Chapter 1
Introduction

- Adapted from Computer Networking: A Top Down Approach, 6th edition, Jim Kurose, Keith Ross
  Addison-Wesley, March 2012
Chapter 1: introduction

Review:
- what’s the Internet?
- what’s a protocol?
- network edge; hosts, access net, physical media
- network core: packet/circuit switching, Internet structure
- performance: loss, delay, throughput
- protocol layers, service models
- 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*

- *Packet switches*: forward packets (chunks of data)
  - *routers* and *switches*
What’s the Internet: “nuts and bolts” view

- **Internet**: “network of networks”
  - Interconnected ISPs
- **Protocols** control sending, receiving of msgs
  - e.g., TCP, IP, HTTP, Skype, 802.11
- **Internet standards**
  - RFC: Request for comments
  - IETF: Internet Engineering Task Force
What’s the Internet: a service view

- **Infrastructure that provides services to applications:**
  - Web, VoIP, email, games, e-commerce, social nets, …

- **provides programming interface to apps**
  - hooks that allow sending and receiving app programs to “connect” to Internet
  - provides service options, analogous to postal service
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 governed 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: other human protocols?
Chapter 1: roadmap

1.1 what is the Internet?
1.2 network edge
   - end systems, access networks, links
1.3 network core
   - packet switching, circuit switching, network structure
1.4 delay, loss, throughput in networks
1.5 protocol layers, service models
1.6 networks under attack: security
1.7 history
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
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?
Access net: digital subscriber line (DSL)

- use *existing* telephone line to central office DSLAM
  - data over DSL phone line goes to Internet
  - voice over DSL phone line goes to telephone net
- < 2.5 Mbps upstream transmission rate (typically < 1 Mbps)
- < 24 Mbps downstream transmission rate (typically < 10 Mbps)
Access net: cable network

frequency division multiplexing: different channels transmitted in different frequency bands
**Access net: cable network**

- **HFC: hybrid fiber coax**
  - asymmetric: up to 30Mbps downstream transmission rate, 2 Mbps upstream transmission rate
- **network** of cable, fiber attaches homes to ISP router
  - homes *share access network* to cable headend
  - unlike DSL, which has dedicated access to central office

---

*data, TV transmitted at different frequencies over shared cable distribution network*
Access net: home network

- wireless devices
  - often combined in single box
- wireless access point (54 Mbps)
- cable or DSL modem
- router, firewall, NAT
- wired Ethernet (100 Mbps)

Introduction 1-14
Enterprise access networks (Ethernet)

- typically used in companies, universities, etc
- 10 Mbps, 100Mbps, 1Gbps, 10Gbps transmission rates
- today, end systems typically connect into Ethernet switch
Wireless access networks

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

**wireless LANs:**
- within building (100 ft)
- 802.11b/g (WiFi): 11, 54 Mbps transmission rate

**wide-area wireless access**
- provided by telco (cellular) operator, 10’ s km
- between 1 and 10 Mbps
- 3G, 4G: LTE
Host: sends packets of data

host sending function:
- takes application message
- breaks into smaller chunks, known as packets, of length $L$ bits
- transmits packet into access network at transmission rate $R$
  - link transmission rate, aka link capacity, aka link bandwidth

$$
\text{packet transmission delay} = \frac{L \text{ (bits)}}{R \text{ (bits/sec)}}
$$
Physical media

- **bit**: propagates between transmitter/receiver 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 5: 100 Mbps, 1 Gbps Ethernet
  - Category 6: 10Gbps
Physical media: coax, fiber

**coaxial cable:**
- two concentric copper conductors
- bidirectional
- 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 Gpbs transmission rate)
- 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)
  - 3G cellular: ~ few Mbps
- satellite
  - Kbps to 45Mbps channel (or multiple smaller channels)
  - 270 msec end-end delay
  - geosynchronous versus low altitude
Chapter 1: roadmap

1.1 what is the Internet?
1.2 network edge
   - end systems, access networks, links
1.3 network core
   - packet switching, circuit switching, network structure
1.4 delay, loss, throughput in networks
1.5 protocol layers, service models
1.6 networks under attack: security
1.7 history
The network core

- mesh of interconnected routers
- packet-switching: hosts break application-layer messages into *packets*
  - forward packets from one router to the next, across links on path from source to destination
  - each packet transmitted at full link capacity
Packet-switching: store-and-forward

- takes \( \frac{L}{R} \) seconds to transmit (push out) \( L \)-bit packet into link at \( R \) bps
- **store and forward**: entire packet must arrive at router before it can be transmitted on next link
- end-end delay = \( 2 \frac{L}{R} \) (assuming zero propagation delay)

**one-hop numerical example:**
- \( L = 7.5 \) Mbits
- \( R = 1.5 \) Mbps
- one-hop transmission delay = 5 sec

more on delay shortly …
Packet Switching: queuing delay, loss

**queueing and loss:**
- If arrival rate (in bits) to link exceeds transmission rate of link for a period of time:
  - packets will queue, wait to be transmitted on link
  - packets can be dropped (lost) if memory (buffer) fills up
Two key network-core functions

**routing**: determines source-destination route taken by packets

- **routing algorithms**

<table>
<thead>
<tr>
<th>header value</th>
<th>output link</th>
</tr>
</thead>
<tbody>
<tr>
<td>0100</td>
<td>3</td>
</tr>
<tr>
<td>0101</td>
<td>2</td>
</tr>
<tr>
<td>0111</td>
<td>2</td>
</tr>
<tr>
<td>1001</td>
<td>1</td>
</tr>
</tbody>
</table>

**forwarding**: move packets from router’s input to appropriate router output
Alternative core: circuit switching

end-end resources allocated to, reserved for “call” between source & dest:

- In diagram, each link has four circuits.
  - call gets 2nd circuit in top link and 1st circuit in right link.
- dedicated resources: no sharing
  - circuit-like (guaranteed) performance
- circuit segment idle if not used by call (*no sharing*)
- Commonly used in traditional telephone networks
Circuit switching: FDM versus TDM

FDM

TDM

Example:
4 users

Introduction 1-27
is packet switching a “slam dunk winner?”

- great for bursty data
  - resource sharing
  - simpler, no call setup
- excessive congestion possible: packet delay and loss
  - protocols needed for reliable data transfer, congestion control
- Q: How to provide circuit-like behavior?
  - bandwidth guarantees needed for audio/video apps
  - still an unsolved problem (chapter 7)

Q: human analogies of reserved resources (circuit switching) versus on-demand allocation (packet-switching)?
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 was driven by **economics** and **national policies**
- Let’s take a stepwise approach to describe current Internet structure
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.
Option: connect each access ISP to a global transit ISP? Customer and provider ISPs have economic agreement.
Internet structure: network of networks

But if one global ISP is viable business, there will be competitors...
Internet structure: network of networks

But if one global ISP is viable business, there will be competitors … which must be interconnected.

Internet exchange point

peering link
**Internet structure: network of networks**

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

... and content provider networks (e.g., Google, Microsoft, Akamai) may run their own network, to bring services, content close to end users.
Internet structure: network of networks

- 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 network (e.g., Google): private network that connects its data centers to Internet, often bypassing tier-1, regional ISPs
Tier-1 ISP: e.g., Sprint

POP: point-of-presence

to/from backbone

peering

to/from customers
Chapter 1: roadmap

1.1 what is the Internet?
1.2 network edge
   - end systems, access networks, links
1.3 network core
   - packet switching, circuit switching, network structure
1.4 delay, loss, throughput in networks
1.5 protocol layers, service models
1.6 networks under attack: security
1.7 history
How do loss and delay occur?

packets *queue* in router buffers

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

packet being transmitted *(delay)*

packets queueing *(delay)*

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

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

- **\( d_{\text{proc}} \): nodal processing**
  - check bit errors
  - determine output link
  - typically < msec

- **\( d_{\text{queue}} \): queueing delay**
  - time waiting at output link for transmission
  - depends on congestion level of router
Four sources of packet delay

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

- \( d_{\text{trans}} \): transmission delay:
  - \( L \): packet length (bits)
  - \( R \): link bandwidth (bps)
  - \( d_{\text{trans}} = L/R \)

- \( d_{\text{prop}} \): propagation delay:
  - \( d \): length of physical link
  - \( s \): propagation speed in medium (~2x10^8 m/sec)
  - \( d_{\text{prop}} = d/s \)

* Check out the Java applet for an interactive animation on trans vs. prop delay
Caravan analogy

- cars “propagate” at 100 km/hr
- toll booth takes 12 sec to service car (bit 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)

- suppose cars now “propagate” at 1000 km/hr
- and suppose toll booth now takes one min to service a car
- **Q:** Will cars arrive to 2nd booth before all cars serviced at first booth?
  - **A:** Yes! after 7 min, 1st car arrives at second booth; three cars still at 1st booth.
Queueing delay (revisited)

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

\[ \text{traffic intensity} = \frac{L}{R} \]

- \( \frac{L}{R} \sim 0 \): avg. queueing delay small
- \( \frac{L}{R} \rightarrow 1 \): avg. queueing delay large
- \( \frac{L}{R} > 1 \): more “work” arriving than can be serviced, average delay infinite!

* Check out the Java applet for an interactive animation on queuing and loss
“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, routes

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

3 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-rt-fa5-1-0 gw.umass.edu (128.119.3.145)  1 ms  1 ms  2 ms
3 cht-vbns gw.umass.edu (128.119.3.130)  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 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 *** * means no response (probe lost, router not replying)
19 fantasia.eurecom.fr (193.55.113.142)  132 ms  128 ms  136 ms

* Do some traceroutes from exotic countries at www.traceroute.org
Packet loss

- queue (aka buffer) preceding link in buffer has finite capacity
- packet arriving to full queue dropped (aka lost)
- lost packet may be retransmitted by previous node, by source end system, or not at all

* Check out the Java applet for an interactive animation on queuing and loss
**Throughput**

- **throughput**: rate (bits/time unit) at which bits transferred between sender/receiver
  - *instantaneous*: rate at given point in time
  - *average*: rate over longer period of time

---

Server sends bits (fluid) into pipe

Pipe that can carry fluid at rate $R_s$ bits/sec

Pipe that can carry fluid at rate $R_c$ bits/sec
Throughput (more)

- \( R_s < R_c \)  What is average end-end throughput?

- \( R_s > R_c \)  What is average end-end throughput?

\textbf{bottleneck link}

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

- per-connection end-end throughput: \( \min(R_c, R_s, R/10) \)
- in practice: \( R_c \) or \( R_s \) is often bottleneck

10 connections (fairly) share backbone bottleneck link \( R \) bits/sec
Chapter 1: roadmap

1.1 what is the Internet?
1.2 network edge
   - end systems, access networks, links
1.3 network core
   - packet switching, circuit switching, network structure
1.4 delay, loss, throughput in networks
1.5 protocol layers, service models
1.6 networks under attack: security
1.7 history
Protocol “layers”

Networks are complex, with 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

layers: each layer implements a service

- via its own internal-layer actions
- relying 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 gate procedure doesn’t affect rest of system

- layering considered harmful?
Internet protocol stack

- **application**: supporting 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
  - Ethernet, 802.11 (WiFi), PPP
- **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 exchange
- Internet stack “missing” these layers!
  - these services, *if needed*, must be implemented in application
  - needed?