Communication Networks

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Materials inspired from Scott Shenker & Jennifer Rexford

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?

Communication Networks

Part 1: General overview

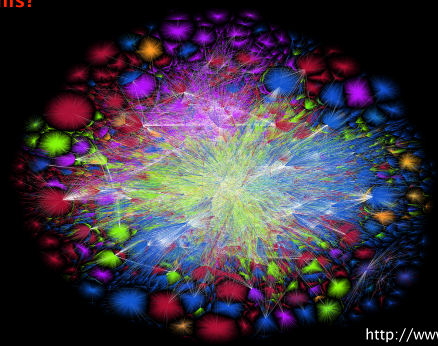
	What is a network made of?
	How is it shared?
	How is it organized?
#4	How does communication happen?
	How do we characterize it?

The Internet should allow

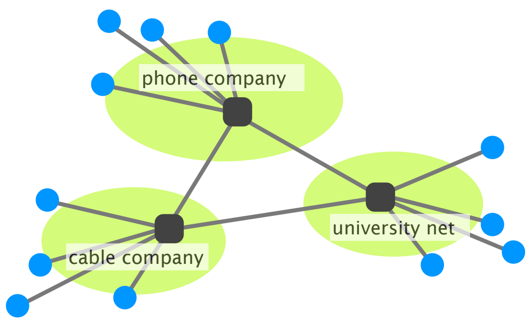
processes on different hosts
to exchange data

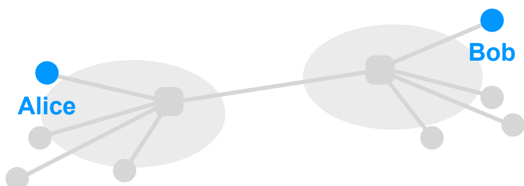
everything else is just commentary…

How do you exchange data in a network as complex as this?



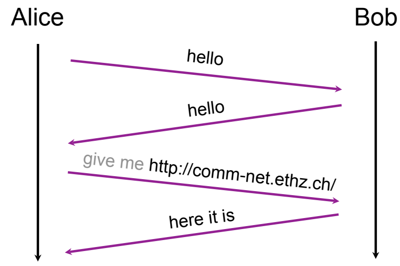
http://www.opte.org





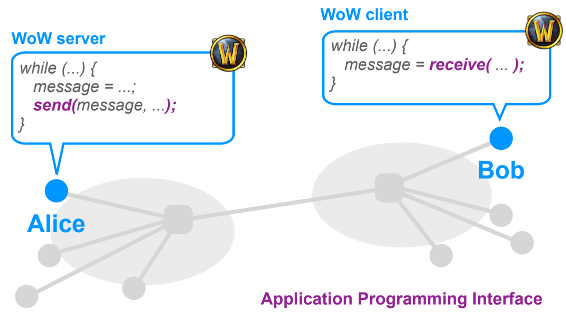
To exchange data, Alice and Bob use a set of network protocols

A protocol is like a conversational convention:
who should talk next and how they should respond

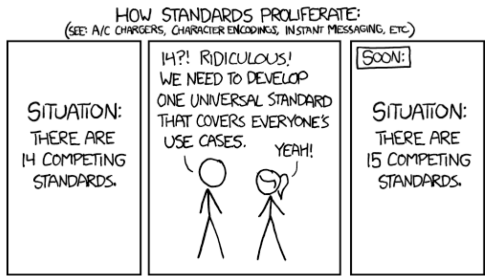


Sometimes implementations are not compliant…

Each protocol is governed by a specific interface



In practice, there exists **a lot** of network protocols.
How does the Internet organize **this?**



https://xkcd.com/927/

Modularity is a key component of any good system

Problem	can't build large systems out of spaghetti code hard (if not, impossible) to understand, debug, update
	need to bound the scope of changes evolve the system without rewriting it from scratch
Solution	Modularity is how we do it …and understand the system at a higher-level

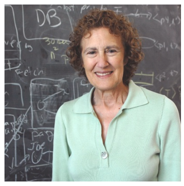


Photo: Donna Coveney

Modularity,
based on abstraction,
is ***the*** way things get done

— *Barbara Liskov*, MIT

To provide structure to the design of network protocols, network designers organize protocols in layers

To provide structure to the design of network protocols, network designers organize protocols in layers

and the network hardware/software that implement them

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

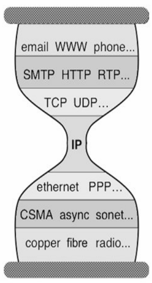
	layer
L5	Application
L4	Transport
L3	Network
L2	Link
L1	Physical

Each layer provides a service to the layer above

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

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



Each layer has a unit of data

	layer	role
L5	Application	exchanges messages between processes
L4	Transport	transports segments between end systems
L3	Network	moves packets around the network
L2	Link	moves frames across a link
L1	Physical	moves bits across a physical medium

Each layer (except for L3) is implemented with different protocols

	layer	protocol
L5	Application	HTTP, SMTP, FTP, SIP, ...
L4	Transport	TCP, UDP, SCTP
L3	Network	IP
L2	Link	Ethernet, Wifi, (A/V)DSL, WiMAX, LTE, ...
L1	Physical	Twisted pair, fiber, coaxial cable, ...

The Internet Protocol (IP) acts as an unifying, network, layer

	layer	protocol
L5	Application	HTTP, SMTP, FTP, SIP, ...
L4	Transport	TCP, UDP, SCTP
L3	Network	IP
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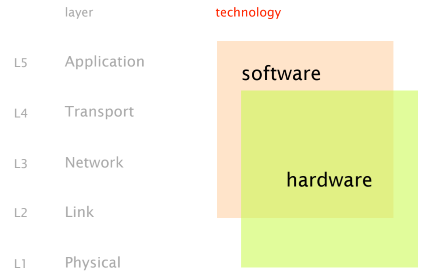
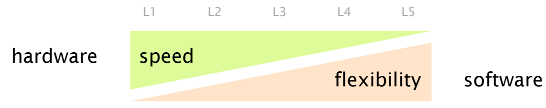
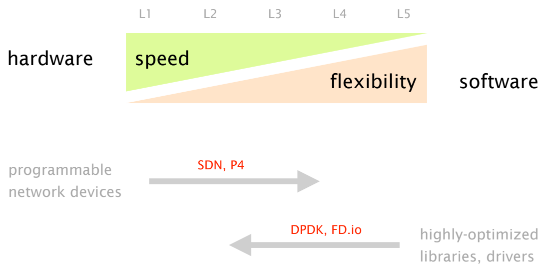
L1	Physical	Twisted pair, fiber, coaxial cable, ...

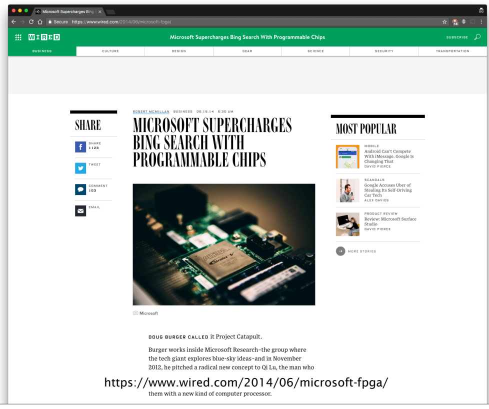
Each layer is implemented with different protocols and technologies



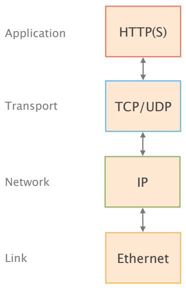


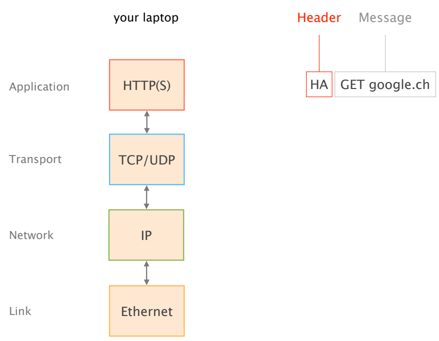
Software and hardware advancements

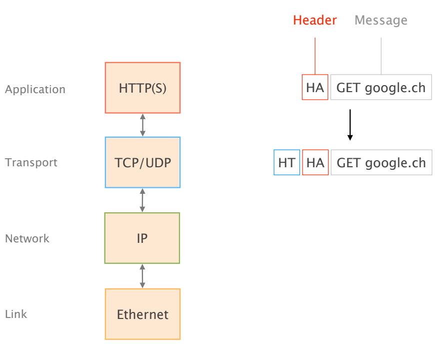


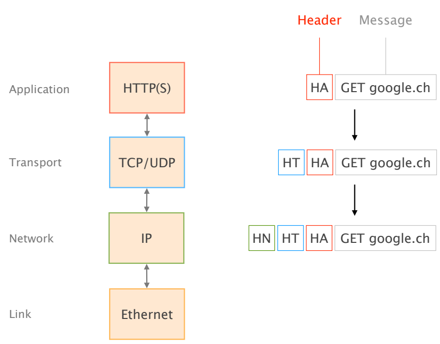


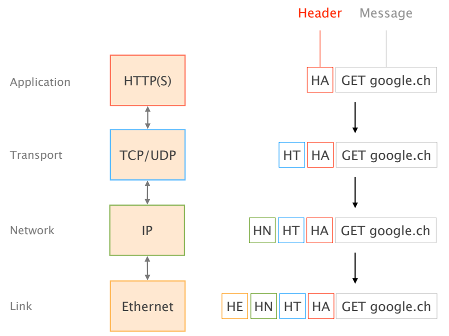
Each layer takes messages from the layer above, and *encapsulates* with its own header and/or trailer



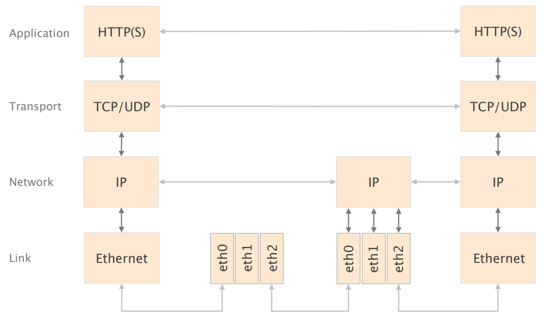




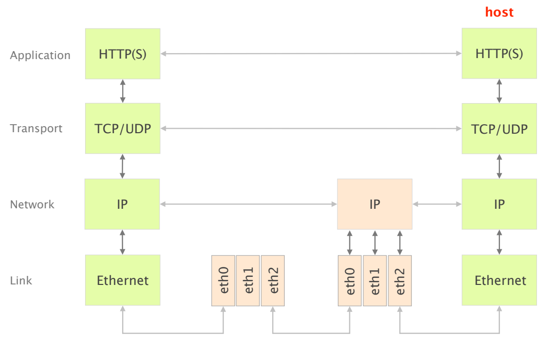




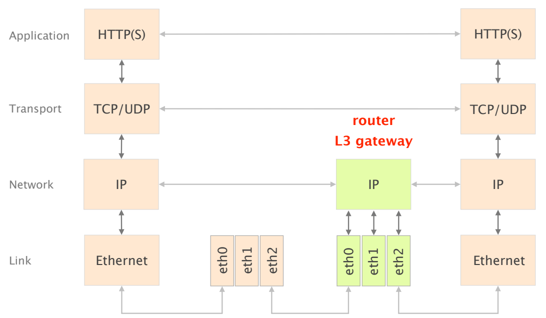
In practice, layers are distributed on every network device



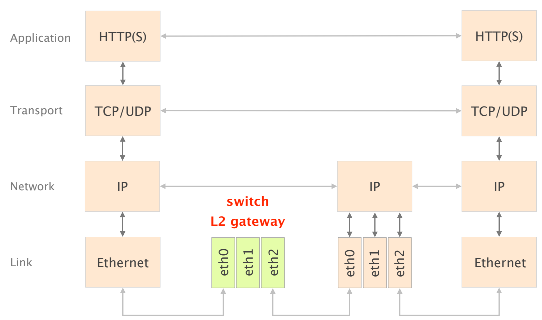
Since when bits arrive they must make it to
the application, all the layers exist on a host



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



Switches act as L2 gateway
as such they only implement L2



Let's see how it looks like in practice
on a host, using Wireshark https://www.wireshark.org

Communication Networks
Part 1: General overview

What is a network made of?

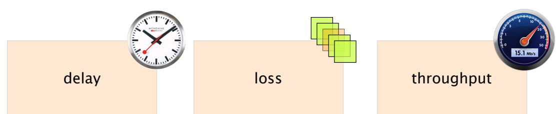
How is it shared?

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

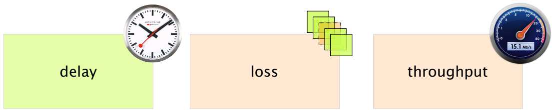


How long does it take for a packet to reach the destination

What fraction of packets sent to a destination are dropped?

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

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

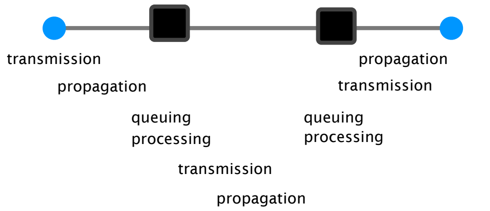


Each packet suffers from several types of delays at *each node* along the path

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

Overall, the main culprits for the overall delay are the transmission, propagation and queuing delays

	transmission	delay	
⊕	propagation	delay	
⊕	processing	delay	*tend to be tiny*
⊕	queuing	delay	
=	total	delay	



The transmission delay is the amount of time required to push all of the bits onto the link

Transmission delay [sec] = packet size [#bits] / link bandwidth [#bits/sec]

Example: 1000 bits / 100 Gbps = 10 ns

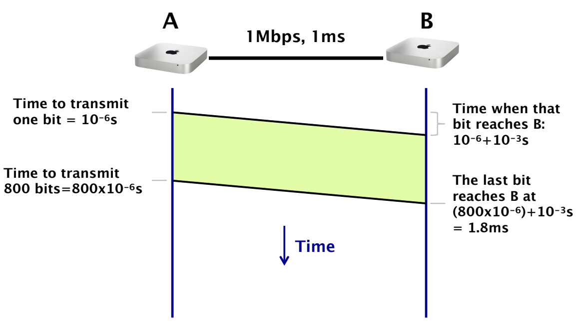
The propagation delay is the amount of time required for a bit to travel to the end of the link

Propagation delay [sec] = link length [m] / propagation speed [m/sec] (fraction of speed of light)

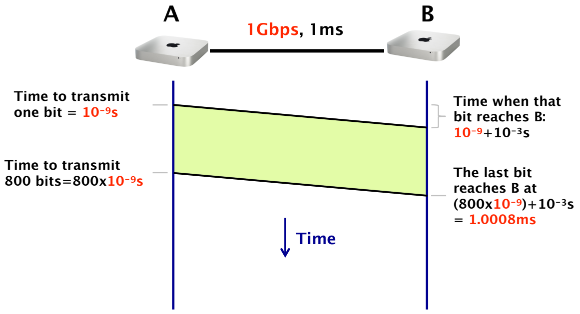
Example: 30 000 m / 2×10^8 m/sec (speed of light in fiber) = 150 µsec

How long does it take for a packet to travel from A to B?
(not considering queuing for now)

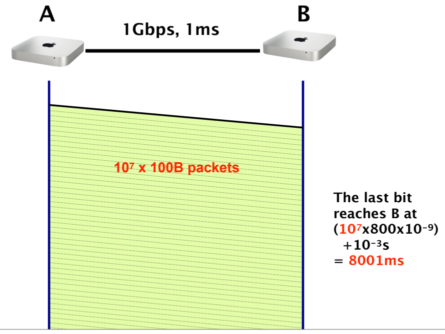
How long does it take to exchange 100 Bytes packet?



If we have a 1 Gbps link,
the total time decreases to 1.0008ms



If we now exchange a 1GB file
split in 100B packets



Different transmission characteristics imply
different tradeoffs in terms of which delay dominates

10^7x100B pkt	1Gbps link	transmission delay dominates
1x100B pkt	1Gbps link	propagation delay dominates
1x100B pkt	1Mbps link	both matter

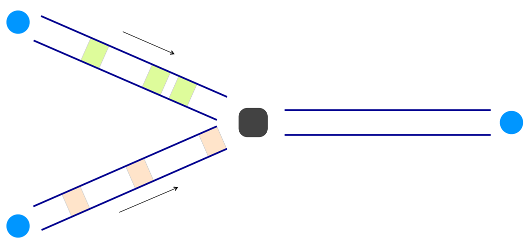
In the Internet, we **can't know** in advance which one matters!

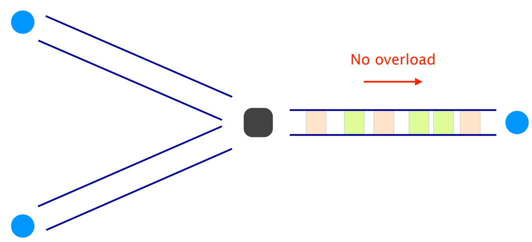
The queuing delay is the amount of time a packet
waits (in a buffer) to be transmitted on a link

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

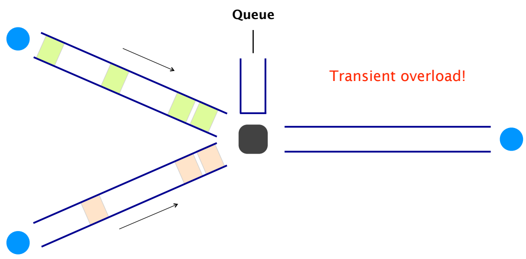
It is characterized with statistical measures
e.g., average delay & variance, probability of exceeding *x*

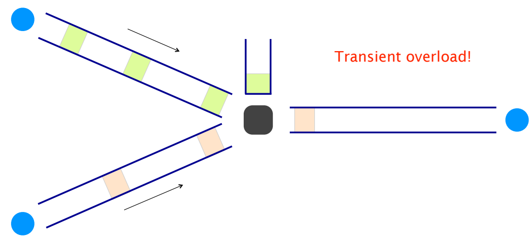
Queuing delay depends on the traffic pattern

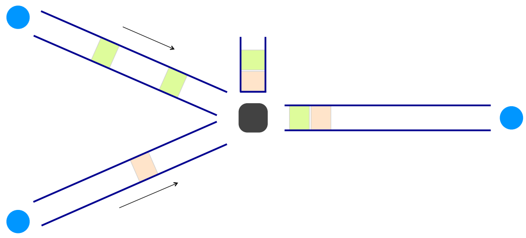


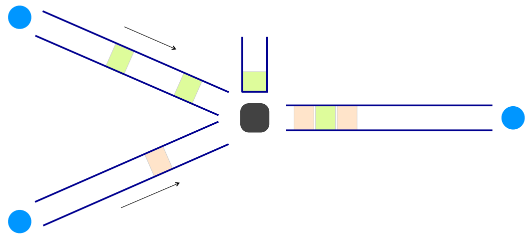


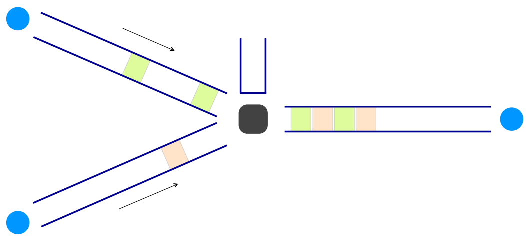
Queuing delay depends on the traffic pattern



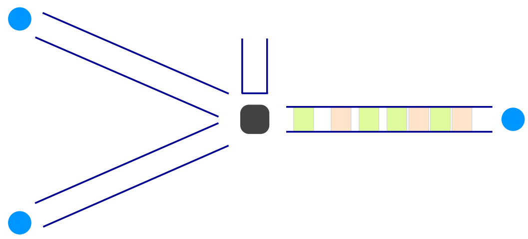








Queues absorb transient bursts,
but introduce queueing delays



The time a packet has to sit in a buffer before
being processed depends on the traffic pattern

Queueing delay depends on:

- arrival rate at the queue
- transmission rate of the outgoing link
- traffic burstiness

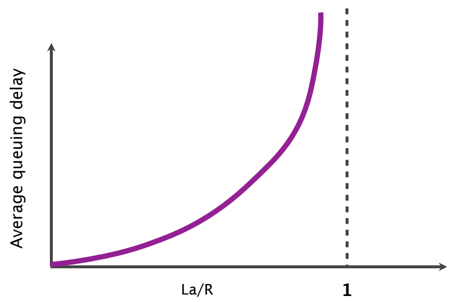
average packet arrival rate	*a*	[packet/sec]
transmission rate of outgoing link	*R*	[bit/sec]
fixed packets length	*L*	[bit]
average bits arrival rate	*La*	[bit/sec]
traffic intensity	*La/R*	

When the traffic intensity is >1, the queue will increase
without bound, and so does the queuing delay

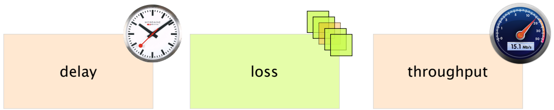
Golden rule

Design your queuing system,
so that it operates far from that point

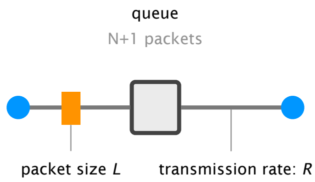
When the traffic intensity is <=1,
queueing delay depends on the burst size



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

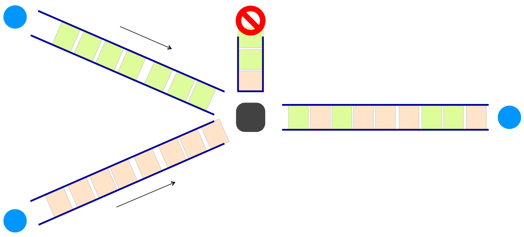


In practice, queues are not infinite.
There is an upper bound on queuing delay.



queuing delay upper bound: N*L/R

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



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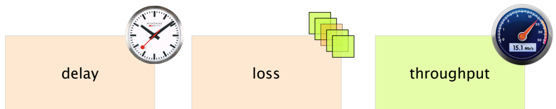
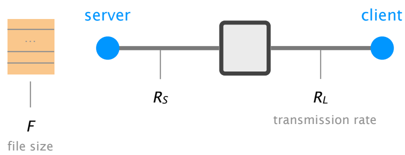


The throughput is the instantaneous rate at which
a host receives data

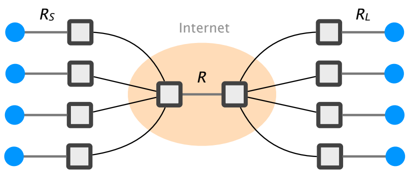
Average throughput [#bits/sec] = data size [#bits] / transfer time [sec]

To compute throughput, one has to consider the
bottleneck link



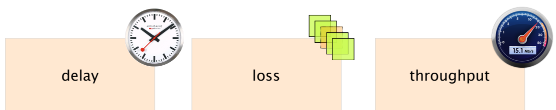
Average throughput $\min(R_S, R_L)$
= transmission rate of the bottleneck link

To compute throughput, one has to consider the
bottleneck link… and the intervening traffic



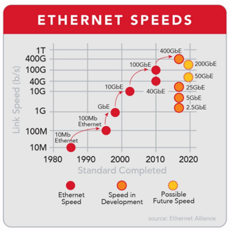
if $4 * \min(R_S, R_L) > R$ the bottleneck is now in the core,
providing each download R/4 of throughput

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



As technology improves, throughput increase & delays are getting lower except for propagation

(speed of light)



source: ciena.com

Because of propagation delays,
Content Delivery Networks move content closer to you

https://globe.akamai.com

Communication Networks

Part 1: General overview

What is a network made of?

How is it shared?

How is it organized?

How does communication happen?

How do we characterize it?

Communication Networks

Part 2: Concepts

routing

reliable delivery

Communication Networks

Part 2: Concepts

routing

reliable delivery

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

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

This week

Next week

routing

reliable delivery

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

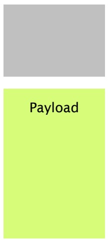
Think of IP packets as envelopes

Packet

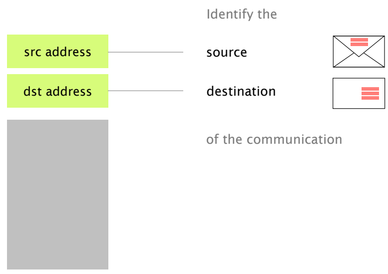
Like an envelope,
packets have a header

Header

Like an envelope,
packets have a payload

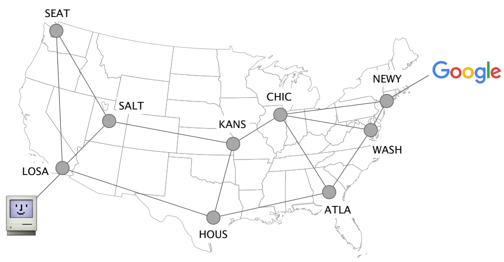


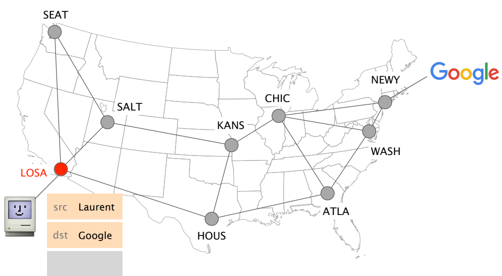
The header contains the metadata
needed to forward the packet

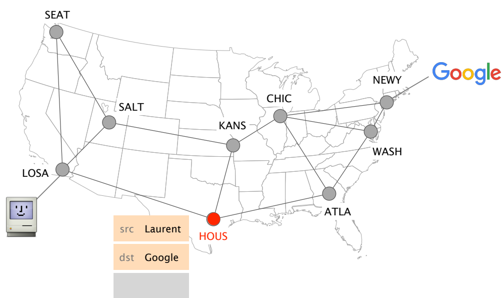


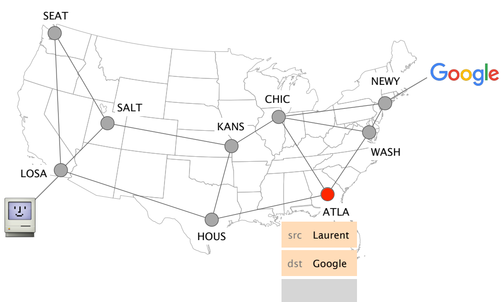
The payload contains
the data to be delivered

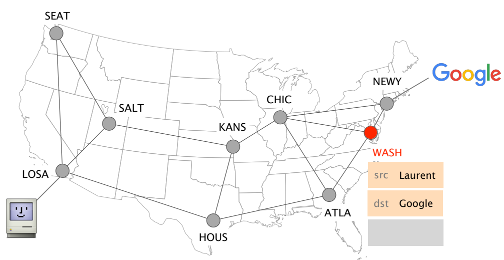
Routers forward IP packets hop-by-hop
towards their destination

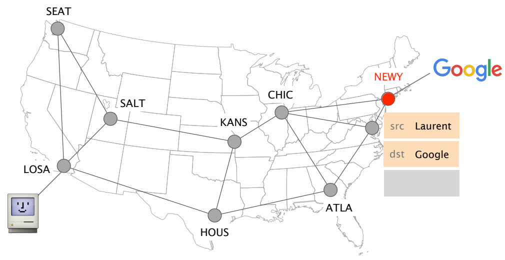


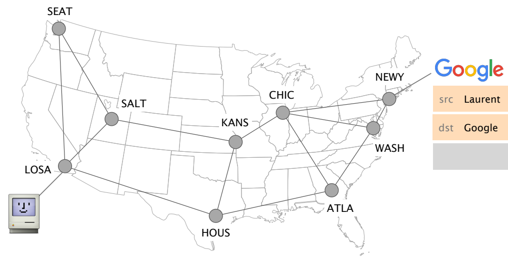




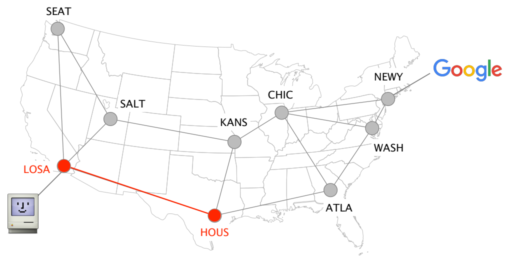


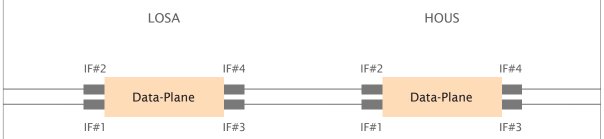




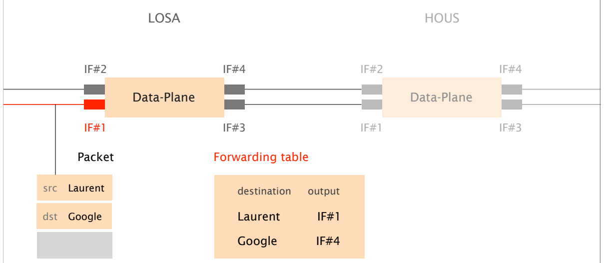


Let’s zoom in on what is going on between **two adjacent routers**

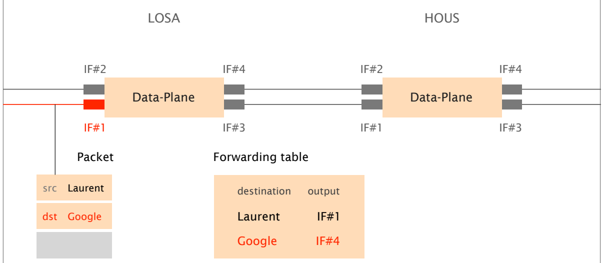


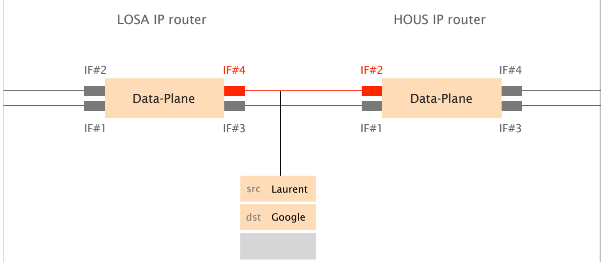


Upon packet reception, routers locally look up their **forwarding table** to know where to send it next

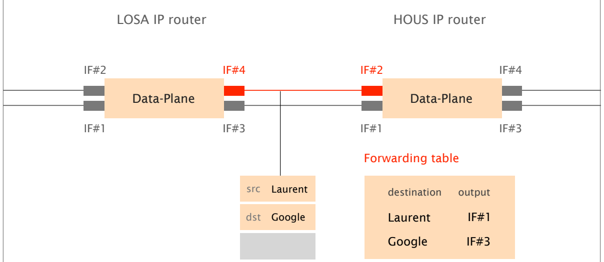


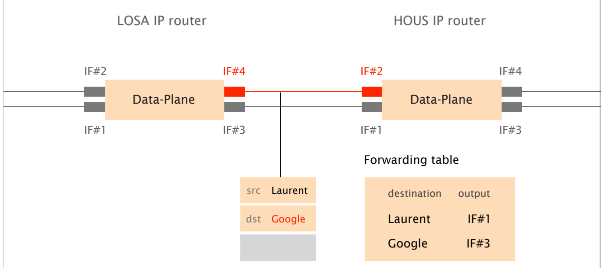
Here, the packet should be directed to IF#4

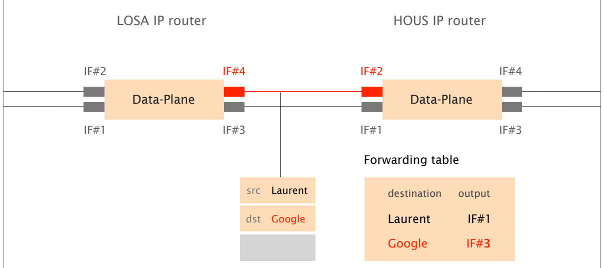


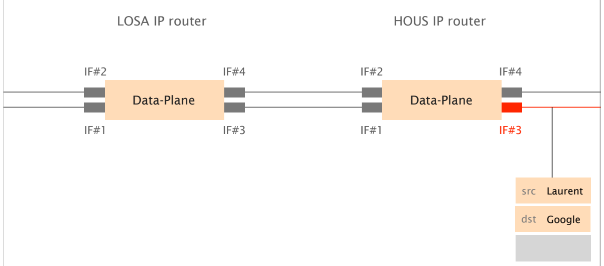


Forwarding is repeated at each router, until the destination is reached









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

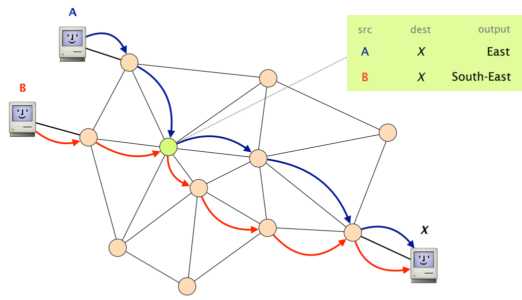
criteria		
	destination	mandatory (why?)
	source	requires n^2 state
	input port	traffic engineering
	+any other header	

destination

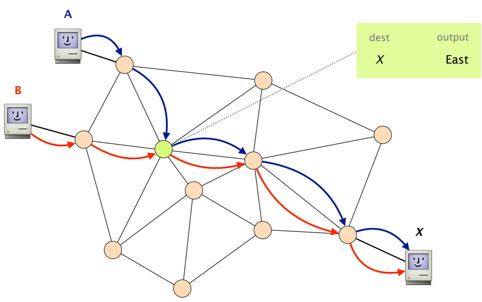
source

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

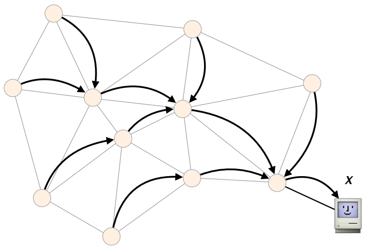


Once path to destination meet, they will *never* split

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

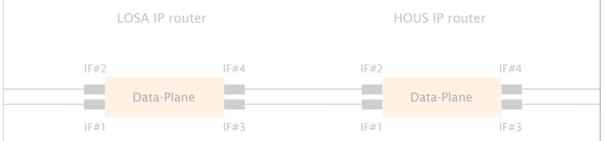
Here is an example of a spanning tree
for destination *X*



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

the default in the Internet

Where are these forwarding tables coming from?

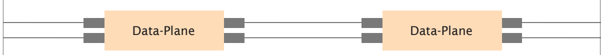


Forwarding table

destination	output
Laurent	IF#1
Google	IF#4

Forwarding table

destination	output
Laurent	IF#1
Google	IF#3



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

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 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

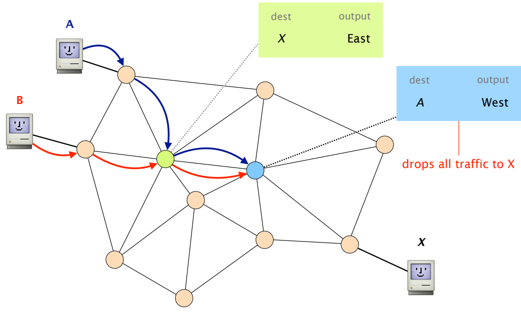
---

sufficient and necessary condition

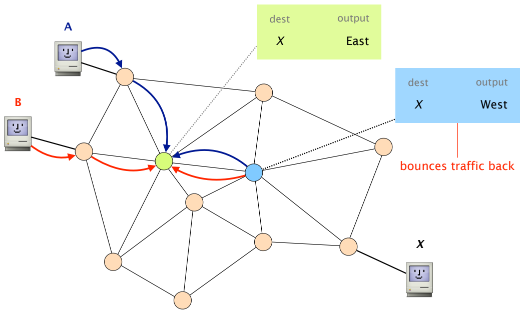
Theorem — a global forwarding state is valid if and only if

- 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



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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

Proving the necessary condition is easy

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

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

Proving the sufficient condition is more subtle

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

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

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

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

question 2 How do we compute valid forwarding state?

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

How do we compute valid forwarding state?

Verifying that a routing state is valid is easy

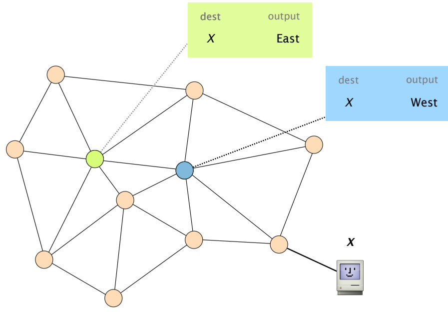
simple algorithm
for one destination

Mark all outgoing ports with an arrow

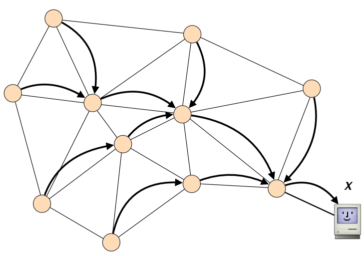
Eliminate all links with no arrow

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

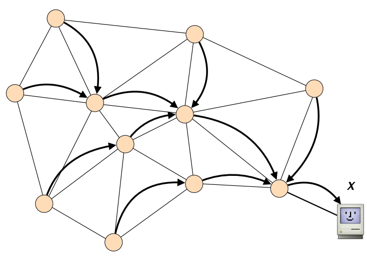
Given a graph with the corresponding forwarding state

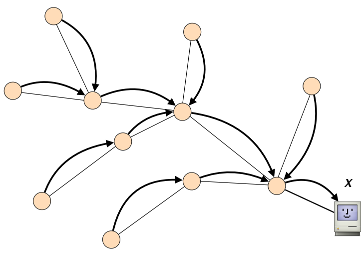


Mark all outgoing ports with an arrow

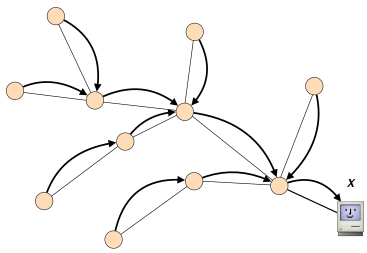


Eliminate all links with no arrow

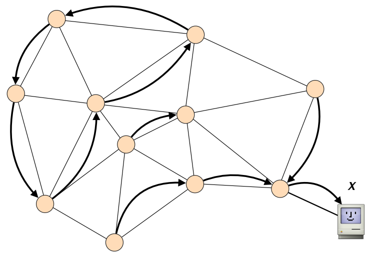




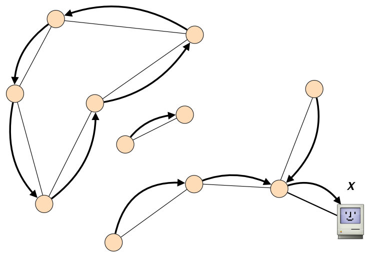
The result is a spanning tree.
This is a valid routing state



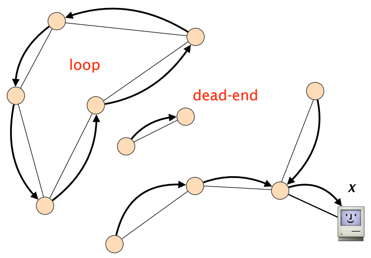
Mark all outgoing ports with an arrow



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