What is this course about?

- Students will learn
  - How networks are designed and structured
  - What is the architecture of the Internet and other networks
  - Some examples of how they are implemented
  - Assess the performance of a network

- Students will be able to
  - Understand and solve performance problems on networks
  - Argue on possible improvements on networks
Course Info

- **Instructor**
  - Georgios Varsamopoulos
  - BY 514
  - M, W, 1:30pm – 2:00pm

- **Teaching Assistant**
  - Priyanka Bagade
  - BYENG 517BA
  - M, W, 2pm-3pm

Use of webpage
http://impact.asu.edu/cse434sp13.html for material,

Use of Blackboard as a dropbox (SafeAssign)

Take Notes! Most testing methods are open-note.

James F. Kurose & Keith W. Ross, Pearson,
ISBN: 0-13-285620-4
About the instructor

- **Name:** Georgios Varsamopoulos
- **Title:** Research Assistant Professor
- **Joined ASU:** 2007 as a post-doctorate researcher

**Research Lab**
- Impact Lab: [http://impact.asu.edu/](http://impact.asu.edu/)

**Research Projects** *(REU positions available)*
- Thermal-aware and sustainable management of computing systems
- BlueTool: Research Infrastructure for sustainable data centers

**Interests**
- resource allocation and management, computer networks, sustainable computing, performance optimization, cyber-physical models
Concerns

- Your Concerns
  - Amount of work
  - Difficulty of programming
  - Required background
  - Usefulness of the course

My concerns

- Here-for-grade or here-for-degree mentality
- Starting homework a couple of days before it is due
- Not using knowledge from previous experience
- Not participating and not challenging the information given
- Plagiarism and other forms of cheating
- Seeing students give up and fail
Course Workload

- Quizzes roughly on a biweekly basis
- About 8 homework assignments
  - 4 homeworks
  - 4 programming assignments
- Three exams
  - Midterm 1: End of February
  - Midterm 2: End of March
  - Final exam

- Grading distribution:
  10% homework assignments
  5% quizzes
  25% programming assignments
  20% each exam (60% altogether)

Grading Rubric:
Ability to solve problem
Understanding of background
Creativity
Clarity
My biggest concern

- Technical writing is **technical**, and your documents are technical **engineering** documents.
  - Engineering documents contain figures and diagrams

- Technical writing skill
  - In five words: **brief**, **exact**, **complete**, **clear**, and **mathematical**

- Research resources
  - The quality and authenticity of your sources is a defining factor of your work's quality
    - The web and wikipedia is ok as a start.
    - Did you know of Google Scholar (scholar.google.com)?
    - Have you ever used the ACM and IEEE online libraries?
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 net, physical media
- network core: packet/circuit switching, Internet structure
- performance: loss, delay, throughput
- security
- protocol layers, service models
- history
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
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

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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
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

- cable modem
- splitter
- cable headend

**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
**Access net: home network**

- **Cable or DSL modem**
- **Router, firewall, NAT**
- **Wired Ethernet (100 Mbps)**
- **Wireless access point (54 Mbps)**
- **Wireless devices**

Often combined in single box.
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

| packet transmission delay | time needed to transmit $L$-bit packet into link | $= \frac{L \text{ (bits)}}{R \text{ (bits/sec)}}$ |

two packets, $L$ bits each
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 Gpbs 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)
  - 11 Mbps, 54 Mbps
- wide-area (e.g., cellular)
  - 3G cellular: ~ few Mbps
- satellite
  - Kbps to 45 Mbps channel (or multiple smaller channels)
  - 270 msec end-end delay
  - geosynchronous versus low altitude
Chapter 1: roadmap

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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
Internet structure: network of networks

**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.
Internet structure: network of networks

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

ISP A

ISP B

ISP C
Internet structure: network of networks

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

... and regional networks may arise to connect access nets to ISPS
… 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
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 $L/R$ 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 = $2L/R$ (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: queueing 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**

  ![Routing Algorithm](image)

<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

![Diagram of packet forwarding](image)
Alternative core: circuit switching

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

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

Example:
4 users

FDM

TDM

Introduction 1-44
Packet switching versus circuit switching

packet switching allows more users to use network!

example:
- 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 at same time is less than .0004 *

Q: how did we get value 0.0004?
Q: what happens if > 35 users?

* Check out the online interactive exercises for more examples
Packet switching versus circuit switching

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)?
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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

**Introduction**

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

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

$$d_{\text{nodal}} = d_{\text{proc}} + d_{\text{queue}} + d_{\text{trans}} + d_{\text{prop}}$$
Four sources of packet delay

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

propagation delay:
- $d_{prop}$
  - $d$: length of physical link
  - $s$: propagation speed in medium ($\sim 2 \times 10^8$ m/sec)
  - $d_{prop} = d/s$

$d_{nodal} = d_{proc} + d_{queue} + d_{trans} + d_{prop}$

*A 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:
  \[ \frac{100\text{km}}{100\text{km/hr}} = 1 \text{ hr} \]
- 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

\[ \frac{a}{R} \sim 0: \text{avg. queueing delay small} \]
\[ \frac{a}{R} \to 1: \text{avg. queueing delay large} \]
\[ \frac{a}{R} > 1: \text{more “work” arriving than can be serviced, average delay infinite!} \]

* 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

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-so7-0-0-0.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)

* 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

![Diagram showing server sending bits into pipe, with link capacities and rates mentioned.]
Throughput (more)

- $R_s < R_c$  What is average end-end throughput?

- $R_s > R_c$  What is average end-end throughput?

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