Now we take a look at the performance of the Internet (an Internet connection) and the factors that influence it.

ISP: Internet Service Provider

- Several Tier-1 ISPs across the world
  - treat each other as equals
  - earn revenue from smaller customer ISPs and customer edge networks

A Whirlwind Introduction to the Internet Overview

- What’s the Internet
- Network core
- Network edge
- Access nets, physical media
- Internet Structure & ISPs
- Performance: loss, delay
- Protocol layers, service models

Internet Structure: Network of Networks

- Roughly Hierarchical
- At center: “tier-1” ISPs (e.g., UUNet, Level 3, Sprint, AT&T), national/international coverage
  - treat each other as equals

Tier-1 providers also interconnect at public network access points (NAPs)

Tier 1 ISP

Tier 1 ISP

Tier 1 ISP

NAP
Internet Structure: Network of Networks

- "Tier-2" ISPs: smaller (often regional) ISPs
  - Connect to one or more tier-1 ISPs, possibly other tier-2 ISPs

- "Tier-3" ISPs and local ISPs
  - Last hop ("access") network (closest to end systems)

Local and tier-3 ISPs are customers of higher tier ISPs connecting them to rest of Internet
So how many ISPs do you think there are?

Network Maps

Just how big are Tier-1 ISPs…?
**OC (Optical carrier)**

- Units of ~ 52Mbps
- **OC-12**: 620 Mbps
- **OC-48**: 2.5 Gbps
- **OC-192**: 10 Gbps

So backbone (Tier-1) ISPs have 100s of hubs, and very fat and multiple fiber links connecting these.

Spans not just the US, but the rest of the world, with both Europe and Asia being major centers.
Lecture 1, Whirlwind Intro II

Green boxes going to leased line customers

2 OC-12 full-duplex links on either side

A high-speed backbone framework for interconnecting the customers and the OC-12s provided by:

• Several high-end blue CISCO routers,
• Four ultra-high-speed orange switching cores,
• and multiple high-speed fiber links.

Summary in a nutshell:

- Very big and diverse (vendors, speeds, topologies)

Now we take a look at the performance of the Internet (an Internet connection) and the factors that influence it.

A Whirlwind Introduction to the Internet Overview

- What’s the Internet
- Network core
- Network edge
- Access nets, physical media
- Internet Structure & ISPs
- Performance: loss, delay
- Protocol layers, service models
The Internet is a store-and-forward network. A primary measure of performance is end-to-end delay. End-to-end delay is the sum of the times spent storing and forwarding a packet at each hop in the network. The storing and forwarding can each be broken down into two sub-components. Processing delays in high-speed routers and typically on the order of microseconds or less. Queuing delays can be on the order of microseconds to milliseconds in practice. Queuing occurs since packets can arrive simultaneously on several input links if only one input link, what kind of queuing can occur? None. Which of these types of delays don’t occur in a circuit-switched network? (queuing, transmission --- other than at first node, processing) Let’s talk about each of these in some detail now. Let’s first consider transmission vs propagation delays, both of which remain constant for a given link… Note that for LANs, $\frac{L}{R} \gg \frac{d}{s}$. Transmission delays are typically on the order of microseconds to milliseconds in practice. Propagation delays in wide-area networks are on the order of milliseconds. 1KB packet on a 100Mbps link $\Rightarrow 8 \times 1000/100 \text{ us} = 80 \text{ us}$ What kind of bandwidths do you encounter on the Internet? Next slide …
Transmission Delay
Telecommunications transmission speed alphabet soup

- DS-1/T-1 = 1.544 Mbps
- DS-3/T-3 = 44.736 Mbps
- OC-1 = 51.84 Mbps
- OC-n = n \times OC-1
  - OC-3 = 3 \times OC-1 (155.52 Mbps)
  - OC-12 = 12 \times OC-1 (622.08 Mbps)
  - OC-48 = 48 \times OC-1 (2,488.32 Mbps/2.5 Gbps)
  - OC-192 = 192 \times OC-1 (9,953.28 Mbps/10 Gbps)

Transmission & Propagation Example
Transmission on a “slow” link

- Time = 0
  - 1,000,000 bytes to send
  - 1,544,000 bps (T-1)
  - 193 bytes/ms
  - 30 ms propagation latency

- Time = 10 ms
  - 998,070 bytes to send
  - 1,930 bytes in the link

- Time = 30 ms
  - 994,210 bytes to send
  - 5,790 bytes in the link

- Time = 5,181.4 ms
  - 0 bytes to send
  - 5,790 bytes in the link
  - 994,210 bytes received
So networks can be viewed as a storage medium. Every few years someone proposes building an ultra-high-speed network and using its carrying capacity as an information storage and distribution mechanism.

In animation,

- Set packet size to 500B: then try 10Mbps, and 1Mbps.
- Then set link length to 100km and try again 10Mbps.

Transmission delay and propagation delay are computable (in advance).

- Queuing delay is not.
  - (Processing delay likely is computable as well.)

Transmission delay is the time to put bits on the wire.

- For a Large (Ethernet MTU)-sized packet this is 1,500 x 8/1 x 10^8 µs/mile.

Propagation delay is more or less the speed of light times distance.

- Approximately 1 µs/mile, 25 ms for 3,000 miles.

Processing delay had better be less than transmission time!

- Queuing delay is unknown but is in multiples of the time to forward an average-sized packet.
  - Unlike the other three, queuing delay can vary from packet to packet.
    - e.g., when 10 packets arrive simultaneously, first one has 0 queuing delay, last one has a large queuing delay.
    - hence, talked about in terms of statistical measures (average, variance, probability of exceeding some value).
Queuing delay depends on:
- rate at which traffic arrives at the queue,
- transmission rate of the link,
- nature of arriving traffic (periodic vs. bursty)

To gain some insight, consider these 3 quantities: \( R, L, a \). And assume infinite buffers.

- When \( La/R < 1 \), only then the nature of arriving traffic impacts the queuing delay.
  - if periodic arrival, no queuing delays!
  - if periodic arrival of bursts of packets: \( N \) packets every \( LN/R \) seconds,
    - average queuing delay = \((N-1)/2 \cdot L/R \) seconds.
  - typical arrival processes are random (animation in next slide).
    - So this graph is merely a qualitative dependence graph.
  - Analogy to highway traffic (as traffic intensity approaches 1, delay increases more rapidly).
    - Small events such as traffic light changes, braking, etc., can increase delays tremendously.

General principles:
- Long-term average arrival rate must equal the transmission capacity of the link. " (Traffic intensity must be equal to 1.0.)
- Note that \( a \) is an average arrival rate. Bursty arrivals are still possible.

Packet loss
- Queue (buffer) preceding link in buffer has finite capacity
- When packet arrives to full queue, packet is dropped (lost)
- Lost packet may be retransmitted by source end system (connection-oriented like TCP), or not retransmitted at all (connection-less like UDP).

Per-Hop Delay ("nodal delay")

\[ d_{\text{nodal}} = d_{\text{proc}} + d_{\text{queue}} + d_{\text{trans}} + d_{\text{prop}} \]

- \( d_{\text{proc}} \) = processing delay
  » typically a few microsecs or less
- \( d_{\text{queue}} \) = queuing delay
  » depends on congestion
- \( d_{\text{trans}} \) = transmission delay
  » = L/R, significant for low-speed links
- \( d_{\text{prop}} \) = propagation delay
  » a few microsecs to hundreds of msecs

- What dominates end-to-end delay?
  » Processing, transmission, queuing delays encountered at each hop
  » End-to-end delay is largely a function of the number of routers encountered along the path from source to destination

Internet Traffic Measurements & Models

- Capture every TCP/IP packet header on Gigabit Ethernet link
- 1 Gbps Ethernet
- Monitor (tcpdump)
- 1 hour trace = 30+ GB file
- Store, sort, process terabytes of data
“Real” Internet delays and routes

- What do “real” Internet delay & loss look like?
- **Traceroute** program: provides delay measurement from source to router along end-to-end Internet path towards destination. For all $i$:
  - sends three packets that will reach router $i$ on path towards destination
  - router $i$ will return packets to sender
  - sender times interval between transmission and reply.
Seeing Paths and Delays in the Internet

- www.traceroute.org

Understanding the Performance of the Internet
Example: What is the delay to cs.utexas.edu?

```shell
>>> traceroute cs.utexas.edu
traceroute: Warning: cs.utexas.edu has multiple addresses; using 128.83.139.9
traceroute to cs.utexas.edu (128.83.139.9), 30 hops max, 38 byte packets
1 ciscokid-cs.net.unc.edu (152.2.31.1) [6.618 ms 0.355 ms 0.358 ms]
2 unc7600.internet.unc.edu (128.109.36.254) 0.412 ms 0.495 ms 0.473 ms
3 rtp7600-gw-to-unc7600-gw.ncrnet (128.109.70.33) 0.908 ms 0.941 ms 0.849 ms
4 nlr-atl-to-rtp7600.ncrnet (128.109.70.106) 10.669 ms 10.381 ms 10.273 ms
5 nlr-atl-to-rtp7600.ncrnet (128.109.70.106) 10.669 ms 10.381 ms 10.273 ms
6 nlr-atl-to-rtp7600.ncrnet (128.109.70.33) 0.908 ms 0.941 ms 0.849 ms
7 nlr-atl-to-rtp7600.ncrnet (128.109.70.106) 10.669 ms 10.381 ms 10.273 ms
8 nlr-atl-to-rtp7600.ncrnet (128.109.70.33) 0.908 ms 0.941 ms 0.849 ms
9 nlr-atl-to-rtp7600.ncrnet (128.109.70.106) 10.669 ms 10.381 ms 10.273 ms
10 cs.utexas.edu (128.83.139.9) 37.390 ms 37.245 ms 37.330 ms
```
Finally we take a look at the software and service architecture of the Internet.

We'll now go into more detail of the nuts-and-bolts and the services of the Internet.

So what is a protocol?

Main Entry: pro-to-col

1: An original draft, minute, or record of a document or transaction

2a: A preliminary memorandum often formulated and signed by diplomatic negotiators as a basis for a final convention or treaty

b: The records or minutes of a diplomatic conference or congress that show officially the agreements arrived at by the negotiators

3a: A code prescribing strict adherence to correct etiquette and precedence (as in diplomatic exchange and in the military services)

b: A set of conventions governing the treatment and especially the formatting of data in an electronic communications system

4: A detailed plan of a scientific or medical experiment, treatment, or procedure
The Nuts & Bolts View
What is a protocol?

- Human protocols:
  - “Do you have the time?”
  - “I have a question”
  - Introductions

- Network protocols:
  - Machines rather than humans
  - All communication activity in Internet governed by protocols

- Both:
  - Specific messages sent
  - Specific actions taken when messages (or other events) received

What is a protocol?
A specification for a set of message exchanges

- Example:
  - Human protocols: Get the time from a stranger
  - Computer protocols: Get the class time from a web server

Protocols define format, order of messages sent and received among network entities, and actions taken on message transmission, receipt

TCP connection request
TCP connection reply
Get http://www.cs.unc.edu/Admin/Schedules

Time

<web page>
To provide structure to the design of network protocols, network designers organize protocols (and the network hardware and software that implements the protocols) in layers. Each layer provides services to the layers above it — called as the service model of the layer. --- relies on the services of the layers below it.

Advantages:
--- modular design:
--- easy to change the implementation of a layer without changing any of the other layers,
--- as long as the APIs below and the services provided above remain the same.

Drawbacks of layering:
--- a layer may duplicate lower-layer functionality
--- functionality in one layer may need information present only in another layer
--- violates the goal of separation of layers.

Conceptually the Internet has a 5-layer stack.
--- There is a more complex and older stack model standardized (and little used) by the OSI that adds two layers below the Application Layer.
--- But the current model would like application designers to decide if they want that functionality, and if so, to implement it themselves (not much demand found for it …)

Some of these layers are implemented in hardware (e.g., on the network interface card); some are implemented in software.
--- And the implementations of some are distributed between end-systems, between end-systems and routers, and between routers (and between bridges and bridges).

The distinction between the link layer and the physical layer is that the former moves packets, the latter moves bits.
--- For example, Ethernet has (or runs over?) many physical layer protocols, one for each of the media Ethernet operates on.
--- But there is one link-layer protocol for Ethernet (and this is what the physical layer protocols all implement).

A Whirlwind Introduction to the Internet Protocol “Layers”

- Networks are complex!
  - Composed of many “pieces”
    - Hosts, routers, links of various media, applications, protocols, hardware, software
- Is there any hope of organizing the structure of the network?
  - Or at least organizing our discussion of networks?

  - Solution!
    - Decompose functions into a “stack” of function “layers”
    - Each layer provides well-defined “services” to the layer above it in the stack…
    - …and uses the services provided by the layer below it

  - Each layer can treat everything below it in the stack as a “black box”
All of these protocols are distributed in nature. None of the protocols work in isolation. Each is implemented only in conjunction and cooperation with the same layer in other nodes.

Important to remember that all the layers do not run at all nodes. Specifically, routers run (and use) only the bottom 3 layers (in their functionality as routers). Switched run (and use) only the bottom two layers. End-systems run and use all 5 layers. Each layer implements a logical channel abstraction. Just as in the airline example each layer implements a logical travel abstraction. Gives the illusion that a direct channel exists between the two communicating peer layers.
For example, consider logical communication in the transport layer. Here’s what happens in a typical transport layer transfer.

At which step is it assuming that there is a logical communication channel between the two communicating protocol peers?

— Send to peer transport layer
— Wait for peer transport layer to respond
— Peer transport delivers data to its application layer

Note again that not all nodes in the network implement (or even know about) all protocol layers. Switches in the network typically don’t know about anything above the network layer. — At most the highest-level function they are concerned with is routing. — Other network nodes such as bridges are dumber and are only concerned with forwarding packets to the destination on the same physical link. (They don’t even know about IP addresses for example.) Thus entities such as bridges are not visible to end-systems.
The messages exchanged by layers are called (technically) protocol data units or simply PDUs.

- In the Internet we give special names to the PDUs at each level in the stack.
- There’s no name for the physical layer PDU as this name depends on the physical layer technology being used.

Lots of good analogies here.

- The Post Office adds its own header to your letter (the bar code on the bottom of the envelope) but they don’t remove it!
- In general, you never worry about how the Post Office delivers your letter once it’s left your hands.
- In companies, internal billing information is imprinted on the letter and covered up by the final stamp.
- Non-Post Office routing information is included in the address for routing within the destination organization.

An important point is that at each intermediate node, a protocol layer can manipulate the corresponding header.

- So no two link layers headers are same in this figure.
- The network headers before and after the router are different.

Encapsulation Flow in Network Layers

Protocol Layering in the Internet

Protocol layering and data formats

- At sender, each layer takes data from above
  - Adds header information to create new data unit
  - Passes new data unit to layer below
- Process reversed at receiver
Protocol Layering in the Internet
Common logical functions in most layers

- Error control
  » Make the logical channel between layers reliable (or simply more reliable)
- Flow control
  » Avoid overwhelming a peer with data
- Segmentation and reassembly
  » Partitioning large messages into smaller ones at the sender and reassembling them at the receiver
- Multiplexing
  » Allowing several higher-level sessions to share a single lower-level connection
- Connection setup
  » Handshaking with a peer

Why Layering?
Dealing with complex systems

- Explicit structure allows identification, relationship of complex system’s pieces
  » Layered reference model for discussion
- Modularization eases maintenance, updating of system
  » Change of implementation of layer’s service transparent to rest of system
- Layering considered harmful?
A Whirlwind Introduction to the Internet

Summary

- Covered a “ton” of material
  - Internet overview
  - What’s a protocol?
  - Network edge, core, access network
  - ISPs
  - Performance: loss, delay
  - Layering and service models

- You now hopefully have:
  - Context, overview, “feel” of networking
  - More depth, detail later in course

- Something dangerous to mumble at parties!