Course Resources

- The textbook
  *Computer Networking: A Top Down Approach Featuring the Internet, 3rd ed.*, Jim Kurose and Keith Ross, Addison-Wesley, 2005
- The course web site
  www.engineering.uiowa.edu/~comcomm
  (announcements, policies, notes, assignments, solutions)
- The text companion site
  www.aw.com/kurose-ross
  (illustrative java applets, self-quizzes, web reference links)

Course Goals

- Introduce key principles underlying modern computer networks and applications.
- Show how these principles are applied in network design and analysis.
- Study current and emerging network protocols, architectures, technologies and applications.

NOTE: This is not a network programming or administration course! Principles, not details (which are changing fast), will be emphasized.

Main Topics:

- Network Applications: HTTP, FTP, DNS, etc.
- Network Protocols: TCP/IP, ATM, etc.
- Network Architectures (LAN, MAN, WAN).
- Multiple Access Technologies: 802.X, etc.
- Data transmission fundamentals: rate, delay.
Expected Background

- Ability to program in C and JAVA will be needed to complete simple sockets programming exercises.
- Knowledge of basic probability (22S:039 level) will aid understanding of network performance issues.

Example: What is the average time $E[\tau]$ required for a successful packet transmission given that:

- Transmissions (Tx) fail independently with probability $p$.
- Success takes $T$ sec. and failure is detected after $T_0 > 2T$ sec.

$E[\tau] = T \cdot P[1\text{st Tx succeeds}] + (T_0 + E[\tau]) \cdot P[1\text{st Tx fails}]$

$= T(1-p) + (T_0 + E[\tau]) \cdot p$

$= \frac{p}{1-p} \cdot T_0 + T$.

Grading

- Friday, July 2: in-class midterm — 30%.
- Friday, July 30: in-class final — 30%.
- Homework — 20%.
- Programming projects—20%.

NOTES:
- All exams will be closed-book. One 2-sided note sheet will be allowed for the midterm, two, for the final.
- Start your reading and assignments early. To avoid drowning in details first identify the key concepts and then relate the details to these concepts.
- All submitted work must be your own.

IMPORTANT ANNOUNCEMENT

- Lectures will meet from 3:00 p.m. to **4:00 pm**, Monday –Thursday.
- No class on Fridays, with the following exceptions:
  - Friday, July 2 (Midterm exam)
  - Friday, July 30 (Final Exam)

Historical Perspective

- Computer networks have only existed for about 35 years.
- Originally, there was a clear distinction between data transmission and other forms of communication.
- In recent years, this distinction has blurred.
- A key factor has been the widespread adoption of digital transmission techniques for all forms of information.
Digital vs. Analog Transmission

- An Analog signal is continuous in time and can take on arbitrary values within some range.
- Digital transmissions represent all information (data, voice, video, etc.) as a finite-rate, binary stream, e.g., ...1101100111010010010001010101...
- This makes digital transmission, transmission using a finite set of analog signals, possible, e.g.,

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\[ 20 \text{Mbps} \Rightarrow 20 \text{bits/µs} \]

Advantages of Digital Transmission

- Information sources can share a common signal set and transmission infrastructure.
- Information compression is possible (e.g. ZIP, GIF, MPEG, MP3, etc).
- Noise and bandwidth are more easily controlled through the use of coding for error control.
- Highly efficient modulation schemes.

The Current Telecommunications Environment

- Much of the current communications infrastructure has changed little in the past 20 years and continues to resist change.
  - We still have largely separate infrastructures for telephone, cable TV, broadcast TV, radio, and computer networks.
  - The ‘last mile’ of local telephone infrastructure is still largely analog.
  - Many of the original network architectures developed in the ’60s and ’70s are still in widespread use today.

Big Changes on the Horizon

- In the last few years there has been enormous growth in the demand for Internet access.
  - As of January 2003, the Internet connected over 171 million host computers.
  - Its size is currently doubling every 33 months!
- The volume of data traffic now exceeds that of voice and analog video.
- The phone carriers are racing to up-grade their networks to integrate multiple services.
An Interesting Historical Perspective

- During the first three decades of computer networking:
  - Telecom infrastructure was designed to carry analog voice and video traffic.
  - Central issue was efficient use of this infrastructure to support digital data communications.
- In the coming decade
  - Telecom infrastructure will primarily carry digital data from various sources.
  - The central issue will be using this infrastructure to integrate delivery of data, voice, video, and other forms of information.

Chapter 1: Introduction

(Reading Assignment: Kurose-Ross Chapter 1)

Our goal:
- get context, overview, "feel" of networking
- more depth, detail later in course
- approach:
  - descriptive
  - 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
- history (read on your own)
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
  - PCs, workstations, servers
  - PDAs, phones, toasters running network apps
- communication links
  - fiber, copper, radio, satellite
  - transmission rate = bandwidth
- routers: forward packets (chunks of data)

"Cool" internet appliances

- World's smallest web server:
  http://www.ocs.cs.umass.edu/~shri/iPic.html
- IP picture frame:
  http://www.celiva.com/
- Web-enabled toaster+weather forecasters:
  http://www.ocs.cs.umass.edu/~shri/iPic.html

What's the Internet: "nuts and bolts" view

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

Introduction 1-18

Introduction 1-19
What's the Internet: a service view
- Communication infrastructure enables distributed applications:
  - Web, email, games, e-commerce, database, voting, file (MP3) sharing
- Communication services provided to apps:
  - Connectionless
  - Connection-oriented
- Currently only "best effort":
  - Can buy increased access (ISP bandwidth)
  - Can not buy delay guarantees

What's a protocol?
- Protocols define format and order of communication, and actions taken after messages sent and received.
- Human and network protocol examples:
  - TCP connection request
  - TCP connection response

A closer look at network structure:
- Network edge: applications and hosts
- Network core:
  - Routers
  - Network of networks
- Access networks, physical media: communication links

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The network edge:

- **end systems (hosts):**
  - run application programs
  - e.g. Web, email
  - at "edge of network"

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

- **peer-peer model:**
  - minimal (or no) use of dedicated servers
  - host interaction is symmetric
  - e.g. Gnutella, KaZaA

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Network edge: connection-oriented service

**Goal:** data transfer between end systems

- handshaking: setup (prepare for) data transfer ahead of time
  - Hello, hello back human protocol
  - 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:
    - helps ensure sender won't overwhelm receiver
  - congestion control:
    - senders "slow down send rate" when network congestion detected.

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Network edge: connectionless service

**Goal:** data transfer between end systems

- same as before!

- **UDP - User Datagram Protocol [RFC 768]:**
  - Internet's connectionless service
  - 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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1.7 Protocol layers, service models
1.8 History
The Network Core

- mesh of interconnected routers
- the fundamental question: how is data transferred through net?
  - circuit switching: dedicated circuit per call e.g. telephone net
  - packet-switching: data sent thru net in discrete "chunks" called "packets"

Network Core: Circuit Switching

End to end resources reserved for "call"
- link bandwidth, switch capacity
- dedicated resources: no sharing
- circuit-like (guaranteed) performance
- call setup required

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
- congestion: packets queue, wait for link use
- store and forward: packets move one hop at a time
- transmit over link
- wait turn at next link
Packet Switching: Statistical Multiplexing

Sequence of A & B packets does not have fixed pattern → statistical multiplexing. In TDM each host gets same slot in revolving TDM frame.

Packet switching versus circuit switching

Packet switching allows more users to use network!
- 1 Mbit link
- each user:
  - 100 kbps when "active"
  - active 10% of time
- circuit-switching:
  - 10 users
- packet switching:
  - with 35 users, probability > 10 active less than .0004

\[ P[>10 \text{ active}] = 1 - \sum_{k=0}^{10} \binom{35}{k} (1.1)^k (1 - 1.1)^{35-k} \]

Packet-switching: store-and-forward

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

Example:
- \( L = 7.5 \text{ Mbits} \)
- \( R = 1.5 \text{ Mbps} \)
- \( \text{delay} = 15 \text{ sec} \)

Assuming negligible propagation delay
Introduction

Packet Switching: Message Segmenting

- Now break the message into 5000 packets
- Each packet 1,500 bits
- 1 msec to transmit packet on one link
- Pipelining: all links work in parallel
- Delay reduced from 15 sec to 5.002 sec

Packet-switched networks: forwarding

- **Goal**: move packets through routers from source to destination
  - we'll study several path selection (i.e. routing) algorithms (chapter 4)
- Datagram network:
  - destination address in packet determines next hop
  - routes may change during session
  - analogy: driving, asking directions
- Virtual circuit network:
  - each packet carries tag (virtual circuit ID), tag determines next hop
  - fixed path (virtual circuit) determined at call setup time, remains fixed thru call
  - routers maintain per-call state

Network Taxonomy

- Telecommunication networks
- Circuit-switched networks
- Packet-switched networks
  - FDM
  - TDM
  - Networks with VC
  - 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 34Kbps upstream and 56Kbps downstream 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 1Mbps upstream, 10 Mbps downstream
- network of cable and fiber attaches homes to ISP router
  - shared access to router among home
  - issues: congestion, dimensioning
- deployment: available via cable companies
**Institutional 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
- deployment: institutions, home LANs happening now
- 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 (WiFi): 11 Mbps
- wider-area wireless access
  - provided by telco operator
  - 3G ~ 384 kbps
  - Will it happen??
  - WAP/GPRS in Europe

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

**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 TP: traditional phone wires, 10 Mbps Ethernet
  - Category 5 TP: similar, but with more twists, 100Mbps Ethernet
**Physical Media: coax, fiber**

- **Coaxial cable:**
  - wire (signal carrier) within a wire (shield)
  - 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., 5 Gbps)
  - 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., WaveLAN)
  - 2 Mbps, 11 Mbps
- wide-area (e.g., cellular)
  - e.g., 36: hundreds of kbps
- satellite
  - up to 50 Mbps channel (or multiple smaller channels)
  - 270 msec end-end delay
  - geosynchronous versus LEOS (delay vs. cost)

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**Internet structure: network of networks**

- roughly hierarchical
- at center: "tier-1" ISPs (e.g., UUNet, BBN/Genuity, Sprint, AT&T), national/international coverage
- treat each other as equals
Tier-1 ISP: e.g., Sprint

Sprint US backbone network

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)

Internet structure: network of networks

- a packet passes through many networks!
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Delay & loss in packet-switched networks

- Packets may encounter delay and even loss on end-to-end path.
- Four sources of delay at each hop:
  1. Nodal processing delay:
     - Bit error check
     - Output link selection (routing)
  2. Queueing delay
     - Wait at output link for transmission (depends on router congestion level)
     - Buffer overflow → loss

![Diagram of network delay components]

Delay in packet-switched networks

3. Transmission delay:
   - \( R \) = link transmission rate (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 (~2x10^8 m/sec)
   - Propagation delay = \( d/s \)

![Diagram of network delay components]

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 booth: 100km/(100km/hr) = 1 hr
- A: 62 minutes

![Diagram of caravan analogy]
Introduction

**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!

**Nodal delay**

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

- \( d_{\text{proc}} \) = processing delay
- Typically a few micros 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 micros to hundreds of msecs

**Queueing delay (revisited)**

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

Traffic intensity = \( La/R \)

- \( La/R \approx 0 \): average queueing delay small
- \( La/R \to 1 \): delays become large
- \( La/R > 1 \): more "work" arriving than can be serviced \( \Rightarrow \) average delay infinite

**Measurement of “average” delay**

- Difficult to measure average packet delay.
- Little’s Law says that for systems that reach steady state (buffers, networks, etc.)

\[ n_{\text{ave}} = a_{\text{ave}} d_{\text{ave}} \]

- \( n_{\text{ave}} \) = average # packets in system
- \( a_{\text{ave}} \) = average packet arrival rate
- \( d_{\text{ave}} \) = average delay per packet

\( \Rightarrow \) average delay can sometimes be computed.

- Reinforces intuition that arrivals to crowded systems experience longer average delays.
- E.g., for the same \( a_{\text{ave}} \), a fast link (or eatery) can have a smaller buffer (waiting area) than a slow one.
Introduction

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 to the i-th router on path towards destination
- i-th router returns packets to sender
- sender times interval between transmission and reply.

```
3 probes
```

```
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-vbrs.gw.umass.edu (128.119.3.130) 6 ms 5 ms 5 ms
4 jn1-lo7-0-0-0.wae.vbns.net (204.147.136.136) 21 ms 16 ms 16 ms
5 ablene-vbrs.ablene.abilene.ucaid.edu (198.35.11.9) 22 ms 18 ms 22 ms
6 abilene-vbrs.abilene.abilene.ucaid.edu (198.35.11.9) 22 ms 18 ms 22 ms
7 abilene-vbrs.abilene.abilene.ucaid.edu (198.35.11.9) 22 ms 18 ms 22 ms
8 62.40.103.253 (62.40.103.253) 104 ms 109 ms 106 ms
9 de.fr1.fr.geant.net (62.40.96.129) 109 ms 102 ms 104 ms
10 de2-1.mel2.de1.de.geant.net (62.40.96.50) 113 ms 110 ms 113 ms
11 renalt-gw.fr1.fr1.mel2.de1.de.geant.net (198.35.11.9) 113 ms 114 ms 112 ms
12 r3t2-nice.cssi.renater.fr (193.48.50.54) 113 ms 114 ms 116 ms
13 r3t2-nice.cssi.renater.fr (193.48.50.54) 113 ms 114 ms 116 ms
14 fantasia.eurecom.fr (193.48.50.54) 113 ms 114 ms 116 ms
```

trans-oceanic link

**Packet loss**

- queue (aka buffer) preceding link in buffer 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
- Packets may also be dropped if they are not successfully delivered within a given time constraint.

```
19 fantasia.eurecom.fr (193.55.113.142) 132 ms 128 ms 136 ms
```

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Protocol "Layers"

**Question:**
Is there any hope of organizing structure of network?
Or at least our discussion of networks?

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 gate procedure doesn't affect rest of system
- layering considered harmful?

Internet protocol stack

- **application**: supporting network applications
  - FTP, SMTP, STTP
- **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"

Layering: logical communication

Each layer:
- distributed
- "entities" implement layer functions at each node
- entities perform actions, exchange messages with peers
Introduction

Layering: logical communication

E.g.: transport
- take data from app
- add addressing, reliability check info to form "datagram"
- send datagram to peer
- wait for peer to ack receipt
- analogy: post office

Layering: physical communication

Protocol layering and data

Each layer takes data from above
- adds header information to create new data unit
- passes new data unit to layer below

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Internet History

1961-1972: Early packet-switching principles
- 1961: Kleinrock - queuing 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 demonstrated publicly
- NCP (Network Control Protocol) first host-host protocol
- first e-mail program
- ARPAnet has 15 nodes
- 1961-1972: Early packet-switching principles

Internet History

1972-1980: Internetworking, new and proprietary nets
- 1970: ALOHAnet satellite network in Hawaii
- 1973: Metcalfe's PhD thesis proposes Ethernet
- 1974: Cerf and Kahn - architecture for interconnecting networks
- 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
- 1972-1980: Internetworking, new and proprietary nets

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: Cnet, BITnet, NSFnet, Minitel
- 100,000 hosts connected to confederation of networks
- 1980-1990: new protocols, a proliferation of networks

Internet History

1990, 2000's: commercialization, the Web, new apps
- Early 1990's: ARPAnet decommissioned
- early 1990's: 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, peer2peer file sharing (e.g., Napster)
  - network security to forefront
  - est. 50 million host, 100 million users
  - backbone links running at Gbps
- 1990, 2000's: commercialization, the Web, new apps
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!