Communication Networks

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Communication Networks

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Materials inspired from Scott Shenker & Jennifer Rexford

Last week on

Communication Networks

Communication Networks

Part 1: General overview

#1 What is a network made of?

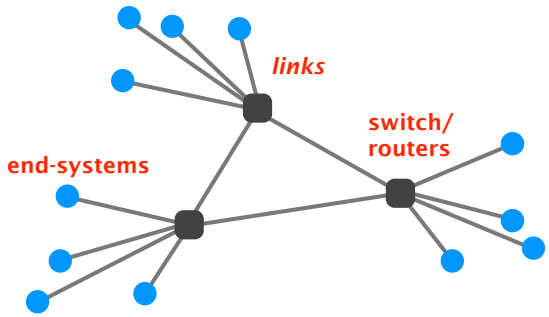
How is it shared?

How is it organized?

How does communication happen?

How do we characterize it?

Networks are composed of three basic components



Communication Networks

Part 1: General overview

What is a network made of?

#2 How is it shared?

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There exist two approaches to sharing:
reservation and on-demand

	Reservation	On-demand
principle	reserve the bandwidth you need in advance	send data when you need

In practice, the approaches are implemented using
circuit-switching or packet-switching

	Reservation	On-demand
implem.	circuit-switching	packet-switching

Pros and cons of circuit switching

advantages	disadvantages
predictable performance	inefficient if traffic is bursty or short
simple & fast switching once circuit established	complex circuit setup/teardown which adds delays to transfer
	requires new circuit upon failure

Pros and cons of packet switching

advantages	disadvantages
efficient use of resources	unpredictable performance
simpler to implement than circuit switching	requires buffer management and congestion control
route around trouble	

Communication Networks

Part 1: General overview

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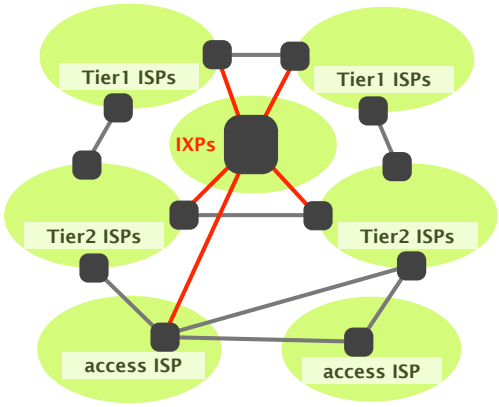


This week on Communication Networks

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?

#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?

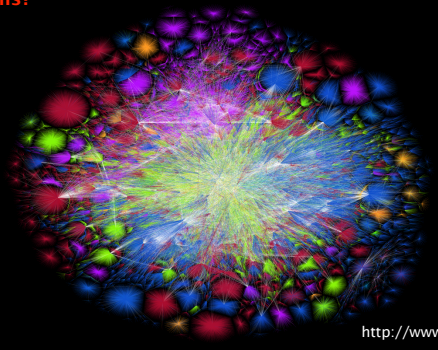
How do we characterize it?

The Internet should allow

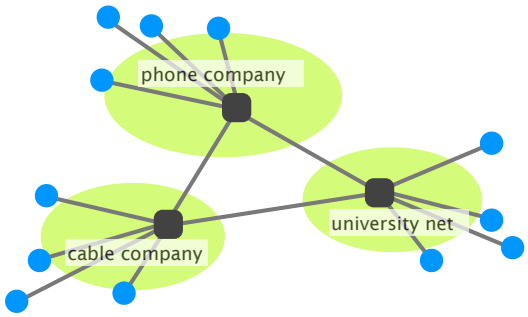
processes on different hosts
to exchange data

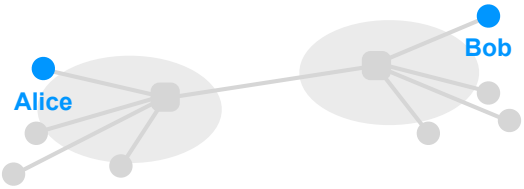
everything else is just commentary…

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



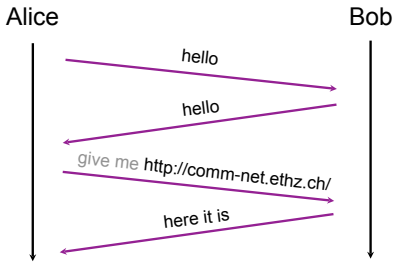
http://www.opte.org





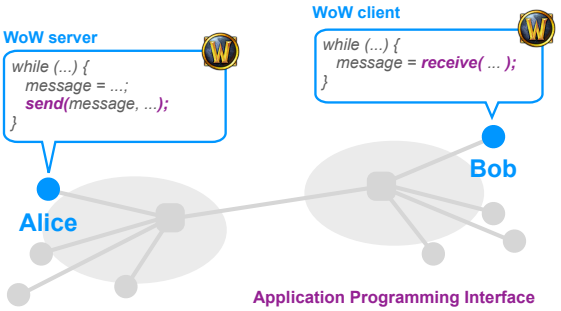
To exchange data, Alice and Bob use a set of network protocols

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

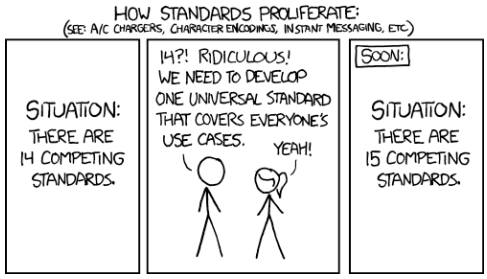


Sometimes implementations are not compliant…

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

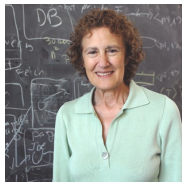


Photo: Donna Coveney

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

and the network hardware/software
that implement them

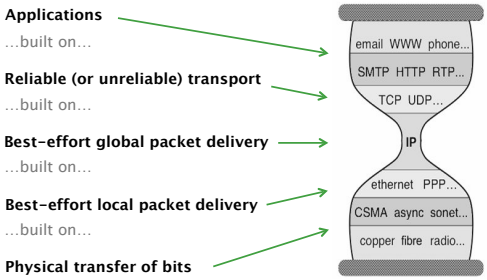
Internet communication can be decomposed
in 5 independent layers (or 7 layers for the OSI model)

	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



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

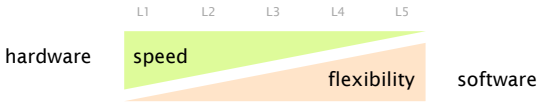
	layer	protocol
L5	Application	HTTP, SMTP, FTP, SIP, …
L4	Transport	TCP, UDP, SCTP
L3	Network	IP
L2	Link	Ethernet, Wifi, (A/V)DSL, WiMAX, LTE, …
L1	Physical	Twisted pair, fiber, coaxial cable, …

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

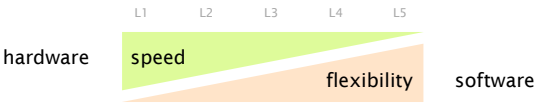
	layer	protocol
L5	Application	HTTP, SMTP, FTP, SIP, …
L4	Transport	TCP, UDP, SCTP
L3	Network	IP
L2	Link	Ethernet, Wifi, (A/V)DSL, Cable, LTE, …
L1	Physical	Twisted pair, fiber, coaxial cable, …

Each layer is implemented with different protocols and technologies

	layer	technology
L5	Application	software
L4	Transport	
L3	Network	hardware
L2	Link	
L1	Physical	



Software and hardware advancements

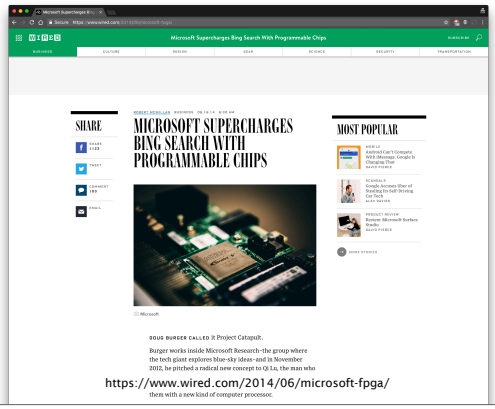


programmable network devices

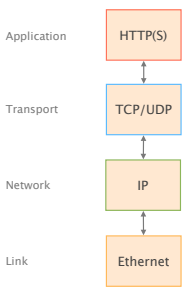
SDN, P4

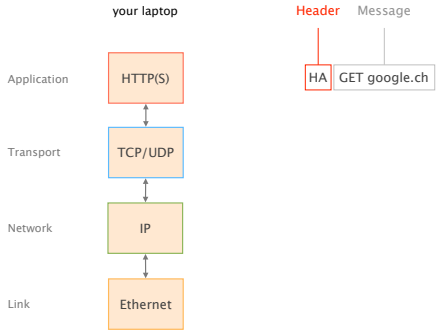
DPDK, FD.io

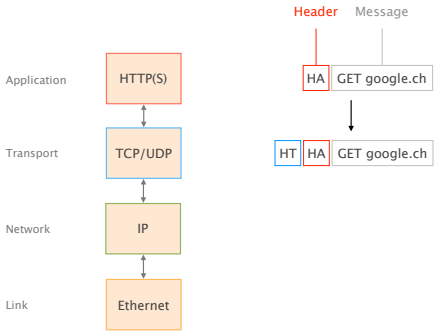
highly optimized libraries, drivers

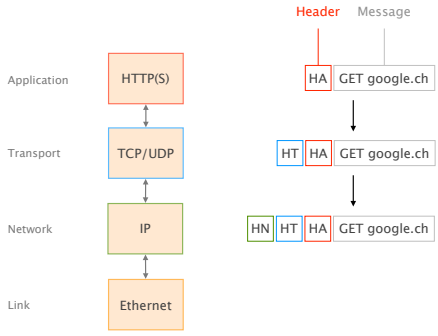


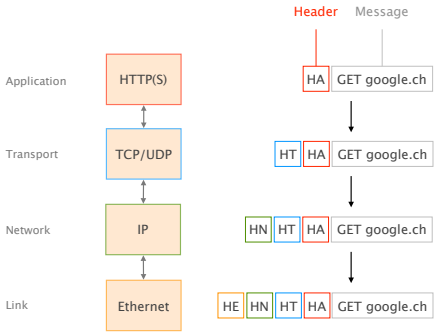
Each layer takes messages from the layer above, and *encapsulates* with its own header and/or trailer



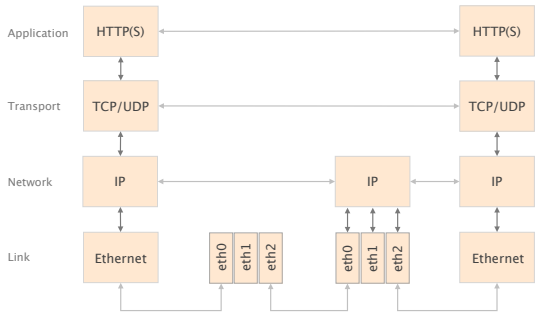




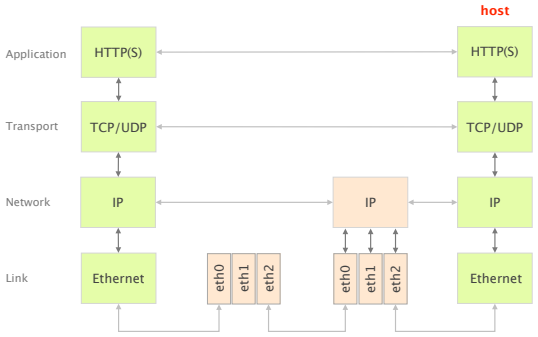




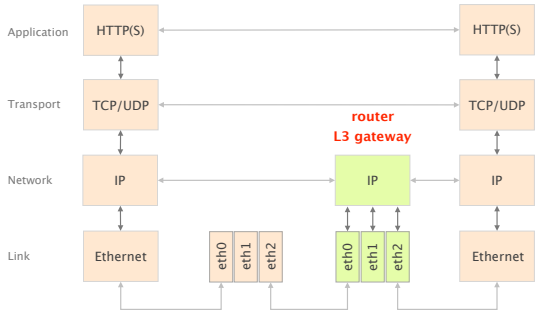
In practice, layers are distributed on every network device



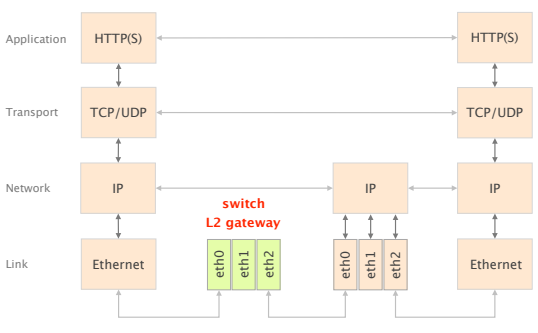
Since when bits arrive they must make it to the application, all the layers exist on a host



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?

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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?

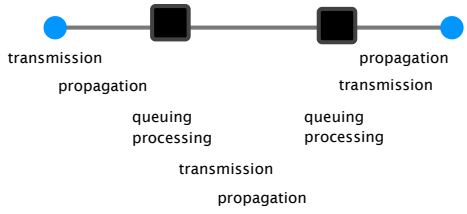
A network *connection* is characterized by its delay, loss rate and throughput

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

$$\text{Transmission delay [sec]} = \frac{\text{packet size [\#bits]}}{\text{link bandwidth [\#bits/sec]}}$$

Example: $\frac{1000 \text{ bits}}{100 \text{ Mbps}}$ = 10 µsec

---

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

$$\text{Propagation delay [sec]} = \frac{\text{link length [m]}}{\text{propagation speed [m/sec]}}$$

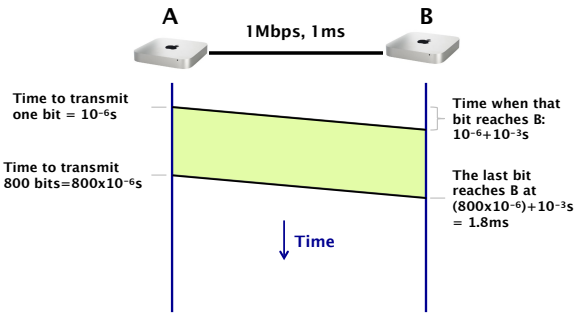
(fraction of speed of light)

Example: $\frac{30\,000 \text{ m}}{2\text{x}10^8 \text{ m/sec}}$ = 150 µsec

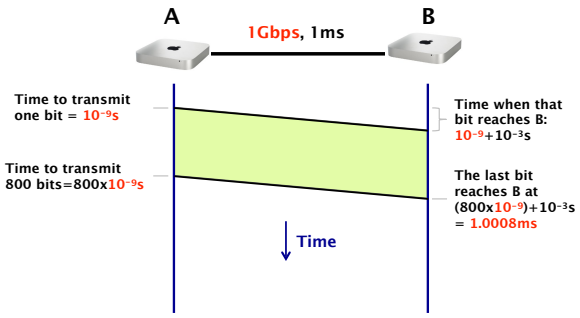
(speed of light in fiber)

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

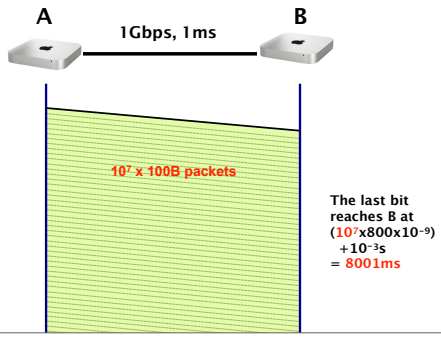
How long does it take to exchange 100 Bytes packet?



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

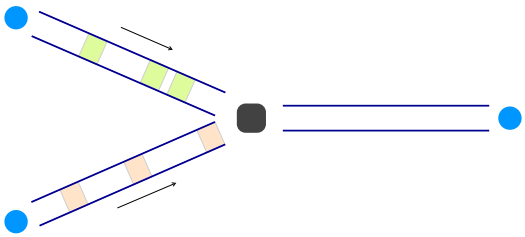
In the Internet, we **can't know** in advance which one matters!

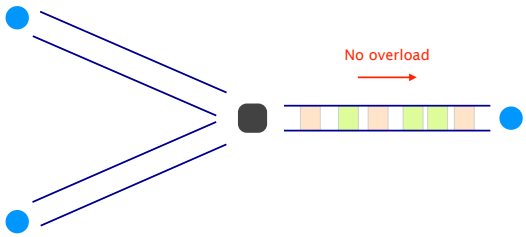
The queuing delay is the amount of time a packet
waits (in a buffer) to be transmitted on a link

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

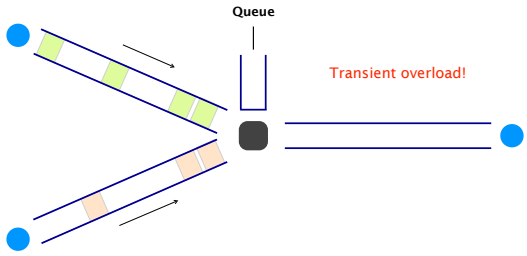
It is characterized with statistical measures
e.g., average delay & variance, probability of exceeding *x*

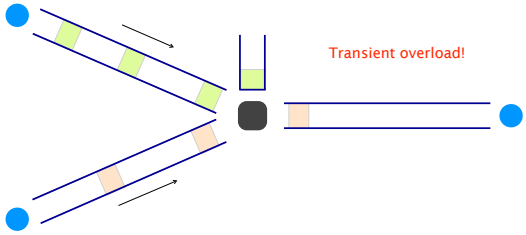
Queuing delay depends on the traffic pattern

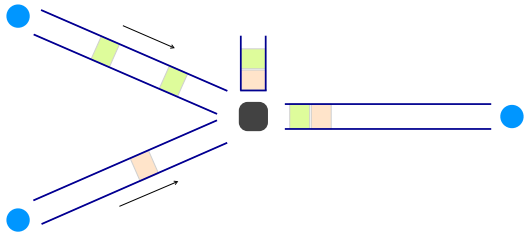


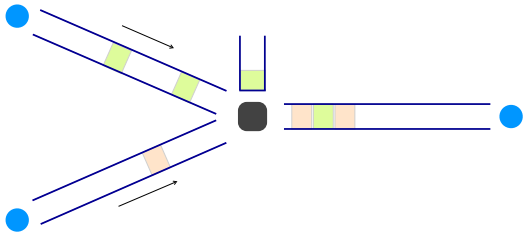


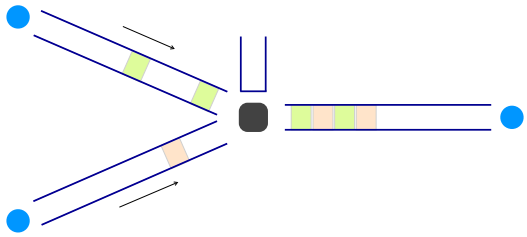
Queuing delay depends on the traffic pattern



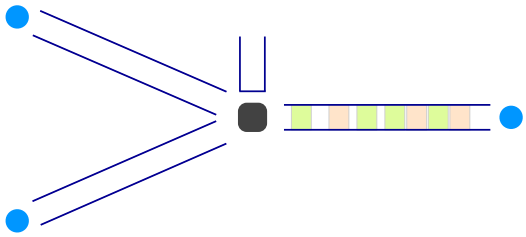








Queues absorb transient bursts,
but introduce queueing delays



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

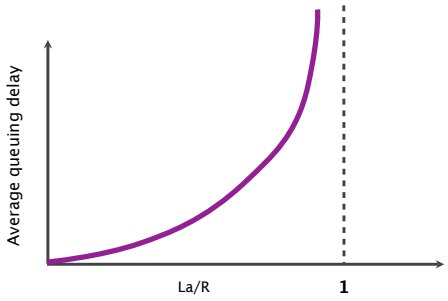
average packet arrival rate	a	[packet/sec]
transmission rate of outgoing link	R	[bit/sec]
fixed packets length	L	[bit]
average bits arrival rate	La	[bit/sec]
traffic intensity	La/R	

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

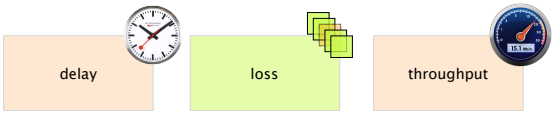
Golden rule

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

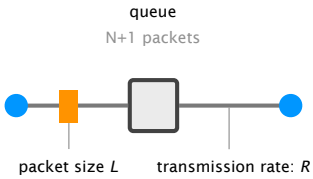
When the traffic intensity is <=1,
queueing delay depends on the burst size



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

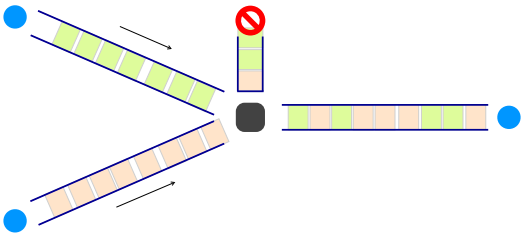


In practice, queues are not infinite.
There is an upper bound on queuing delay.



queuing delay upper bound: N*L/R

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

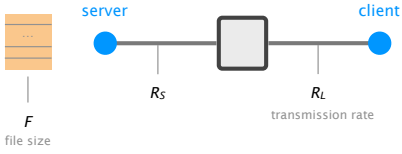


A network *connection* is characterized by
its delay, loss rate and throughput

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

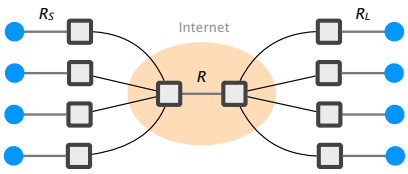
$$\text{Average throughput}\ [\#bits/sec] = \frac{\text{data size}\ [\#bits]}{\text{transfer time}\ [sec]}$$

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)

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

http://wwwnui.akamai.com/gnet/globe/index.html

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What is a network made of?

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How does communication happen?

How do we characterize it?

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?

This week

routing

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

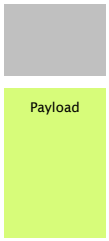
Next week

reliable delivery

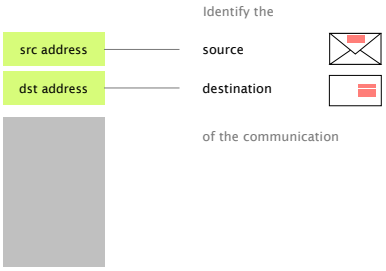
Think of **IP packets** as **envelopes**

Like an envelope,
packets have **a header**

Like an envelope,
packets have **a payload**

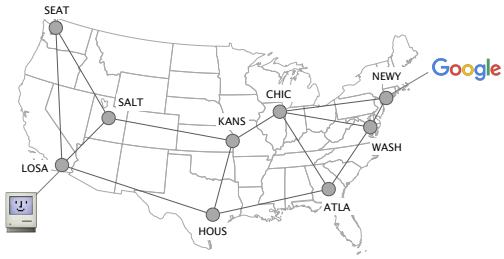


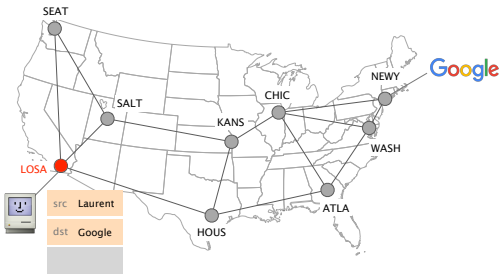
The **header** contains the **metadata**
needed **to forward** the packet

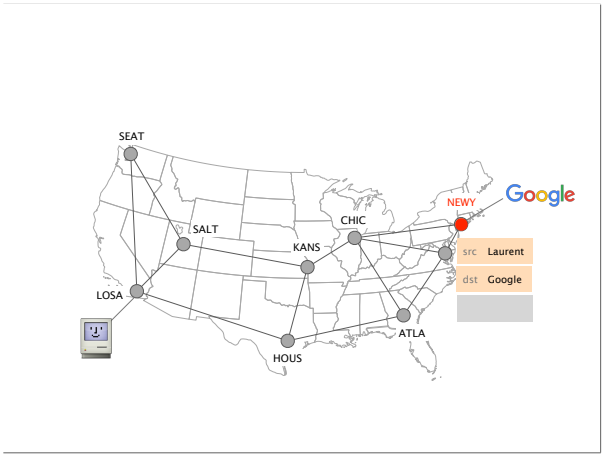


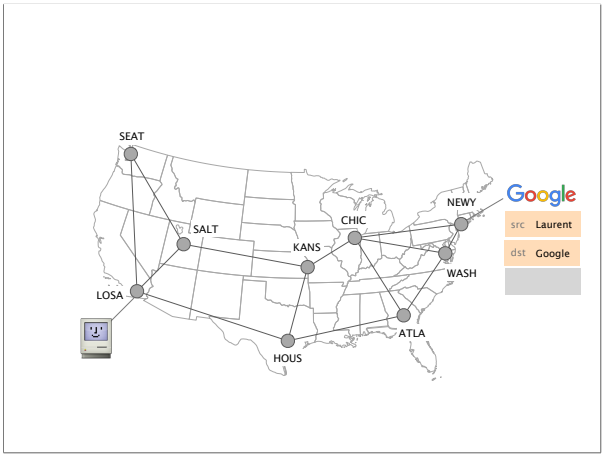
The **payload** contains
the **data to be delivered**

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



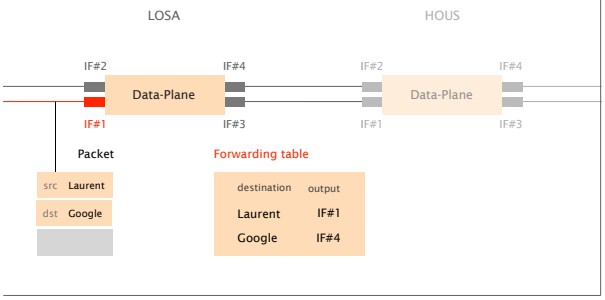




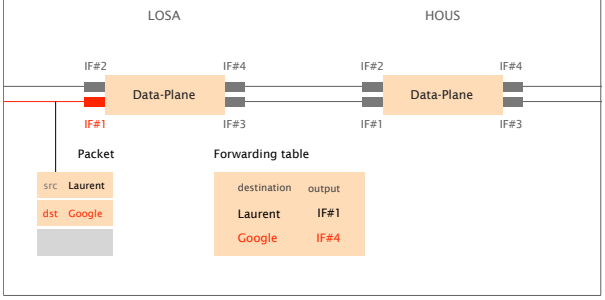


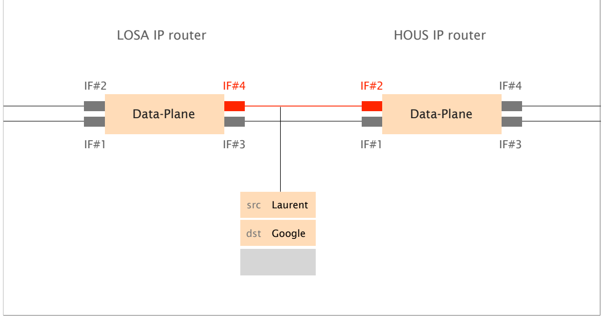
Let's zoom in on what is going on between **two adjacent routers**

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

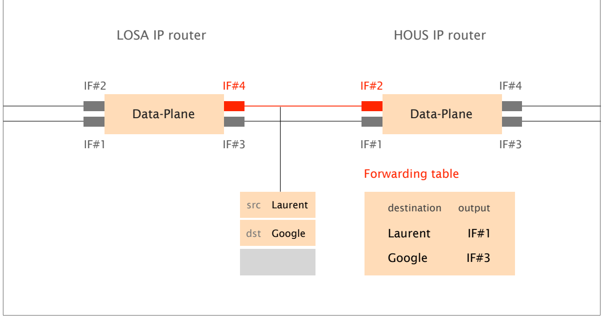


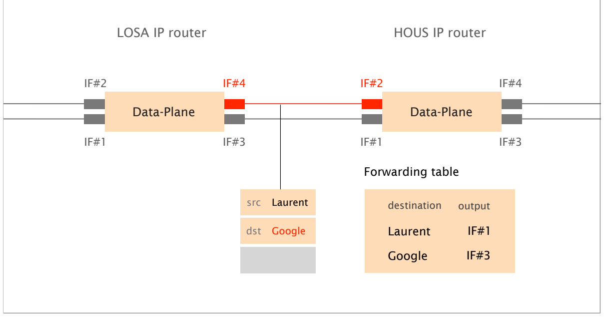
Here, the packet should be directed to IF#4

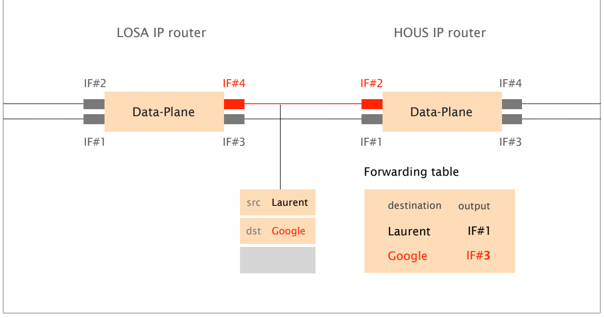


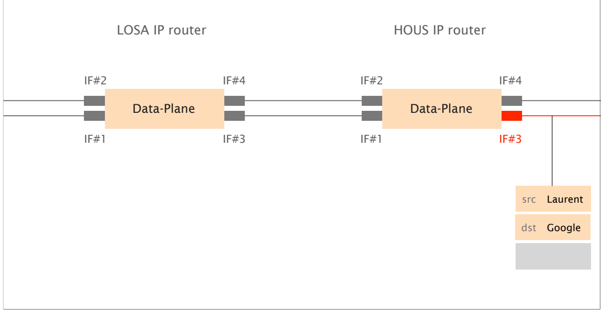


Forwarding is repeated at each router,
until the destination is reached









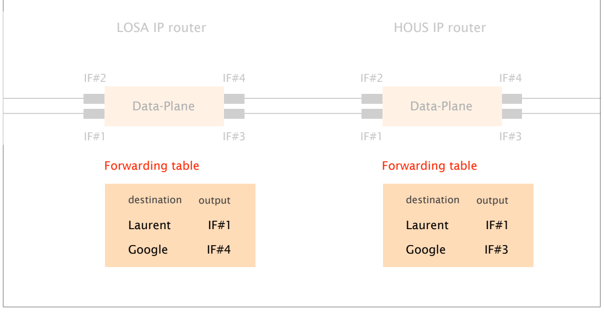
Forwarding decisions necessarily depend on
the destination, but can also depend on other criteria

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

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

the default in the Internet

Where are these forwarding tables coming from?

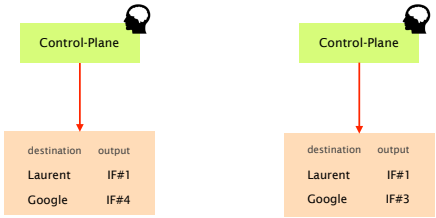


In addition to **a data-plane**,
routers are also equipped with **a control-plane**

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 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

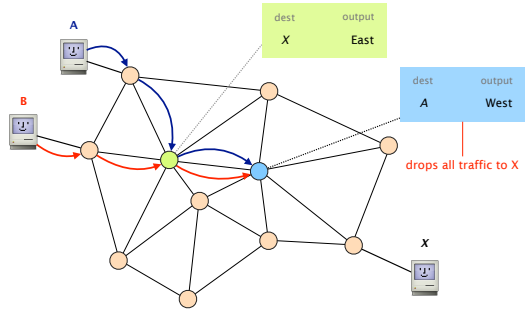
it always delivers packets
to the correct destination

sufficient and necessary condition

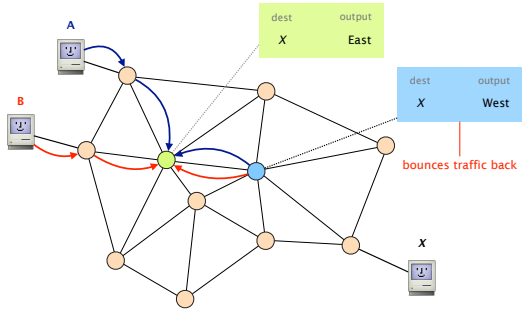
Theorem: a global forwarding state is valid if and only if

- 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



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