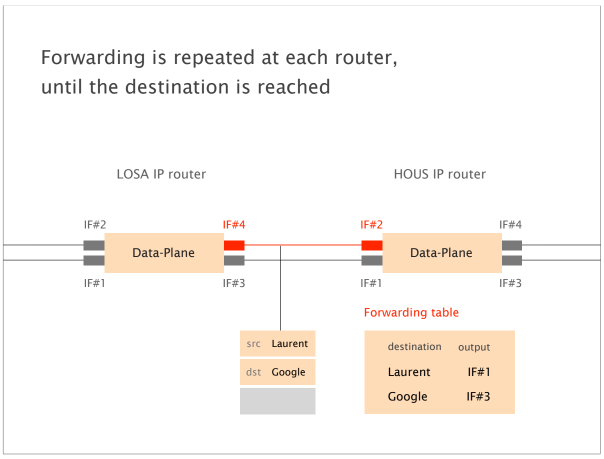

Let’s zoom in on what is going on
between two adjacent routers
SEAT
SALT
LOSA
KANS
CHIC
NEWY
WASH
HOUS
ATLA
Google

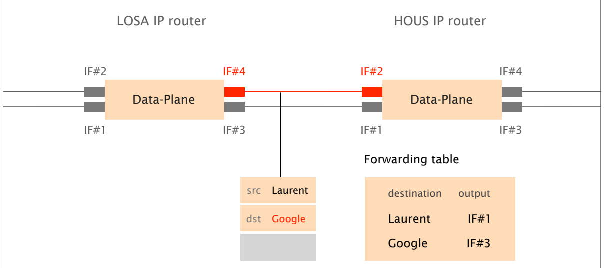

LOSA
HOUS
IF#2
IF#4
Data-Plane
IF#1
IF#3
IF#2
IF#4
Data-Plane
IF#1
IF#3

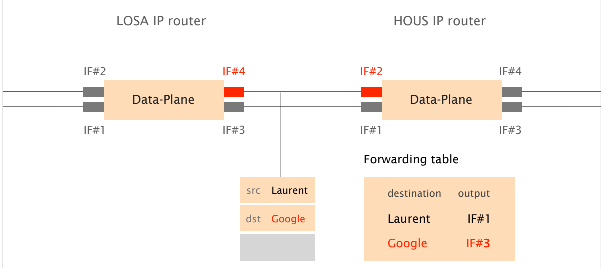

Upon packet reception, routers locally look up
their forwarding table to know where to send it next
LOSA
HOUS
IF#2
IF#4
Data-Plane
IF#1
IF#3
IF#2
IF#4
Data-Plane
IF#1
IF#3
Packet
src Laurent
dst Google
Forwarding table
destination output
Laurent IF#1
Google IF#4

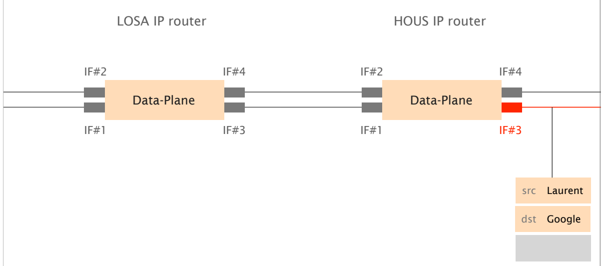

Here, the packet should be directed to IF#4
LOSA
HOUS
IF#2
IF#4
Data-Plane
IF#1
IF#3
IF#2
IF#4
Data-Plane
IF#1
IF#3
Packet
src Laurent
dst Google
Forwarding table
destination output
Laurent IF#1
Google IF#4


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


Forwarding 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 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

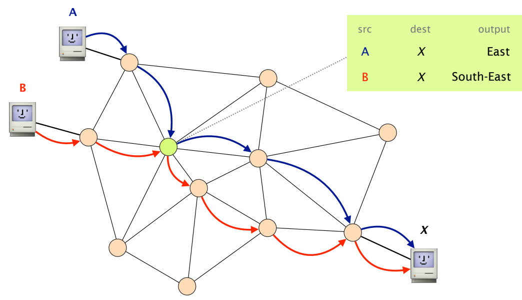
| criteria | | |
|---|---|---|
| | destination | mandatory (why?) |
| | source | requires $n^2$ state |
| | input port | traffic engineering |
| | other header | |

destination

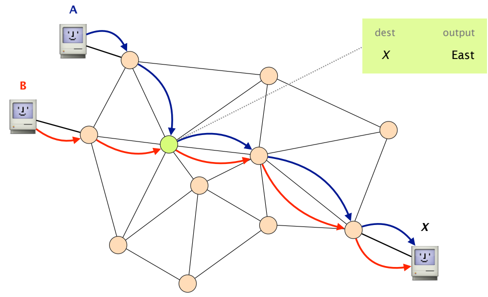
source

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

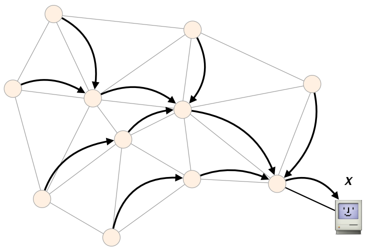



Once path to destination meet, they will *never* split

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

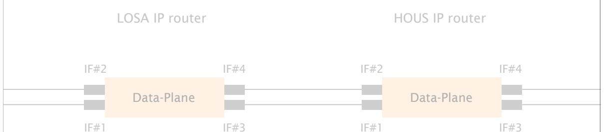
Here is an example of a spanning tree
for destination *X*




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

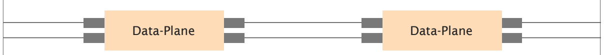
the default in the Internet

Where are these forwarding tables coming from?




| destination | output |
|---|---|
| Laurent | IF#1 |
| Google | IF#4 |

| destination | output |
|---|---|
| Laurent | IF#1 |
| Google | IF#3 |



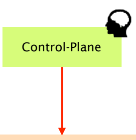

In addition to **the data-plane**,
routers are also equipped with **a control-plane**


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

Roles

- Routing
- Configuration
- Statistics
- …

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




| destination | output |
|---|---|
| Laurent | IF#1 |
| Google | IF#4 |

| destination | output |
|---|---|
| Laurent | IF#1 |
| Google | IF#3 |

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

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

## Forwarding *vs* Routing
summary

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

## The goal of routing is to compute valid global forwarding state

definition — a global forwarding state is valid if

it always delivers packets to the correct destination

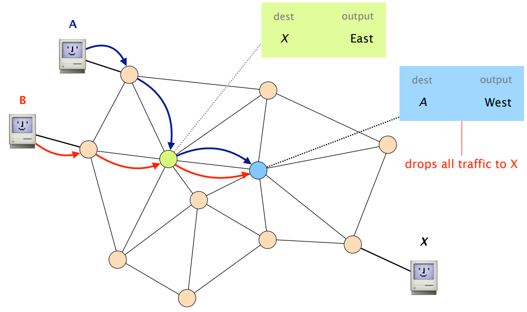
---

sufficient and necessary condition

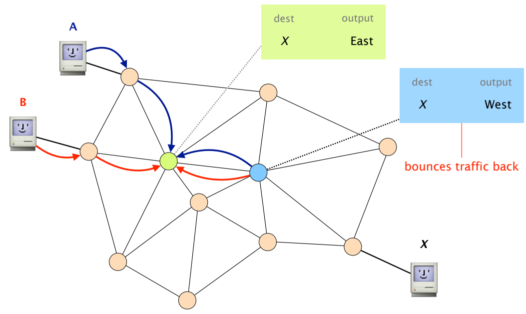
Theorem — a global forwarding state is valid if and only if

- there are no dead ends
  no outgoing port defined in the table
- there are no loops
  packets going around the same set of nodes

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




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

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sufficient and necessary condition

Theorem — a global forwarding state is valid if and only if

- there are no dead ends
  *i.e.* no outgoing port defined in the table
- there are no loops
  *i.e.* packets going around the same set of nodes

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

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

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

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

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

Theorem — If a routing state is valid then there are no loops or dead-end

Proof — If you run into a dead-end or a loop you'll never reach the destination so the state cannot be correct **(contradiction)**

## Proving the **sufficient** condition is **more subtle**

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

Proof — There is only a finite number of ports to visit

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

As such, the packet must eventually reach the destination

---

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

question 2 — How do we compute valid forwarding state?

---

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

How do we compute valid forwarding state?

---

## **Verifying** that a routing state is **valid** is **easy**

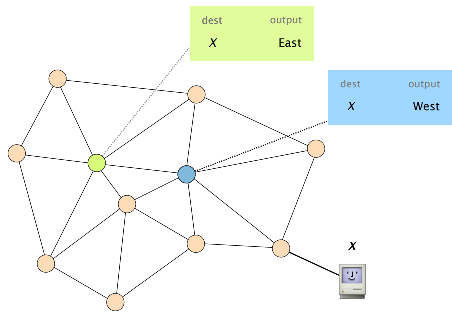
simple algorithm
for one destination

Mark all outgoing port with an arrow

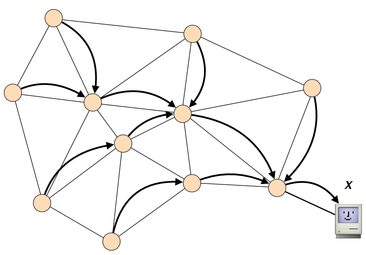
Eliminate all links with no arrow

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

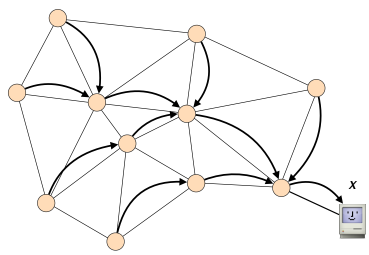
## Given a graph with the corresponding forwarding state

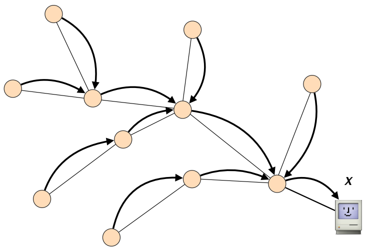



## Mark all outgoing ports with an arrow

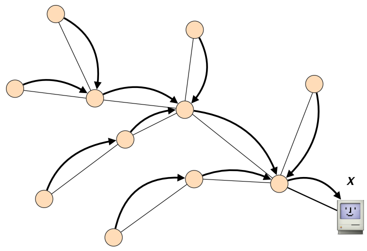



## Eliminate all links with no arrow

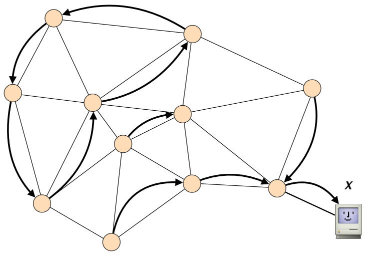




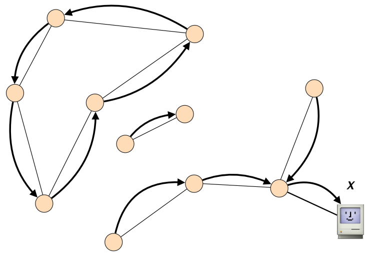

The result is a spanning tree.
This is a valid routing state



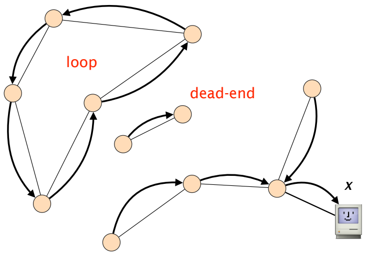

Mark all outgoing ports with an arrow




Eliminate all links with no arrow




The result is not a spanning-tree.
The routing state is not valid




How do we verify that a forwarding state is valid?

question 2 How do we compute valid forwarding state?

Producing valid routing state is harder

prevent dead ends
easy

prevent loops
hard

Producing valid routing state is harder
but doable

prevent dead ends
easy

prevent loops
hard

This is the question
you should focus on

Most routing protocols out there differ in
how they avoid loops

prevent loops
hard

Before I give you all the answers
it's your turn

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

*instructions given in class*

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

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

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

simple algorithm

Take an arbitrary topology

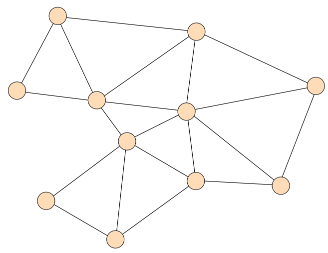
Build a spanning tree and
ignore all other links

Done!

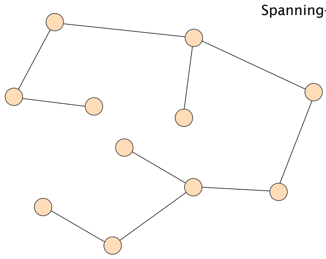
Why does it work?

Spanning-trees have only one path
between any two nodes

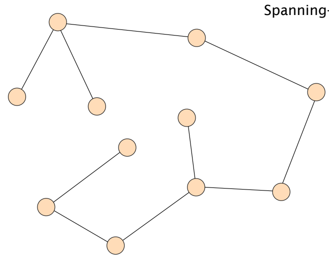
In practice,
there can be ***many*** spanning-trees for a given topology

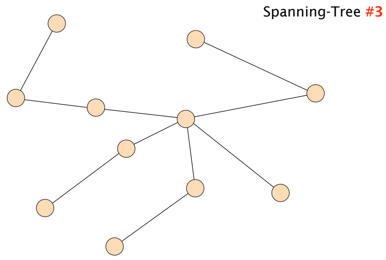


Spanning-Tree #1



Spanning-Tree #2



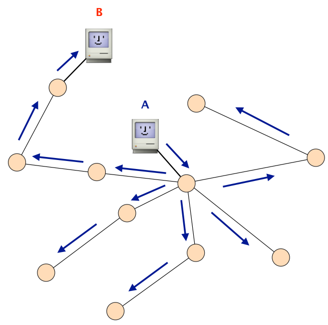



We'll see how to compute a spanning-tree
in two weeks. For now, **assume it is possible**

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

literally just flood
the packets everywhere

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




While flooding works,
it is quite wasteful

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

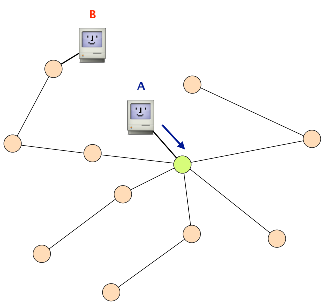
intuition

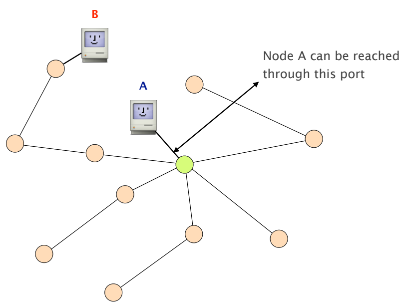
if

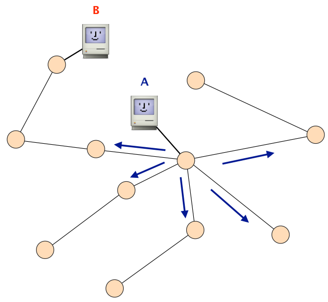
flood packet from node *A*
entered switch *X* on port *4*

then

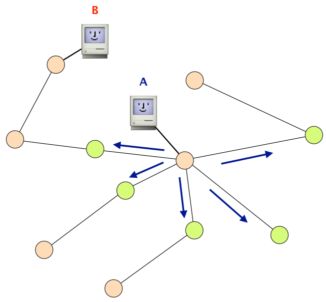
switch *X* can use port *4*
to reach node *A*



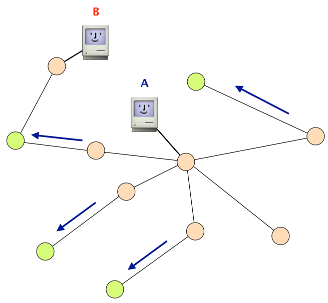





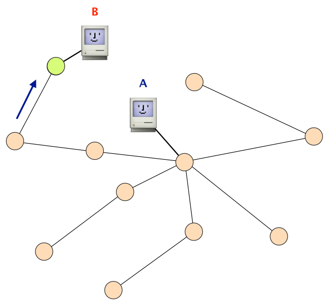

All the green nodes learn how to reach A



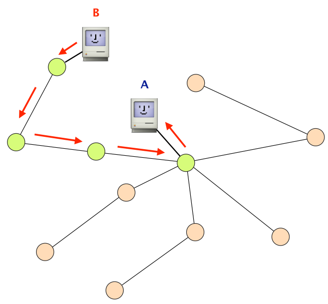

All the green nodes learn how to reach A



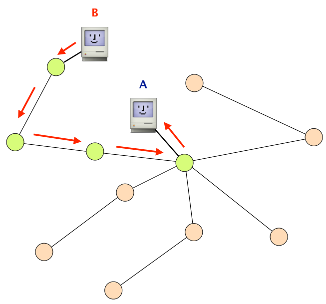

All the nodes in the network know
on which port A can be reached




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




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




## Routing by flooding on a spanning-tree
in a nutshell

Flood first packet to node you're trying to reach
all switches learn where you are

When destination answers, some switches learn where it is
some because packet to you is not flooded anymore

The decision to flood or not is done on each switch
depending on who has communicated before

## Spanning-Tree in practice
used in Ethernet

| advantages | disadvantages |
| --- | --- |
| plug-and-play<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 |

In practice, operators tend to dislike Spanning-Tree…

Essentially,
there are three ways to compute valid routing state

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

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

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

Initialization

S = {*u*}
for all nodes *v*:
    if (*v* is adjacent to *u*):
        D(*v*) = c(*u*,*v*)
    else:
        D(*v*) = ∞

Loop

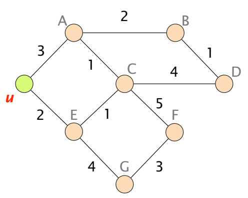
while *not* all nodes in S:
    add *w* with the smallest D(*w*) to S
    update D(*v*) for all adjacent *v* not in S:
        D(*v*) = min{D(*v*), D(*w*) + c(*w*,*v*)}

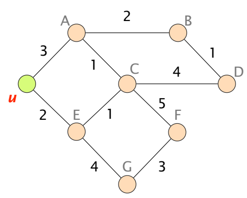
*u* is the node running the algorithm

S = {*u*}
for all nodes *v*:
    if (*v* is adjacent to *u*):
        D(*v*) = c(*u*,*v*)    *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*

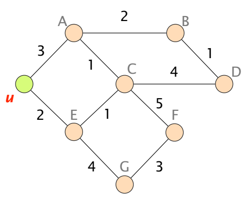


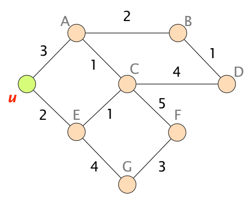

Initialization

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

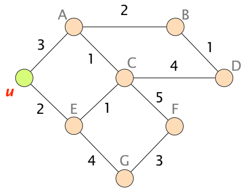



| D(.) = | | S = {u} |
|---|---|---|
| A | 3 | |
| B | ∞ | |
| C | ∞ | |
| D | ∞ | |
| E | 2 | |
| F | ∞ | |
| G | ∞ | |



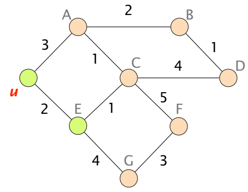

Loop

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}

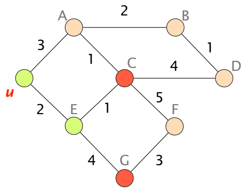
| | |
|---|---|
| A | 3 |
| B | ∞ |
| C | ∞ |
| D | ∞ |
| E | 2 — smallest D(*w*) |
| F | ∞ |
| G | ∞ |




add E to S

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

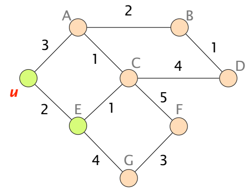
| | |
|---|---|
| A | 3 |
| B | ∞ |
| C | ∞ |
| D | ∞ |
| E | 2 |
| F | ∞ |
| G | ∞ |




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} |

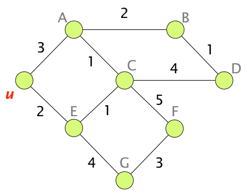
Now, do it by yourself




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

| | |
|---|---|
| A | 3 |
| B | ∞ |
| C | 3 |
| D | ∞ |
| E | 2 |
| F | ∞ |
| G | 6 |

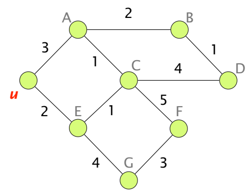
Here is the final state




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

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

From the shortest-paths,
*u* can **directly compute its forwarding table**

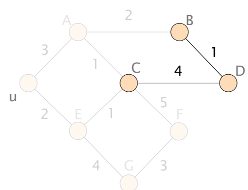



Forwarding table

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

To build this global view
**routers essentially solve a jigsaw puzzle**

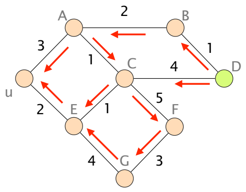
Initially,
routers only know **their ID and their neighbors**




D only knows,
it is connected to B and C

along with the weights to reach them
(by configuration)

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



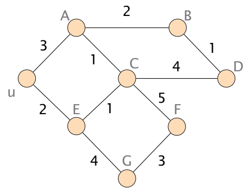

D's Advertisement

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

---

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

required for correctness
see exercise




---

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

---

Essentially,
there are three ways to compute valid routing state

| | | |
|---|---|---|
| | Use tree-like topologies | Spanning-tree |
| | Rely on a global network view | Link-State<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 $y$

---

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Each node bundles these distances into one message (called a vector)

until convergence — 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 $y$

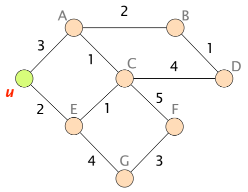
Each node bundles these distances into one message (called a vector)

until convergence — that it repeatedly sends to all its neighbors

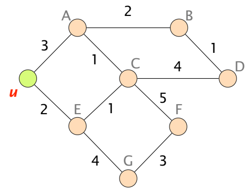
Each node updates its distances based on neighbors' vectors:

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

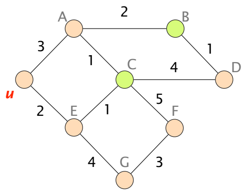



$d_x(y) = \min\{ c(x,v) + d_v(y) \}$

over all neighbors *v*

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

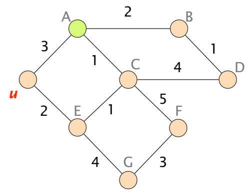
To unfold the recursion,
let's start with the direct neighbor of D




$d_B(D) = 1$

$d_C(D) = 4$

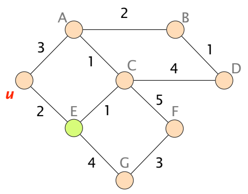
B and C announce their vector to their neighbors,
enabling A to compute its shortest-path




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

$= 3$

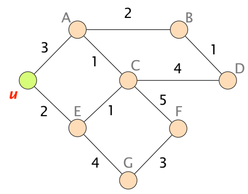
As soon as a distance vector changes,
each node propagates it to its neighbor




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

$= 5$

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

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