CSE 461: Computer Networks

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Who we are
ICTD

- Information and Communication Technology for Development
  - Development -> Poverty Alleviation (not software development)
  - Broad field covering health, justice, and access

- Why?
  - Lots of natural intuition from Alaska, I know rural.
  - Able to use networking skill -> Many opportunities (NSRC)

- My subfield: Cellular access
- My Answer: Community Cellular
BE THE PHONE COMPANY.

No more waiting for coverage: now you can build cellular networks yourself.

Learn More
TAs Now!
5th Year Master’s student (1st Qtr)
Interested in security & NLP

Favorite Video Game:
LoZ Twilight Princess
Yibo Cao

- Is stuck in a snowstorm :(

Class Structure
Assignments

3 Projects: (25 + 25 + 25)%

- Turn in on canvas
- 3 Projects based on Mininet – A Software Defined Networking (SDN) simulator
  - Intro to mininet
  - Routing and switching
  - Bufferbloat
Assignments

3 Projects: (25 + 25 + 25)%

Weekly Reading Responses: 15%

• Set of (2) readings for each topic covered during class lecture
• Will try to do classic + cutting edge
• Everyone must generate a response by 11:59PM the Monday before class on canvas. Response includes:
  1) A summary of the paper and its contribution.
  2) A question you would like resolved in group discussion.
  3) A critique of the work, be it methodological, theoretical, or other.
Assignments

3 Projects: (25 + 25 + 25)%
Weekly Reading Responses: 15%
Paper Leads: 10%

• Everyone must lead a paper discussion once in the quarter. This involves:
  • Reading the paper particularly closely
  • Reading peer responses and generating the best topics of discussion
  • Guiding the group through the discussion of that paper. It’s your job to keep it lively.
• Sign up for the papers online.
Assignments

3 Projects: (25 + 25 + 25)%
Weekly Reading Responses: 15%
Paper Leads: 10%

Late Policy: Each person gets three late days. Late days will be decided at end of quarter and selected as to have the most positive impact.
Administrivia

• Office hours
  • Opportunity to have more personal interactions with both me and the TAs.

• Tools
  • Canvas Announcements: Primary mechanism for communication about class changes.
  • Canvas Assignments: Responses and projects
  • Canvas Discussion: Back and forth discussions on class content
  • Canvas Gradebook: Grades will be posted here

• Slides
  • Adapted from David Wetherall, his talks are online
  • I will be posting my own slides right before lecture as well
Questions?
CSE 461: Computer Networks
Focus of the course
Focus of the course (in today’s terms)
Focus of the course (2)

- Three “networking” topics:

<table>
<thead>
<tr>
<th>Distributed systems</th>
<th>CSE 552</th>
</tr>
</thead>
<tbody>
<tr>
<td>Networking</td>
<td>CSE 561</td>
</tr>
<tr>
<td>Communications</td>
<td>EE 506</td>
</tr>
</tbody>
</table>
The Main Points

1) To learn the fundamentals of computer networks
   • Learn how the Internet works
     1) What really happens when you “browse the web”?
        TCP/IP, DNS, HTTP, NAT, VPNs, 802.11 etc
     • Understand why the internet is designed how it is designed
       • SDN, Load Balancers, Architectures
Why learn the Fundamentals?

1. Apply to all computer networks
2. Intellectual interest
3. Change / reinvention
Fundamentals – Intellectual Interest

• Example key problem: Reliability!
  • Any part of the Internet might fail
  • Messages might be corrupted
  • So how do we provide reliability?

• Reliability solutions
  • Codes to detect/correct errors
  • Routing around failures ...
## Fundamentals – Intellectual Interest (2)

<table>
<thead>
<tr>
<th>Key problem</th>
<th>Example solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliability despite failures</td>
<td>Codes for error detection/correction (§3.2, 3.3)</td>
</tr>
<tr>
<td></td>
<td>Routing around failures (§5.2)</td>
</tr>
<tr>
<td>Network growth and evolution</td>
<td>Addressing (§5.6) and naming (§7.1)</td>
</tr>
<tr>
<td></td>
<td>Protocol layering (§1.3)</td>
</tr>
<tr>
<td>Allocation of resources (e.g., bandwidth)</td>
<td>Multiple access (§4.2)</td>
</tr>
<tr>
<td></td>
<td>Congestion control (§5.3, 6.3)</td>
</tr>
<tr>
<td>Security against various threats</td>
<td>Confidentiality of messages (§8.2, 8.6)</td>
</tr>
<tr>
<td></td>
<td>Authentication of communicating parties (§8.7)</td>
</tr>
</tbody>
</table>
Fundamentals – Reinvention

• The Internet is constantly being re-invented!
  • Growth over time and technology trends drive upheavals in Internet design and usage
• Today’s Internet is different from yesterday’s
  • And tomorrow’s will be different again
  • But the fundamentals remain the same
Fundamentals – Reinvention

• Many billions of Internet hosts and growing ...
  • 5B+ on Cell Networks
  • 3B+ on Internet

Source: Internet Systems Consortium (www.isc.org)
Fundamentals – Reinvention

• Examples of upheavals in the past 1-2 decades

<table>
<thead>
<tr>
<th>Change</th>
<th>Enabling Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emergence of the web</td>
<td>Content Distribution Networks</td>
</tr>
<tr>
<td>Piracy</td>
<td>Peer-to-peer file sharing</td>
</tr>
<tr>
<td>Voice over IP (VoIP)</td>
<td>Quality of Service (QoS)*</td>
</tr>
<tr>
<td>Internet of Things</td>
<td>IPv6</td>
</tr>
<tr>
<td>Mobile Devices</td>
<td>Wireless Networking</td>
</tr>
</tbody>
</table>

*mostly actually enormous spare capacity
Fundamentals – Reinvention (4)

• Upcoming/Ongoing upheavals?

<table>
<thead>
<tr>
<th>Change</th>
<th>Enabling Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fake News</td>
<td>Social Media</td>
</tr>
<tr>
<td>No-power devices?</td>
<td>Backscatter</td>
</tr>
<tr>
<td>Generic Networks?</td>
<td>SDN</td>
</tr>
<tr>
<td>Ubiquitous Networks?</td>
<td>Satellite/Long-Distance Networks</td>
</tr>
<tr>
<td>BBR/QUIC</td>
<td>High-Bandwidth Mobile (4G/5G)</td>
</tr>
</tbody>
</table>
The Main Points

1) To learn the fundamentals of computer networks

• **Learn how the Internet works**
  1) What really happens when you “browse the web”?
    
    TCP/IP, DNS, HTTP, NAT, VPNs, 802.11 etc

• Understand why the internet is designed how it is designed
  
  • SDN, Load Balancers, Architectures
Who cares about the internet?

1. Curiosity
2. Impact on our world
3. Job prospects!
From this experimental network (~1970)...

To this...
To this! (2011)
And this (2015)!

- An everyday institution used at work, home, and on-the-go
- Visualization contains millions of servers
  - Red = .com,
  - Yellow = .org
- Network now contains literally 3 billion people!
Internet – Societal Impact

• An enabler of societal change
  • Easy access to knowledge
  • Electronic commerce
  • Personal relationships
  • Private communications
Internet – Economic impact

• An engine of economic growth
  • Information sources
    • And lots of ethical questions!
  • Online marketplaces
  • Social media/Crowdsourcing
The Main Points

1) To learn the fundamentals of computer networks
   • Learn how the Internet works
     1) What really happens when you “browse the web”?
        TCP/IP, DNS, HTTP, NAT, VPNs, 802.11 etc
   • Understand why the internet is designed how it is designed
     • SDN, Load Balancers, Architectures
Architectures

• Lots of ways to build networks with different **tradeoffs**

• Goals:
  • Open Access (Internet)
    • Safety--, Security--, Flexibility++, Privacy++
  • Identity First (Cellular)
    • Safety++, Security++, Privacy --, Flexibility--
  • Centralized (Comcast)
    • Complexity++, Freedom--
  • Decentralized (Mesh)
    • Complexity--, Freedom++
The Main Points

1) To learn the fundamentals of computer networks

2) To learn about where networks are going
   • Know modern advances and technologies
     BBR/QUIC, SDN, TOR, etc...
   • See future agendas and changes
     The end of the Internet?
Not a Course Goal

To learn IT job skills

• How to configure specific equipment or technologies
  • e.g., Cisco certifications,
  • Technical whack-a-mole

• But course material is relevant, and we use hands-on tools
  • Hopefully you’ll be able to use these tools to build stuff at the end of class
The Agenda

1) To learn the fundamentals of computer networks (lecture available online)
   • 1.5 hr of lecture content a week
2) To learn about where networks are going (not available online)
   • 1 hour of paper discussion a week (following last week’s lecture content)
Questions?
History of the Internet
What are some pre-Internet communication technologies?
Optical Semaphores

• Basic idea: Use visual indications of letters to signal next tower.

• Claude Chappe (France, 1792): Built 556 of these stations across France for communicating about war effort.

• First Message: “Si vous réussissez, vous serez bientôt couverts de gloire” (If you succeed, you will soon bask in glory) – 16km

• “Mechanical Internet”
Le réseau Chappe en France

Directions (date de création)
- 1793-1800
- 1800-1815
- 1815-1830
- Après 1830

Lignes (date de création)
- 1793-1800
- 1800-1815
- 1815-1830
- Après 1830
Telegraph

• Robust work in trying to use electricity to transmit information instead.
• Many problems: Didn’t have consistent generators so coding was hard; some solutions used a wire for each letter.
• Eventually Gauss developed working system: Positive signal would move needle one way, negative another then alphabet
• Cooke and Wheatstone build this ->
Telegraph

- Samuel Morse changes this to have the signal move a pen, creating a mark.
- Morse first message: was in 1838
  - 3 miles in New Jersey
- More famously sent "WHAT HATH GOD WROUGHT?“ 44 miles between DC and Baltimore
- Core innovation: Relays at frequent intervals that send a message through ten miles (16 km) of wire.
Telephone

• Basic problem: How to modulate voice onto electrical signals
• Reis (1861 Germany): "Das Pferd frisst keinen Gurkensalat" (The horse does not eat cucumber salad). Speech issues.
• Elisha Gray (1876) patents first method for encoding.
• Bell (1876) makes first call: "Mr. Watson, come here, I want to see you." Wins patent war.
Circuit-Switching

• In January 1878, the first telephone switch went into operation in New Haven Connecticut
• Establish a complete circuit every time there’s a communication
• Still the case in cellular!
  • Circuit is established to “packet gateway”
Issues w/ Circuit Switching

• ?
Issues w/ Circuit Switching

• Large setup cost
  • Switching costs all along circuit

• Contention
  • Only X links, what if X+1 want to use?

• Inefficient
  • Circuit established even if not in use

• Fragile
  • Intermediary links go down circuit is broken

USAF wanted their networks to survive nuclear strikes... circuits would not.
Pre-internet: Packetization

The solution focused on three big ideas:

1. Use decentralized network with multiple paths between any two points
2. Divide user messages into message blocks, later called **packets**
3. Deliver these messages by store and forward switching.
Pre-Internet: Why Packetization?

• Efficiency
  • Lines only used when trafficked

• Handles contention
  • Queue packets

• Robust
  • Routes can change

• Kleinrock (UCLA, 1969)
  • UCLA -> SRI
  • “Lo” – Was supposed to be “LOGIN” but crashed
Efficiency: Statistical Multiplexing

• Sharing of network bandwidth between users according to the statistics of their demand
  • (Multiplexing basically means sharing)
  • Useful if:
    • users are mostly idle and/or
    • traffic is bursty

• Key question:
  • How much does it help?
Efficiency: Statistical Multiplexing (2)

• Example: Users in an ISP network
  • Network has 100 Mbps (units of bandwidth)
  • Each user subscribes to 5 Mbps, for videos
  • But a user is active only 50% of the time ...

• How many users can the ISP support?
  • With dedicated bandwidth for each user:
  • Probability all bandwidth is used: (assuming independent users)
Efficiency: Statistical Multiplexing (3)

• With 30 independent users, still unlikely (2% chance) to need more than 100 Mbps!
  • Binomial probabilities

→ Can serve more users with the same size network
  • Statistical multiplexing gain is 30/20 or 1.5X
  • But may get unlucky; users will have degraded service
Pre-Internet: Networks

Started building individual packet networks at different institutions:

• Octopus Network
  • 4 Machines at the Lawrence Livermore National Lab

• ALOHAnet
  • Wireless packets at University of Hawaii

• CYCLADES
  • French network exploring network responsibilities

• ARPANET
  • First packet network, a few universities online
The Beginning – ARPANET

• ARPANET by U.S. DoD was the precursor to the Internet
  • Motivated for resource sharing
  • Launched with 4 nodes in 1969, grew to hundreds
  • First “killer app” was email
ARPANET

- In the early ARPANET
  - Internetworking became the basis for the Internet
  - Pioneered by Cerf & Kahn in 1974, later became TCP/IP
  - They are popularly known as the “fathers of the Internet”

Vint Cerf

© 2009 IEEE

Bob Kahn

© 2009 IEEE
Rough Internet Timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>Estimated Hosts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1969</td>
<td>$10^3$</td>
</tr>
<tr>
<td>1982</td>
<td>$10^6$</td>
</tr>
<tr>
<td>1995</td>
<td>$10^9$</td>
</tr>
<tr>
<td>2013</td>
<td></td>
</tr>
</tbody>
</table>

1: ARPANET
2: NSFNET
3: Modern Internet & Web

Computer Networks
ARPANET Geographical Map (Dec. 1978)

“IMPs” were early routers

56 kbps links

Source: ARPANET Information Brochure, DCA 1979
Growing Up – NSFNET

• NSFNET ’85 supports educational networks
  • Initially connected supercomputers, but became the backbone for all networks
• Classic Internet protocols we use emerged
  • TCP/IP (transport), DNS (naming), Berkeley sockets (API) ’83, BGP (routing) ’93
• Much growth from PCs and Ethernet LANs
  • Campuses, businesses, then homes
  • 1 million hosts by 1993 ...
Growing Up - NSFNET
Early Internet Architecture

• Hierarchical, with NSFNET as the backbone

- NSFNET Backbone
  - Regional Network
    - Customer
  - Regional Network
    - Customer
  - Regional Network
    - Customer

56 kbps links in ’85
1.5 Mbps links in ’88
45 Mbps links in ‘91
Modern Internet – Birth of the Web

- After ’95, connectivity is provided by large ISPs who are competitors
  - They connect at Internet eXchange Point (IXP) facilities
  - Later, large content providers connect
- Web bursts on the scene in ’93
  - Key idea: Hyperlink
  - Growth leads to CDNs, ICANN in ‘98
  - Most bits are video (soon wireless)
  - Content is driving the Internet
Modern Internet Architecture

• Complex business arrangements affect connectivity
  • Still decentralized, other than registering identifiers
Modern Internet Architecture (2)

Major Transit ISPs:
• Level 3 (200,000mi of fiber)
• Century Link (550,000mi)
• ATT (410,000mi)
• Verizon (500,000mi)

Major Regional ISPs:
• Dakotanet
• Dixienet
• Local telecoms (e.g., MTA)
• US West
Network Components
Parts of a Network
Parts of a Network

host       router       link       app
## Component Names

<table>
<thead>
<tr>
<th>Component</th>
<th>Function</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Application</strong>, or app, user</td>
<td>Uses the network</td>
<td>Skype, iTunes, Amazon</td>
</tr>
<tr>
<td><strong>Host</strong>, or end-system, edge device, node, source, sink</td>
<td>Supports apps</td>
<td>Laptop, mobile, desktop</td>
</tr>
<tr>
<td><strong>Router</strong>, or switch, node, hub, intermediate system</td>
<td>Relays messages between links</td>
<td>Access point, cable/DSL modem</td>
</tr>
<tr>
<td>Link, or channel</td>
<td>Connects nodes</td>
<td>Wires, wireless</td>
</tr>
</tbody>
</table>
Parts of a Network

host  router  link  app
Parts of a Network
Types of Links

• Full-duplex
  • Bidirectional

• Half-duplex
  • Bidirectional

• Simplex
  • unidirectional
Wireless Links

• Message is broadcast
  • Received by all nodes in range
  • Not a good fit with our model
Wireless Links (2)

• Often show logical links
  • Not all possible connectivity
A Small Network

• Connect a couple of computers

• Next, a large network ...
## Computer network names by scale

<table>
<thead>
<tr>
<th>Scale</th>
<th>Type</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vicinity</td>
<td>PAN (Personal Area Network)</td>
<td>Bluetooth (e.g., headset)</td>
</tr>
<tr>
<td>Building</td>
<td>LAN (Local Area Network)</td>
<td>WiFi, Ethernet</td>
</tr>
<tr>
<td>City</td>
<td>MAN (Metropolitan Area Network)</td>
<td>Cable, DSL</td>
</tr>
<tr>
<td>Country</td>
<td>WAN (Wide Area Network)</td>
<td>Large ISP</td>
</tr>
<tr>
<td>Planet</td>
<td>The Internet (network of all networks)</td>
<td>The Internet!</td>
</tr>
</tbody>
</table>
Internetworks

• An internetwork, or internet, is what you get when you join networks together
  • Just another network

• The Internet (capital “I”) is the internet we all use
Network Boundaries

• What part is the “network”?
Network Boundaries (2)

• What part represents an “ISP”?
Network Boundaries (3)

• Cloud as a generic network
Key Interfaces

• Between (1) apps and network, and (2) network components
What API should networks provide?
Networks Need Modularity

• The network does much for apps:
  • Make and break connections
  • Find a path through the network
  • Transfers information reliably
  • Transfers arbitrary length information
  • Send as fast as the network allows
  • Shares bandwidth among users
  • Secures information in transit
  • Lets many new hosts be added
  • ...

Computer Networks
Networks Need Modularity

- The network does much for apps:
  - Make and break connections
  - Find a path through the network
  - Transfers information reliably
  - Transfers arbitrary length information
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  - Shares bandwidth among users
  - Secures information in transit
  - Lets many new hosts be added
  - ...

We need a form of modularity, to help manage complexity and support reuse
Protocols and Layers

• **Protocols and layering** is the main structuring method used to divide up network functionality
  • Each instance of a protocol talks virtually to its peer using the protocol
  • Each instance of a protocol uses only the services of the lower layer
Protocols and Layers (2)

- Protocols are horizontal, layers are vertical

![Diagram of protocols and layers]
Protocols and Layers (3)

• Set of protocols in use is called a protocol stack
Protocols and Layers (4)

• Protocols you’ve probably heard of:
  • TCP, IP, 802.11, Ethernet, HTTP, SSL, DNS, ...
    and many more
Protocols and Layers (5)

• Protocols you’ve probably heard of:
  • TCP, IP, 802.11, Ethernet, HTTP, SSL, DNS, ...
    and many more

• An example protocol stack
  • Used by a web browser on a host that is wirelessly connected to the Internet
Encapsulation

• **Encapsulation** is the mechanism used to effect protocol layering
  • Lower layer wraps higher layer content, adding its own information to make a new message for delivery
  • Like sending a letter in an envelope; postal service doesn’t look inside
Encapsulation (2)

- Message “on the wire” begins to look like an onion
  - Lower layers are outermost

```
802.11  IP  TCP  HTTP
   IP  TCP  HTTP
     IP  TCP  HTTP
        IP  TCP  HTTP
```

```
802.11  IP  TCP  HTTP
   IP  TCP  HTTP
     IP  TCP  HTTP
        IP  TCP  HTTP
```
Encapsulation (3)

- HTTP
- TCP
- IP
- 802.11
Encapsulation (4)

• Normally draw message like this:
  • Each layer adds its own header

<table>
<thead>
<tr>
<th>802.11</th>
<th>IP</th>
<th>TCP</th>
<th>HTTP</th>
</tr>
</thead>
</table>

First bits on the wire    Last bits

• More involved in practice
  • Trailers as well as headers, encrypt/compress contents
  • Segmentation (divide long message) and reassembly
Demultiplexing

• Incoming message must be passed to the protocols that it uses
Demultiplexing (2)

• Done with **demultiplexing keys** in the headers

![Diagram showing demultiplexing process with Ethernet, IP, TCP, HTTP, UDP, SMTP, DNS, ARP, and incoming message.](image-url)
Advantage of Layering

• Information hiding and reuse
Advantage of Layering (2)

• Information hiding and reuse

Browser

HTTP
TCP
IP
802.11

Server

HTTP
TCP
IP
802.11

or

Browser

HTTP
TCP
IP
Ethernet

Server

HTTP
TCP
IP
Ethernet
Advantage of Layering (3)

• Using information hiding to connect different systems
Advantage of Layering (4)

- Information hiding to connect different systems
Advantage of Layering (5)

- Information hiding to connect different systems
Disadvantages of Layering

• ?
Disadvantage of Layering

• Adds overhead
  • More problematic with short messages

• Hides information
  • App might care about network properties (e.g., latency, bandwidth, etc)
  • Network may need to know about app priorities (e.g., QoS)
## OSI Layers

<table>
<thead>
<tr>
<th>Layer</th>
<th>Function</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Application (7)</strong></td>
<td>Services that are used with end user applications</td>
<td>SMTP,</td>
</tr>
<tr>
<td><strong>Presentation (6)</strong></td>
<td>Formats the data so that it can be viewed by the user Encrypt and decrypt</td>
<td>JPG, GIF, HTTPS, SSL, TLS</td>
</tr>
<tr>
<td><strong>Session (5)</strong></td>
<td>Establishes/ends connections between two hosts</td>
<td>NetBIOS, PPTP</td>
</tr>
<tr>
<td><strong>Transport (4)</strong></td>
<td>Responsible for the transport protocol and error handling</td>
<td>TCP, UDP</td>
</tr>
<tr>
<td><strong>Network (3)</strong></td>
<td>Reads the IP address form the packet.</td>
<td>Routers, Layer 3 Switches</td>
</tr>
<tr>
<td><strong>Data Link (2)</strong></td>
<td>Reads the MAC address from the data packet</td>
<td>Switches</td>
</tr>
<tr>
<td><strong>Physical (1)</strong></td>
<td>Send data on to the physical wire.</td>
<td>Hubs, NICS, Cable</td>
</tr>
</tbody>
</table>
Protocols and Layering

• The real internet protocol stacks:

1. Link
   - Ethernet
   - 3G
   - Cable
   - DSL
   - 802.11

2. Internet
   - IP

3. Transport
   - TCP
   - UDP

4. Application
   - SMTP
   - HTTP
   - RTP
   - DNS

“Narrow waist”
Course Reference Model

- We mostly follow the Internet
  - A little more about the Physical layer, and alternatives

<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Application - Programs that use network service</td>
</tr>
<tr>
<td>4</td>
<td>Transport - Provides end-to-end data delivery</td>
</tr>
<tr>
<td>3</td>
<td>Network - Send packets over multiple networks</td>
</tr>
<tr>
<td>2</td>
<td>Link - Send frames over one or more links</td>
</tr>
<tr>
<td>1</td>
<td>Physical - Send bits using signals</td>
</tr>
</tbody>
</table>
Lecture Progression

• Bottom-up through the layers:

<table>
<thead>
<tr>
<th>Layer</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>HTTP, DNS, CDNs</td>
</tr>
<tr>
<td>Transport</td>
<td>TCP, UDP</td>
</tr>
<tr>
<td>Network</td>
<td>IP, NAT, BGP</td>
</tr>
<tr>
<td>Link</td>
<td>Ethernet, 802.11</td>
</tr>
<tr>
<td>Physical</td>
<td>wires, fiber, wireless</td>
</tr>
</tbody>
</table>

• Followed by more detail on cross-cutting elements:
  • Quality of service, Security (VPN, SSL)