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
- network core
- access net, physical media
- Internet/ISP structure
- performance: loss, delay
- protocol layers, service models
- network modeling
Chapter 1: roadmap

1.1 What is the Internet?
1.2 Network edge
1.3 Network core
1.4 Network access and physical media
1.5 Internet structure and ISPs
1.6 Delay & loss in packet-switched networks
1.7 Protocol layers, service models
1.8 History
What’s the Internet: “nuts and bolts” view

- millions of connected computing devices: *hosts* = *end systems*
- running *network apps*
- *communication links*:
  - fiber, copper, radio, satellite
  - transmission rate = *bandwidth*
- *routers*: forward packets (chunks of data)
“Cool” internet appliances

IP picture frame
http://www.ceiva.com/

World’s smallest web server
http://www-ccs.cs.umass.edu/~shri/iPic.html

Web-enabled toaster + weather forecaster

Internet phones
What’s the Internet: “nuts and bolts” view

- **protocols** coordinate exchange of messages:
  - Who gets to transmit?
  - What path to take?
  - What message format?
  - How to respond to failure?
  - e.g., TCP, IP, HTTP, FTP, PPP

- **Internet: “network of networks”**
  - loosely hierarchical
  - public Internet Vs private intranet

- Internet standards
  - RFC: Request for comments
  - IETF: Internet Engineering Task Force
What’s the Internet: a service view

- Communication infrastructure enables distributed applications:
  - Web, email, games, e-commerce, file sharing

- Communication services provided to apps:
  - Connectionless unreliable
  - Connection-oriented reliable

Can you give an analogy of this in real life services
What’s a protocol?

**human protocols:**
- “what’s the time?”
- “I have a question”
- introductions

  ... specific msgs sent

  ... specific actions taken when msgs received, or other events

**network protocols:**
- machines rather than humans
- all communication activity in Internet coordinated by protocols

  protocols define format, order of msgs sent and received among network entities, and actions taken on msg transmission, receipt
What’s a protocol?

a human protocol and a computer network protocol:

Q: This one trivial. Can u think of a more complex case?
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A closer look at network structure:

- **network edge:** applications and hosts

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

- **access networks, physical media:** communication links
The network edge:

- end systems (hosts):
  - run application programs
  - e.g. Web, email

- client/server model
  - client host requests, receives service from always-on server
  - e.g. Web browser/server; email client/server

- peer-peer model:
  - minimal use of dedicated servers
  - e.g. Skype, BitTorrent, KaZaA
Network edge: connection-oriented service

**Goal:** data transfer between end systems

- **Connection:** prepare for data transfer ahead of time
  - Request / Respond
  - *set up “state”* in two communicating hosts

- **TCP - Transmission Control Protocol**
  - Internet’s connection-oriented service

**TCP service** [RFC 793]

- **reliable, in-order byte-stream data transfer**
  - loss: acknowledgements and retransmissions

- **flow control:**
  - sender won’t overwhelm receiver

- **congestion control:**
  - senders “slow down sending rate” when network congested
Network edge: connectionless service

**Goal:** data transfer between end systems
  - same as before!

- **UDP - User Datagram Protocol [RFC 768]:**
  - connectionless
  - unreliable data transfer
  - no flow control
  - no congestion control

**App’s using TCP:**
- HTTP (Web), FTP (file transfer), Telnet (remote login), SMTP (email)

**App’s using UDP:**
- streaming media, teleconferencing, DNS, Internet telephony
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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-end resources reserved for “call”

- link bandwidth, switch capacity
- dedicated resources: no sharing
- circuit-like (guaranteed) performance
- call setup required

Analogy: When president travels, a CS path set up.
Network Core: Circuit Switching

network resources (e.g., bandwidth) divided into “pieces”

- pieces allocated to calls

- resource piece *idle* if not used by owning call (*no sharing*)

- dividing link bandwidth into “pieces”
  - frequency division
  - time division
Circuit Switching: FDM and TDM

FDM

Example:
4 users

TDM
FDM Vs TDM

- What are the tradeoffs?
  - (Dis)Advantage of dividing frequency?
  - (Dis)Advantage of dividing time?
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
- 500 msec to establish end-to-end circuit

Let’s work it out!
Another 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 FDM with 24 channels (frequencies)
  - 500 msec to establish end-to-end circuit

Let’s work it out!
Network Core: Packet Switching

Each end-end data stream divided into packets
- User A, B packets share network resources
- Each packet uses full link bandwidth
- Resources used as needed

Resource contention:
- Aggregate resource demand can exceed amount available
  - Packets queue up

Store and forward:
- Packets move one hop at a time
  - Node receives complete packet before forwarding

Bandwidth division into “pieces”
- Dedicated allocation
- Resource reservation
Packet Switching: Statistical Multiplexing

Sequence of A & B packets does not have fixed pattern, shared on demand ⇒ statistical multiplexing.

TDM: each host gets same slot in revolving TDM frame.
Compare

Thoughts on tradeoffs between packet switching and circuit switching?

Which one would you take?

Under what circumstances?

Why?
Packet switching versus circuit switching

Packet switching allows more users to use network!

- 1 Mb/s link
- each user:
  - 100 kb/s when "active"
  - active 10% of time
- circuit-switching:
  - 10 users
- packet switching:
  - with 35 users, probability > 10 active less than .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 reliability, congestion control

- Q: How to provide circuit-like behavior?
  - bandwidth guarantees needed for audio/video apps
  - still unsolved (chapter 7)
Packet-switching: store-and-forward

- Takes L/R seconds to transmit (push out) packet of L bits on to link or R bps
- Entire packet must arrive at router before it can be transmitted on next link: store and forward
- delay = 3L/R (assuming zero propagation delay)

Example:
- L = 7.5 Mbits
- R = 1.5 Mbps
- delay = 15 sec

more on delay shortly ...
Packet-switched networks: forwarding

- **Goal:** move packets through routers from source to destination
  - we’ll study several path selection (routing) algorithms (chap 4)

- **datagram network:**
  - *destination address* in packet determines next hop
  - routes may change during session
  - analogy: driving, asking directions

- **virtual circuit network:**
  - packet carries tag (virtual circuit ID), tag determines next hop
  - fixed path determined at *call setup time*, remains fixed thru call
  - *routers maintain per-call state*
Network Taxonomy

- Circuit-switched networks
  - FDM
  - TDM

- Packet-switched networks
  - Networks with VCs
  - Datagram Networks

- Datagram network is *not* either connection-oriented or connectionless.
- Internet provides both connection-oriented (TCP) and connectionless services (UDP) to apps.
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Access networks and physical media

Q: How to connect end systems to edge router?

- residential access nets
- institutional access networks (school, company)
- mobile access networks

Keep in mind:

- bandwidth (bits per second) of access network?
- shared or dedicated?
Residential access: point to point access

- Dialup via modem
  - up to 56Kbps direct access to router (often less)
  - Can’t surf and phone at same time: can’t be “always on”

- **ADSL**: asymmetric digital subscriber line
  - up to 1 Mbps upstream (today typically < 256 kbps)
  - up to 8 Mbps downstream (today typically < 1 Mbps)
  - **FDM**: 50 kHz - 1 MHz for downstream
    - 4 kHz - 50 kHz for upstream
    - 0 kHz - 4 kHz for ordinary telephone
Residential access: cable modems

- HFC: hybrid fiber coax
  - asymmetric: up to 30Mbps downstream, 2 Mbps upstream

- network of cable and fiber attaches home to ISP router
  - homes share access to router

- deployment: available via cable TV companies
Residential access: cable modems

Diagram: http://www.cabledatacomnews.com/cmic/diagram.html
Cable Network Architecture: Overview

Typically 500 to 5,000 homes
Cable Network Architecture: Overview
Cable Network Architecture: Overview
**Cable Network Architecture: Overview**

**FDM:**

- **cable headend**
- **cable distribution network**
- **home**

**Channels:**

1. V V V V V V V V V
2. I I I I I I I I D D D T
3. D D D D D D D A A R
4. E E E E E E E T T O
5. O O O O O O O A A L
DSL vs Cable Modem

- DSL is point to point
  Thus data rate does not reduce when neighbor uses his/her DSL

- But, DSL uses twisted-pair, and transmission technology cannot support more than ~10Mbps

- Cable Modems share the pipe to the cable headend.
  Thus, your data rate can reduce when neighbors are surfing concurrently

- However, fibre optic lines have significantly higher data rate (fat pipe)
  Even if other users, data rate may still be higher

The debate / competition continues …
Company access: local area networks

- Company/univ local area network (LAN) connects end system to edge router

- Ethernet:
  - shared or dedicated link connects end system and router
  - 10 Mbs, 100Mbps, Gigabit Ethernet

- LANs: chapter 5
Wireless access networks

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

- wireless LANs:
  - 802.11b/g (WiFi): 11 or 54 Mbps

- wider-area wireless access
  - provided by telco operator
  - 3G ~ 384 kbps
    - Will it happen??
  - GPRS in Europe/US
Home networks

Typical home network components:
- ADSL or cable modem
- router/firewall/NAT
- Ethernet
- wireless access point

![Diagram of home network components](image-url)
Physical Media

- **Bit**: propagates between transmitter/rcvr pairs

- **Physical link**: what lies between transmitter & receiver

- **Guided media**:
  - signals propagate in solid media: copper, fiber, coax

- **Unguided media**:
  - signals propagate freely, e.g., radio

**Twisted Pair (TP)**

- **Two insulated copper wires**
  - Category 3: traditional phone wires, 10 Mbps Ethernet
  - Category 5: 100Mbps Ethernet
Physical Media: coax, fiber

Coaxial cable:
- two concentric copper conductors
- bidirectional
- baseband:
  - single channel on cable
  - legacy Ethernet
- broadband:
  - multiple channels on cable
  - HFC

Fiber optic cable:
- glass fiber carrying light pulses, each pulse a bit
- high-speed operation:
  - high-speed point-to-point transmission (e.g., 10’s-100’s Gps)
- low error rate: repeaters spaced far apart; immune to electromagnetic noise
Physical media: radio

- signal carried in electromagnetic spectrum
- no physical “wire”
- bidirectional
- propagation environment effects:
  - reflection
  - obstruction by objects
  - interference

Radio link types:
- terrestrial microwave
  - e.g. up to 45 Mbps channels
- LAN (e.g., Wifi)
  - 11Mbps, 54 Mbps
- wide-area (e.g., cellular)
  - e.g. 3G: hundreds of kbps
- satellite
  - Kbps to 45Mbps channel (or multiple smaller channels)
  - 270 msec end-end delay
  - geosynchronous versus low altitude
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Internet structure: network of networks

- roughly hierarchical
- at center: “tier-1” ISPs (e.g., MCI, Sprint, AT&T, Cable and Wireless), national/international coverage
  - treat each other as equals

Tier-1 providers interconnect (peer) privately

Tier-1 providers also interconnect at public network access points (NAPs)
Tier-1 ISP: e.g., Sprint

Sprint US backbone network

POP: point-of-presence

to/from backbone

peering

to/from customers

1. Tier-1 ISP: e.g., Sprint

2. Sprint US backbone network

3. POP: point-of-presence

4. to/from backbone

5. peering

6. to/from customers
“Tier-2” ISPs: smaller (often regional) ISPs
- Connect to one or more tier-1 ISPs, possibly other tier-2 ISPs
Internet structure: network of networks

- “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
Internet structure: network of networks

- a packet passes through many networks!
- local (taxi) $\rightarrow$ T1 (bus) $\rightarrow$ T2 (domestic) $\rightarrow$ T3 (international)
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How do loss and delay occur?

- packets \textit{queue} in router buffers
  - packet arrival rate to link exceeds output link capacity
  - packets queue, wait for turn

- packet being transmitted \textit{(delay)}

- packets queuing \textit{(delay)}

- free (available) buffers: arriving packets dropped \textit{(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 ($\approx 2 \times 10^8$ m/sec)
   - propagation delay = $d/s$

Note: $s$ and $R$ are very different quantities!
Caravan analogy

- Cars “propagate” at 100 km/hr
- Toll booth takes 12 sec to service a car (transmission time)
- car~bit; caravan ~ packet
- Q: How long until caravan is lined up before 2nd toll booth?

- Time to “push” entire caravan through toll booth onto highway = 12*10 = 120 sec
- Time for last car to propagate from 1st to 2nd toll both: 100km/(100km/hr)= 1 hr
- A: 62 minutes
Caravan analogy (more)

- Cars now “propagate” at 1000 km/hr
- Toll booth now takes 1 min to service a car
- Q: Will cars arrive to 2nd booth before all cars serviced at 1st booth?
  - Yes! After 7 min, 1st car at 2nd booth and 3 cars still at 1st booth.
  - 1st bit of packet can arrive at 2nd router before packet is fully transmitted at 1st router!
    - See Ethernet applet at AWL Web site
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
Queueing delay (revisited)

- \( R = \) link bandwidth (bps)
- \( L = \) packet length (bits)
- \( a = \) average packet arrival rate

Traffic intensity = \( \frac{L \cdot a}{R} \)

- \( \frac{L \cdot a}{R} \approx 0 \): average queueing delay small
- \( \frac{L \cdot a}{R} \to 1 \): delays become large
- \( \frac{L \cdot a}{R} > 1 \): more “work” arriving than can be serviced, average delay infinite!
“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.
"Real" Internet delays and routes

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

1  cs-gw (128.119.240.254)  1 ms  1 ms  2 ms
2  border1-rt-fa5-1-0.gw.umass.edu (128.119.3.145)  1 ms  1 ms  2 ms
3  cht-vbns.gw.umass.edu (128.119.3.145)  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.ual.edu (198.32.11.9)  22 ms  18 ms  22 ms
7  nycm-wash.abilene.ual.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  *** *means no response (probe lost, router not replying*
19 fantasia.eurecom.fr (193.55.113.142)  132 ms  128 ms  136 ms
Packet loss

- queue (aka buffer) preceding link has finite capacity

- when packet arrives to full queue, packet is dropped (aka lost)

- lost packet may be retransmitted by previous node, by source end system, or not retransmitted at all
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Protocol “Layers”

Networks are complex!

- many “pieces”:
  - hosts
  - routers
  - links of various media
  - applications
  - protocols
  - hardware, software

Question:
Is there any hope of organizing structure of network?

Or at least our discussion of networks?
### Organization of air travel

- **ticket (purchase)**
- **baggage (check)**
- **gates (load)**
- **runway takeoff**
- **airplane routing**

- **ticket (complain)**
- **baggage (claim)**
- **gates (unload)**
- **runway landing**
- **airplane routing**

- a series of steps
Layering of airline functionality

<table>
<thead>
<tr>
<th>ticket (purchase)</th>
<th>ticket (complain)</th>
<th>ticket</th>
</tr>
</thead>
<tbody>
<tr>
<td>baggage (check)</td>
<td>baggage (claim)</td>
<td>baggage</td>
</tr>
<tr>
<td>gates (load)</td>
<td>gates (unload)</td>
<td>gate</td>
</tr>
<tr>
<td>runway (takeoff)</td>
<td>runway (land)</td>
<td>takeoff/landing</td>
</tr>
<tr>
<td>airplane routing</td>
<td>airplane routing</td>
<td>airplane routing</td>
</tr>
</tbody>
</table>

**Layers:** each layer implements a service

- **Same layers communicate**
  - Baggage section of RDU only calls baggage section of LAX
- **Layers rely on services provided by layer below**
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
  - e.g., change in baggage procedure doesn’t affect rest of system (as long as all baggage sections know)
- layering considered harmful?
Internet protocol stack

- **application**: supporting network applications
  - FTP, SMTP, HTTP
- **transport**: host-host data transfer
  - TCP, UDP
- **network**: routing of datagrams from source to destination
  - IP, routing protocols
- **link**: data transfer between neighboring network elements
  - PPP, Ethernet
- **physical**: bits “on the wire”
Encapsulation

source

message segment

datagram

frame

application
transport
network
link
physical

H_1 H_n H_t M

link
physical

network
link
physical

destination

H_n H_t M

H_1 H_n H_t M

H_i H_n H_t M

switch

H_i H_n H_t M

router

H_i H_n H_t M

Introduction 1-69
Introduction: Summary

Covered a “ton” of material!
- Internet overview
- what’s a protocol?
- network edge, core, access network
  - packet-switching versus circuit-switching
- Internet/ISP structure
- performance: loss, delay
- layering and service models
- history

You now have:
- context, overview, “feel” of networking
- more depth, detail to follow!
Questions?
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Internet History

1961-1972: Early packet-switching principles

- 1961: Kleinrock - queueing theory shows effectiveness of packet-switching
- 1964: Baran - packet-switching in military nets
- 1967: ARPAnet conceived by Advanced Research Projects Agency
- 1969: first ARPAnet node operational

- 1972:
  - ARPAnet public demonstration
  - NCP (Network Control Protocol) first host-host protocol
  - first e-mail program
  - ARPAnet has 15 nodes
Internet History

1972-1980: Internetworking, new and proprietary nets

- **1970**: ALOHAnet satellite network in Hawaii
- **1974**: Cerf and Kahn - architecture for interconnecting networks
- **1976**: Ethernet at Xerox PARC
- **late 70’s**: proprietary architectures: DECnet, SNA, XNA
- **late 70’s**: switching fixed length packets (ATM precursor)
- **1979**: ARPAnet has 200 nodes

Cerf and Kahn’s internetworking principles:
- minimalism, autonomy - no internal changes required to interconnect networks
- best effort service model
- stateless routers
- decentralized control

Define today’s Internet architecture
Internet History

1980-1990: new protocols, a proliferation of networks

- 1983: deployment of TCP/IP
- 1982: smtp e-mail protocol defined
- 1983: DNS defined for name-to-IP-address translation
- 1985: ftp protocol defined
- 1988: TCP congestion control
- New national networks: Csnet, BITnet, NSFnet, Minitel
- 100,000 hosts connected to confederation of networks
Internet History

1990, 2000’s: commercialization, the Web, new apps

- Early 1990’s: ARPAnet decommissioned
- early 1990s: Web
  - hypertext [Bush 1945, Nelson 1960’s]
  - HTML, HTTP: Berners-Lee
  - 1994: Mosaic, later Netscape
  - late 1990’s: commercialization of the Web

Late 1990’s – 2000’s:

- more killer apps: instant messaging, P2P file sharing
- network security to forefront
- est. 50 million host, 100 million+ users
- backbone links running at Gbps