Chapter 1: Introduction

Our goal:
- get "feel" and terminology
- more depth, detail later in course
- approach:
  - use Internet as example

Overview:
- what’s the Internet?
- what’s a protocol?
- network edge: hosts, access nets, physical media
- network core: packet/circuit switching, Internet structure
- performance: loss, delay, throughput
- protocol layers, service models
- security
- history

Chapter 1: roadmap

1.1 What is the Internet?
1.2 Network edge
   - end systems, access networks, links
1.3 Network core
   - circuit switching, packet switching, network structure
1.4 Delay, loss and throughput in packet-switched networks
1.5 Protocol layers, service models
1.6 Networks under attack: security
1.7 History
What's the Internet: “nuts and bolts” view

- billions of connected computing devices:
  - hosts = end systems
  - running network apps
- communication links
  - fiber, copper, coax, radio, satellite
  - transmission rate
- Routers and switches forward packets

What's the Internet: architecture & protocols

- Internet: “network of networks”
  - loosely hierarchical
  - public Internet versus private intranet
- protocols control sending, receiving of msgs
  - e.g., TCP, IP, HTTP, Skype, Ethernet
- Internet standards
  - RFC: Request for comments
  - IETF: Internet Engineering Task Force

What are required for global connectivity?
What's the Internet: a service view

- communication infrastructure enables distributed applications:
  - Web, VoIP, email, games, e-commerce, file sharing
- communication services provided to apps:
  - reliable data delivery from source to destination
  - "best effort" (unreliable) data delivery

What's a protocol?

- human protocols:
  - "what's the time?"
  - "I have a question"
  - introductions
- network protocols:
  - machines rather than humans
  - all communication activity in Internet governed by protocols

Protocols define format, order of msgs sent and received among network entities, and actions taken on msg transmission, receipt, or timeout
**What's a protocol?**

A human protocol and a computer network protocol:

- **Hi**
- **Hi**
- **Got the time?**
- **2:00**

**Q: Other human protocols?**

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**From physical media to communication channels—basic concepts (not in textbook)**
Modulation and Demodulation

- Common examples: radio, television channels for analog signals
  - Bandwidth in hertz

- Can also be used for digital signals (encoding binary data)

\[ A \cos(2\pi f_0 t + \theta) \]

Shannon's Theorem

\[ C = B \log_2 (1 + S/N) \]

where
- \( C \) max capacity in bits/sec
- \( B \) bandwidth in hertz
- \( S/N \) signal to noise ratio
FDM vs. TDM

Duration of frame (or superframe) is 125 μsec in digital telephone networks

TDM in Telephone Networks

- Why 125 μsec for frame duration?
- **Sampling Theorem:** An analog signal can be reconstructed from samples taken at a rate equal to twice the signal bandwidth
- Bandwidth for voice signals is 4 KHz; for high fidelity music, 22.05 KHz per channel
- Sampling rate for voice = 8000 samples/sec or one voice sample every 125 μsec
- Digital voice channel (uncompressed), 8 bits x 8000/sec = 64 Kbps
Other Multiplexing Techniques

- **Space division multiplex**
  - Same frequency used in different cables
  - Same frequency used in different (nonadjacent) cells

- **Wavelength division multiplex**
  - Light pulses sent at different wavelengths in optical fiber

- **Code division multiplex** (in chapter 6 of text)
  - e.g., CDMA for cell phones

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A closer look at network structure:

- **network edge:**
  - hosts: clients and servers
  - servers often in data centers

- **access networks, physical media:** wired, wireless communication links

- **network core:**
  - interconnected routers
  - network of networks

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Access net: digital subscriber line (DSL)

- use FDM in telephone line to central office DSLAM
  - data over DSL line goes to Internet
  - voice over DSL line goes to telephone net

- asymmetric bandwidths/transmission rates (data download much faster than upload)
Access net - hybrid fiber coax (HFC)

Data service
- homes share coax cable to cable headend
  (unlike DSL, which has dedicated access to central office)
- data channels have asymmetric rates and they are shared by homes - multiple access protocol required for uplink

Fiber to the home (Verizon, Google) - all optical switches

Access net: home network

wireless devices
often combined in single box
wireless access point
to/from headend or central office
cable or DSL modem
router, firewall, NAT
wired Ethernet

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Enterprise access networks (Ethernet)

- today, end systems typically connect into Ethernet switch
  - 10 Mbps, 100Mbps, 1Gbps, 10Gbps transmission rates
- A large enterprise network is connected to multiple ISPs
  - multi-homing

Wireless access networks

- shared wireless access network connects end system to router
  - via base station aka “access point”

wireless LANs:
  - within building (100 ft)
  - 802.11g/n/ac (WiFi)

wide-area wireless access
  - provided by telco (cellular) operators, 10's km
  - 3G, 4G: LTE
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The Network Core

- mesh of interconnected routers
- the fundamental question: how is data transferred through net?
  - circuit switching: dedicated circuit per call: telephone net
  - packet-switching: data sent thru net in discrete “chunks”
Network Core: Circuit Switching

End-to-end resources reserved for each “call”
- E.g., link bandwidth
  - FDM, TDM
- end-to-end circuit-like (guaranteed) performance
- call setup required
  - resource piece idle if not used by the call (no sharing)

Numerical example

- How long does it take to send a file of 640,000 bits from host A to host B over a circuit-switched network?
  - all links are 1.536 Mbps
  - each link uses TDM with 24 slots/sec (i.e., one slot per circuit)
  - 500 msec to establish end-to-end circuit

Let's work it out!
Packet Switching: Statistical Multiplexing

- Sequence of A & B packets does not have fixed pattern
- Bandwidth shared on demand → statistical multiplexing
- Queueing delay, packet loss

Network Core: Packet Switching

- Each end-end data stream divided into packets
- Packets of different users share network resources
- Each packet uses full link bandwidth
- Resource contention:
  - Aggregate resource demand can exceed amount available
  - Congestion: packets queue, wait for link use
  - Store and forward: packets move one hop at a time
    - Each node receives the complete packet before forwarding it
Disadvantage of store-and-forward

- takes \( L/R \) seconds to transmit (push out) a message of \( L \) bits into a link at \( R \) bps
- store and forward: entire message must arrive at router before it can be transmitted on next link

Example:
- \( L = 7.5 \) Mbits
- \( R = 1.5 \) Mbps
- End-to-end delay more than 15 seconds
- A file/message larger than maximum packet size is transmitted as multiple packets
Packet Switching versus Message Switching

Advantages of packet switching
- Smaller end-to-end delay from pipelining
- Less data loss from transmission errors

Disadvantages of packet switching
- More header bits
- Additional work to do segmentation and reassembly

Packet switching versus circuit switching
- 1 Mb/s link
- each user:
  - 100 kb/s when “active”
  - active 10% of time (a “bursty” user)
- circuit-switching:
  - 10 users
- packet switching:
  - with 35 users, probability > 10 active at same time is less than 0.0004
  - Q: how did we get value 0.0004?
Packet switching versus circuit switching

Is packet switching a “slam dunk winner?”

- great for bursty data
  - resource sharing
  - simpler, no call setup
- excessive congestion -> packet delay and loss
  - protocols needed for reliable data transfer, congestion control
- Q: How to provide circuit-like behavior?
  - bandwidth guarantees needed for
    - interactive audio/video apps
    - providing virtual links to enterprise network customers (under service contracts)

Network Taxonomy

Any technology can be used in link layer of Internet under IP

VC examples: ATM networks, MPLS tunnels

Internet won!
Internet structure: network of networks

- End systems connect to Internet via access ISPs (Internet Service Providers)
  - Residential, company, and university ISPs

- Access ISPs in turn must be interconnected
  - so that any two hosts can send packets to each other

- Resulting network of networks is very complex
  - Evolution of today’s network was driven by economics and national policies

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Question: given millions of access ISPs, how to connect them together?
Internet structure: network of networks

Option: connect each access ISP to every other access ISP?

connecting each access ISP to each other directly doesn’t scale: \( O(N^2) \) connections.

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Internet structure: network of networks

Option: connect each access ISP to a global transit ISP:
1. Financed by US government: DARPAnet, NSFnet
2. Customer and provider ISP have an economic agreement?

global ISP

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But if one global ISP is viable business, there will be competitors....
Tier-1 ISP: e.g., Sprint

Internet structure: network of networks

... and regional networks may arise to connect access nets to ISPs
Internet structure: network of networks

... and a content provider network (e.g., Akamai, Google, Microsoft) may run its own network to bring services, content close to end users

- at center: small # of well-connected large networks
  - “tier-1” commercial ISPs (e.g., Level 3, Sprint, AT&T, NTT), national & international coverage
  - content provider networks (e.g., Google): private network that connects its data centers to Internet, often bypassing tier-1 and regional ISPs
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How do loss and delay occur?

- packet arrival rate to link temporarily exceeds output link capacity
- packets queue, wait for turn

Free (available) buffers: arriving packets dropped (loss) if no free buffers
Four sources of packet delay

- 1. nodal processing:
  - check bit errors
  - determine output link

- 2. queueing
  - time waiting at output link for transmission
  - depends on congestion level of router

Delay in packet-switched networks

3. Transmission delay:
   - \( R \): link bandwidth (bps)
   - \( L \): packet length (bits)
   - time to send bits into link = \( L/R \)

4. Propagation delay:
   - \( d \): length of physical link
   - \( s \): propagation speed in medium (~2×10^8 m/sec)
   - propagation delay = \( d/s \)

Note: \( s \) and \( R \) are very different quantities!
**End-to-End Delay**

- **Nodal delay** (from when last bit of packet arrives at this node to when last bit arrives at next node)
  \[ d_{nodal} = d_{proc} + d_{queue} + d_{trans} + d_{prop} \]

- **End-to-end delay over** \( N \) **identical nodes/links from client** \( c \) **to server** \( s \) (**from when last bit of packet leaves client to when last bit arrives at server**)  
  \[ d_{c-s} = d_{prop} + Nd_{nodal} \]

- **Round trip time (RTT)**
  \[ RTT = d_{c-s} + d_{s-c} + t_{server} \]
  where \( t_{server} \) is server processing time

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**“Real” Internet delays and routes**

- What do “real” Internet delay & loss look like?

  - **traceroute program**: provides delay measurement from source to router along end-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.

![traceroute diagram]
"Real" Internet delays and routes

traceroute: gaia.cs.umass.edu to www.eurecom.fr

Three delay measurements from gaia.cs.umass.edu to cs-gw.cs.umass.edu

1  cs-gw (128.119.240.254)  1 ms 1 ms  2 ms
2  border1-at-fa5-1-0.gw.umass.edu (128.119.3.145) 1 ms 1 ms  2 ms
3  cht-vbns.gw.umass.edu (128.119.3.130)  6 ms 5 ms  5 ms
4  jn1-at1-0-0-19.wor.vbns.net (204.147.132.129) 16 ms 11 ms 13 ms
5  jn1-so7-0-0-0.wae.vbns.net (204.147.136.136) 21 ms 18 ms 18 ms
6  abilene-vbns.abilene.ucaid.edu (198.32.11.9)  22 ms 18 ms 22 ms
7  nycm-wash.abilene.ucaid.edu (198.32.8.46)  22 ms 22 ms 22 ms
8  62.40.103.253 (62.40.103.253)  104 ms 109 ms 106 ms
9  de2-1.de1.de.geant.net (62.40.96.129) 109 ms 102 ms 104 ms
10  de.fr1.fr.geant.net (62.40.96.50)  113 ms 121 ms 114 ms
11  renater-gw.fr1.fr.geant.net (62.40.103.54) 112 ms 114 ms 112 ms
12  nio-n2.cssi.renater.fr (193.51.206.13) 111 ms 114 ms 116 ms
13  nice.cssi.renater.fr (195.220.98.102) 123 ms 125 ms 124 ms
14  r3t2-nice.cssi.renater.fr (195.220.98.110) 126 ms 126 ms 124 ms
15  eurecom-valbonne.r3t2.ft.net (193.48.50.54) 135 ms 128 ms 133 ms
16  194.214.211.25 (194.214.211.25) 126 ms 128 ms 126 ms
17  * * *
18  * * *
19  fantasia.eurecom.fr (193.55.113.142) 132 ms 128 ms 136 ms

* means no response (probe lost, router not replying)

Queueing delay (waiting time)

- R: link bandwidth (bps)
- L: packet length (bits)
  - service rate = R/L (pkts/sec)
- λ: packet arrival rate
  - traffic intensity = arrival rate/service rate = λL/R
- λL/R ~ 0: average queueing delay small
- λL/R → 1: delays become large
- λL/R > 1: more "work" arriving than can be served, average delay infinite!
  - In reality, buffer overflow when λL/R → 1
Packet loss

- buffer in router for each link has finite capacity
- lost packet may be retransmitted by previous node, by source end system, or not at all

Throughput - rate at which bits are transferred from source to destination (in bits/sec.)

- $R_s < R_c$  
  end-end throughput less than $\text{____?}$

- $R_s > R_c$  
  end-end throughput less than $\text{____?}$

bottleneck link

link on end-end path that constrains end-end throughput
Throughput: Internet scenario

- Per-connection end-to-end throughput is approximately $\min(R_c, R_s, R/10)$.
  - Actually sharing a bottleneck equally is ideal but unrealistic.

- In practice: $R_c$ or $R_s$ is often the bottleneck.
- Or the server is the bottleneck.

10 connections (fairly) share backbone bottleneck link $R$ bits/sec

Little’s law and a useful queueing delay formula

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**Little’s Law**

**Average population**

\[ \text{average population} = (\text{average delay}) \times (\text{throughput rate}) \]

**Throughput rate**

\[ \text{throughput rate} = \frac{N}{T} \]

Where \( N \) is the number of departures and \( T \) is the duration of the experiment.

**Average delay**

\[ \text{average delay} = \frac{1}{N} \sum_{i=1}^{N} \text{delay}_i \]

Where \( N \) is the number of departures.

**Average population**

\[ \text{average population} = \frac{1}{\tau} \int_{0}^{\tau} n(t) \, dt \]

Where \( \tau \) is the duration of the experiment.
random variable $x$

samples $x_1, x_2, \ldots, x_n$

mean (average) $\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i$

second moment $\bar{x}^2 = \frac{1}{n} \sum_{i=1}^{n} (x_i)^2 \geq (\bar{x})^2$

mean residual life $= \frac{\bar{x}^2}{2\bar{x}} \geq \frac{\bar{x}}{2}$

Special case: $x$ is a constant

$\bar{x}^2 = (\bar{x})^2$

mean residual life $= \frac{(\bar{x})^2}{2\bar{x}} = \frac{\bar{x}}{2}$

---

random variable $x$

with discrete values $x_1, x_2, \ldots, x_m$

let $p_i = \text{probability } [x = x_i]$ for $i = 1, 2, \ldots, m$

by definition

mean $\overline{x} = \sum_{i=1}^{m} x_i p_i$

second moment $\overline{x^2} = \sum_{i=1}^{m} x_i^2 p_i$

(Aside: For a continuous random variable, use integration instead of summation.)

2/3/2016
**Single-Server Queue**

\[ \lambda \rightarrow \text{queue} \quad \mu \rightarrow \text{server} \]

- $\bar{x}$: average service time, in seconds
- $\mu$: service rate, in jobs/second ($\mu = 1/\bar{x}$)
- $\lambda$: arrival rate, in jobs/second
- $\rho$: utilization of server

**Conservation of flow**

\[ \lambda = \rho \mu \]
\[ \rho = \frac{\lambda}{\mu} = \frac{1}{\bar{x}} \]

---

**M/G/1 queue**

- **Single server**
  - does not idle when there is work, no overhead, i.e., it performs 1 second of work per second
  - FIFO service
- **Arrivals according to a Poisson process at rate $\lambda$ jobs/second**
- **Service times of arrivals are $x_1, x_2, \ldots, x_i \ldots$ which are independent, identically distributed (with a general distribution)**
- **Average service time is $\bar{x}$, average wait is $W$, average delay is $T = W + \bar{x}$**
Let $U(t)$ be the unfinished work at time $t$

\[ U(t) \]

**Derivation of $W$**

Time average of unfinished work is

\[
\overline{U} = \frac{1}{\tau} \int_{0}^{\tau} U(t) dt
\]

\[
= \frac{1}{\tau} \left( \frac{1}{2} \sum_{i=1}^{n} x_i^2 + \sum_{i=1}^{n} x_i w_i \right) \quad \text{x_i and w_i are independent}
\]

\[
= \frac{n}{\tau} \left( \frac{1}{2} \bar{x}_i^2 + \bar{x}_i \bar{w}_i \right) \quad \text{where } \bar{x}_i w_i = \bar{x}_i \times \bar{w}_i
\]

For Poisson arrivals, the average wait is equal to $\overline{U}$ from the *Poisson arrivals see time average (PASTA)* Theorem
Derivation of $W$ (cont.)

- The average wait is

$$W = \lambda\left(\frac{1}{2}x^2 + xW\right) = \frac{\lambda x^2}{2} + \lambda x W = \frac{\lambda x^2}{2} + \rho W$$

$$W(1 - \rho) = \frac{\lambda x^2}{2}$$

$$W = \frac{\lambda x^2}{2(1 - \rho)}$$

Pollaczek-Khinchin (P-K) mean value formula

Average delay is

$$T = \bar{x} + W = \bar{x} + \frac{\lambda \bar{x}^2}{2(1 - \rho)}$$

Also called Pollaczek-Khinchin (P-K) mean value formula
**Special Cases**

1. Service times have an exponential distribution (\(\text{M/M/1}\)). We then have
   \[
   \bar{x}^2 = 2(\bar{x})^2
   \]
   \[
   W = \frac{\lambda(2)(\bar{x})^2}{2(1 - \rho)} = \frac{\lambda(\bar{x})^2}{1 - \rho} = \frac{\rho \bar{x}}{1 - \rho}
   \]
   \[
   T = W + \bar{x}
   \]
   \[
   = \frac{\rho \bar{x}}{1 - \rho} + \bar{x} = \frac{\rho \bar{x} + \bar{x} - \rho \bar{x}}{1 - \rho}
   \]
   \[
   = \frac{\bar{x}}{1 - \rho} = \frac{\rho - 1}{1 - \rho} \frac{1}{\lambda}
   \]

   T decreases as \(\lambda\) increases

   \[
   \lambda \to 10\lambda
   \]
   \[
   \mu \to 10\mu
   \]
   \[
   \rho = \frac{10\lambda}{10\mu} = \frac{\lambda}{\mu}
   \]

2. Service times are constant (deterministic)

   \[
   \bar{x}^2 = (\bar{x})^2
   \]
   \[
   W = \frac{\lambda(\bar{x})^2}{2(1 - \rho)} = \frac{\rho \bar{x}}{2(1 - \rho)}
   \]
   \[
   T = \frac{\rho \bar{x}}{2(1 - \rho)} + \bar{x} = \frac{(\rho + 2 - 2\rho)\bar{x}}{2(1 - \rho)}
   \]
   \[
   T = \frac{\rho(2 - \rho)}{2(1 - \rho)} \frac{1}{\lambda}
   \]

   T decreases as \(\lambda\) increases
Two Servers and Two Queues:

60 jobs/sec → 100 jobs/sec

60 jobs/sec → 100 jobs/sec

Single Higher Speed Server:

120 jobs/sec → 200 jobs/sec

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Layered architecture

- as reference model for protocol design by community effort
  - decompose a large system into smaller pieces which can be designed and implemented by different people/teams
- modularity eases maintenance and evolution of system
  - allows changes in implementation method so long as API remains the same, e.g., different Ethernet technologies
- strict layering often violated for efficient protocol implementation
  - cross-layer design

Each protocol

- involves two or more peers
- two kinds of specifications
  - service interface: operations a local user can perform on a protocol entity and get results
  - peer-to-peer protocol: format and meaning of messages exchanged by protocol entities (also called peers) to provide protocol service
- The term "protocol" generally refers to peer-to-peer spec
Internet protocol stack

- **application**: protocols that support network applications
  - FTP, SMTP, HTTP
- **transport**: process-process data transfer
  - TCP, UDP
- **network**: routing of datagrams from source to destination
  - IP, routing protocols
- **link**: data transfer between neighboring network elements
  - PPP, Ethernet, 802.11 (WiFi)
- **physical**: bits "on the wire"

ISO/OSI reference model

- **presentation**: allow applications to interpret meaning of data, e.g., encryption, compression, machine-specific conventions
- **session**: synchronization, checkpointing, recovery of data exchanged
- Internet stack “missing” these layers!
  - these services, if needed, must be implemented in application (or application protocol)
  - very wise decision for ARPAnet!
Internet Architecture

- Internet Engineering Task Force (IETF)
- application protocols support applications
- multiplexing and demultiplexing
- hourglass shape (only IP in network layer)
  - best effort service => any delivery service can be used by IP
- limitation of hourglass

Encapsuation

- Protocol peers provide a data delivery service
- How do protocol peers in different machines exchange protocol messages between themselves?
  - In protocol header encapsulated and de-encapsulated
Logical communication between peers

E.g.: transport
- accept data from application
- add addressing, reliability check info to form a message
- send message to peer via a delivery service
- wait for peer’s reply (ack)

Physical path of data

Each layer takes data (service data unit) from above
- adds header to create its own protocol data unit
- passes protocol data unit to layer below

Note A: In the past, a switch implements only two layers (physical and link). Nowadays many switches function as routers (3 layers)
Note B: layer 2½ possible
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End of Chapter 1