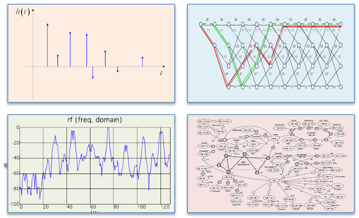


INTRODUCTION TO EECS II

DIGITAL COMMUNICATION SYSTEMS

6.02 Spring 2012
Lectures #24 & 25

Course Eval!

A Brief History of the Internet
Wrap-up of 6.02

Some pictures from Prof. Randy Katz, UC Berkeley
Several pictures from Wikipedia

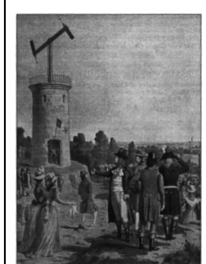
It is anticipated that the whole of the populous parts of the United States will, within two or three years, be covered with net-work like a spider's web.

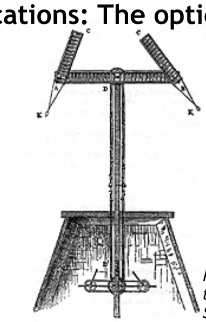
When was this sentence written?

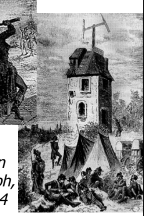
1848

About the *electric telegraph*
In The London Anecdotes, 1848
As quoted in Tom Standage, *The Victorian Internet*

Visual communications: The optical telegraph (1790s)





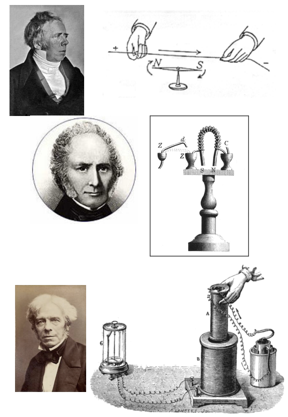


Pics: Proc. Symp. on the Optical Telegraph, Stockholm, June '94

- Chappe (1763-1805), a "defense contractor"; 1st message successfully sent in 1794
- 1799: Napoleon seizes power; sends "*Paris is quiet, and the good citizens are content.*"
- 1814: Extends from Paris to Belgium & Italy
- 1840: 4000 miles, 556 stations, 8 main lines, 11 sublines, each hop ~10 km
- Many "advanced" techniques: switching, framing, codes, redundant relays, message acks, priority messages, error notification, primitive encryption!

Advances in Electricity and Magnetism (Late 18th and 19th centuries)

- Jean-Antoine Nollet (1746): "electricity travels fast" experiment… on humans!
- Oersted (Copenhagen), 1820: demonstrated electricity's ability to deflect a needle
- Sturgeon (London), 1825: electromagnet demo
- Joseph Henry, 1830: 1-mile demo: current through long wires using *electric relay*, causing bell to ring!
- Faraday (London), 1831: EM induction experiments (induction ring), basis for motors
  - "World's greatest experimentalist"



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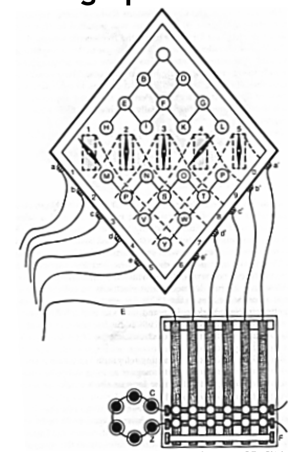
The Electric Telegraph

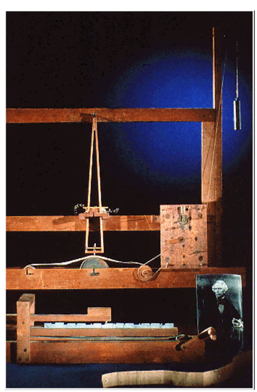
- Cooke and Wheatstone, Railroad Telegraph, 1837

- First pickpocket arrest: 1844
- First murder arrest: 1845



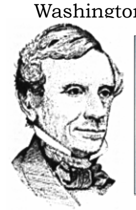
6.02 Spring 2012 Lecture 25, Slide #6

The Morse-Vail Telegraph



1836: Morse design
Vail: powerful electromagnets
Morse Code (1835-1837)

- By Morse & Vail
- 1838: demo' d over 2 miles
- 1844: US-sponsored demo between Baltimore and Washington DC



America's first telegram (1844)

6.02 Spring 2012 Lecture 25, Slide #7

Dots and Dashes Span the Globe

- 1852: First international telegram
- Reuters establishes "Telegraph News Network"
- 1858: First transatlantic cable laid by the Atlantic Telegraph Co.
  - US President & Queen Victoria exchange telegrams
  - Line fails in a few months
- 1866: New cable & technology developed by William Thompson (Lord Kelvin), scientific advisor to the company
  - Proposed using copper for cabling, analyzed data rates, etc.

Lecture 25, Slide #8

Early Uses

Valentine by a Telegraph Clerk (male)
to a Telegraph Clerk (female):

"The tendrils of my soul are twined
With thine, though many a mile apart,
And thine in close-coiled circuits wind
Around the needle of my heart.

"Constant as Daniell, strong as Grove,
Ebullient through its depths like Smee,
My heart pours forth its tide of love,
And all its circuits close in thee.

"O tell me, when along the line
From my full heart the message flows,
What currents are induced in thine?
One click from thee will end my woes."

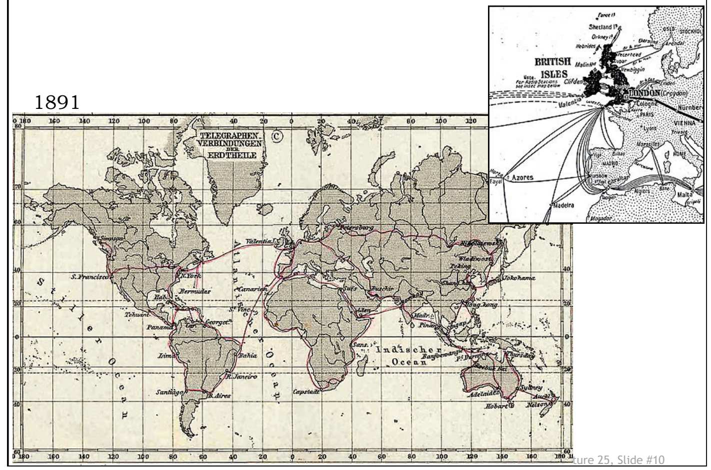
Through many an Ohm the Weber flew,
And clicked this answer back to me, --
"I am thy Farad, staunch and true,
Charged to a Volt with love for thee."

Who or what are Daniell, Grove and Smee?!

A: Types of batteries

"The Victorian Internet"

1891



Dots and Dashes Span The Globe

- Communications arms race in the Imperial Age
  - No nation could trust its messages to a foreign power
  - 1893: British-owned Eastern Telegraph Company and the French crisis in Southeast Asia
  - 1914: British cut the German overseas cables within hours of the start of WW I
  - Germany retaliates by cutting England's Baltic cables and the overland lines to the Middle East through Turkey
- Strategic necessity: circumventing the tyranny of the telegraph lines owned by nation states

Wireless to the Rescue!

James Clerk Maxwell (1831-1879)

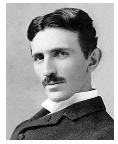
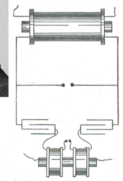
"... we have strong reason to conclude that light itself -- including radiant heat, and other radiations if any -- is an electromagnetic disturbance in the form of waves propagated through the electromagnetic field according to electromagnetic laws." *Dynamical Theory of the Electromagnetic Field*, 1864.

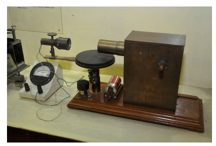
Heinrich Hertz (1857 - 1894)

- 1886-88: Demonstrated experimentally the wave character of electrical transmission in space, validating Maxwell's theory

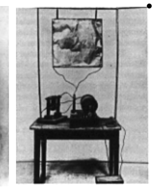
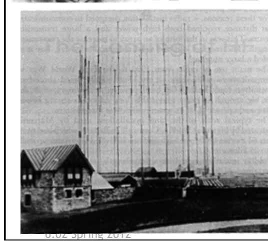
Wireless Telegraphy - I

- 1893-94: Nikola Tesla demonstrates wireless communication using *spark gap transmitter* in St. Louis, and then in Europe
- 1894: Jagdish Chandra Bose invents the *coherer*, a device to detect EM waves (semiconductor crystals)
  - Public demo of microwave communication
  - "*The invisible light can pass through brick walls, buildings, etc. Therefore messages can be transmitted… without the mediation of wires.*"
  - Anticipated the existence of semiconductors 60 years ahead!



Wireless Telegraphy - Commercialization

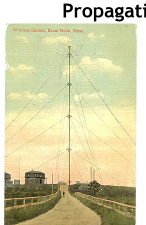
- Guglielmo Marconi
  - 1896: announces his invention of radio
  - 1897: awarded British patent for radio (much controversy over priority)
  - 1897: Demonstrates system on Salisbury Plain to British Royal Navy, who becomes an early customer
  - 1901: First wireless transmission across the Atlantic
  - 1907: Regular commercial service commenced
- Lee de Forest
  - Invents a vacuum tube device called the "audion"
  - Competes with Marconi wireless: interference due to spark gap transmitters (wide bandwidth)

Wireless Telegraph: Modulation

From Brant Rock tower, radio age was sparked
By Carolyn Y. Johnson, Globe Staff | July 30, 2006

MARSHFIELD, MA -- A century ago*, radio pioneer *Reginald A. Fessenden* used a massive 420-foot radio tower that dwarfed Brant Rock to send voice and music to ships along the Atlantic coast, in what has become known as the world's first voice radio broadcast.

Audio Signals Carried on Electromagnetic Waves Propagating through the Atmosphere



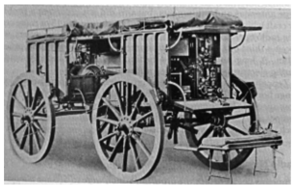
*Christmas Eve, 1906

Fessenden and Armstrong

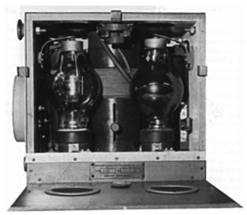
Amplitude modulation (Fessenden's *heterodyne* principle)
Fessenden started scientific work with Edison
His application to Edison said
"Do not know anything about electricity, but can learn pretty quick."
Edison wrote back to say
"Have enough men now that do not know about electricity."
Was awarded around 500 patents!

Edwin Armstrong: Frequency modulation (FM)
"Superheterodyne receiver" (1918)
Convert received signal to an *intermediate* frequency for more convenient processing

Wireless in Warfare



"Portable" radio, circa 1915



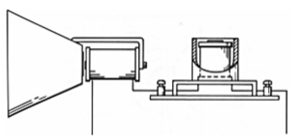
Airborne radio telephone, post WW I

In the Meantime, in the Wired World…

- The telegraph learns to talk
- Morse telegraph: no multiplexing
  - Only one message sent/received at a time
- Second half of 19th century: many researchers work on improving capacity
- Idea: send messages at different pitches
  - Alexander Graham Bell – harmonic telegraph
  - Develops way to send different source frequencies by adjusting current levels

The Telephone

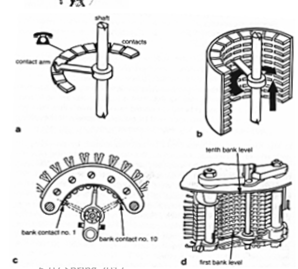
Alexander Graham Bell
- 1876: 2-mile wired phone conversation between Cambridgeport and Boston

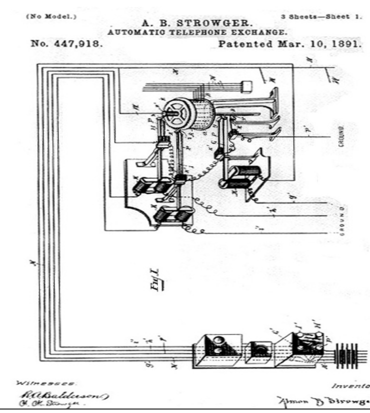


- Bell and Elisha Gray patent conflict
- Bell offers to sell patents to Western Union for $100,000, who refuse.
- Bell Telephone Company founded 9 July 1877.
- 1879: Chairman of Western Union says he would be happy to pay $25M for telephone; Bell refuses
- Western Union competes using rival system designed by Thomas Edison and Elisha Gray. Bell sues and wins. Many many lawsuits over next decades

Mechanical Telephone Switch

Almon Brown Strowger (1839 - 1902)
- 1889: Invents the "girl-less, cuss-less" telephone system

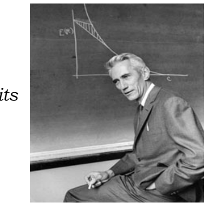




"Ma Bell" and the Telcos

- Bell's patents expire in 1890s; over 6000 independent operators spring up
  - 1910: Bell System controls 50% of local telephone market
  - 1913: AT&T & U.S. reach *Kingsbury Agreement*: AT&T becomes regulated monopoly while promising "universal" telephone service
- 1950: Bell controls 84% of the local telephone access market
- 1984: Divesture of "Ma Bell" (Judge Greene)
- 1996: Trivestiture of AT&T Bell (AT&T, Lucent, NCR)
- 2000s: The death of the classic wired telephone network

The Golden Age of Information Theory



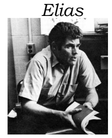
- Claude Shannon, 1948: *A Mathematical Theory of Communication*
- MIT Master's Thesis (1937)
  - *A symbolic analysis of relay and switching circuits*
  - Connected Boolean algebra to logic circuits
  - Very influential in digital circuit design.
  - "Most important Masters thesis of the century"
- MIT PhD (1940)
  - *An algebra for theoretical genetics*
  - To analyze dynamics of Mendelian populations
- Joined Bell Labs (until 1956)
  - "A mathematical theory of cryptography"
- Returned to MIT as Professor (1956-78)
- Seminal findings on *channel capacity*, among many other things

Coding

- Source codes
  - Shannon-Fano coding: proposed in Shannon's 1948 work, attributed there to Fano (first prefix-free code; all codewords within one bit of –log(p_i)
  - Huffman codes: 1950, MIT
  - 1970s: Ziv & Lempel, & later Lempel-Ziv-Welch
- Channel coding: towards capacity
  - Hamming code (1950)
  - Convolutional codes (Elias, 1955)
  - Sequential decoding (Wozencraft, Fano)
  - Trellis decoding (Viterbi, 1967)
  - Low-density parity check (LDPC) codes (Gallager, 1960): far ahead of its time!
  - Turbo codes (1993)
- Cf. *The Road to Capacity* by Forney & Costello
- Still an active research area

Hamming

Elias

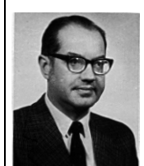


Fano

Viterbi

Gallager

The Dawn of Packet Switching



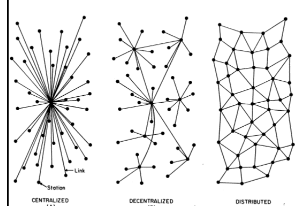


FIG. 1 — Centralized, Decentralized and Distributed Networks

ARPA: 1957, in response to Sputnik

Paul Baran (RAND Corp)

- Early 1960s: New approaches for survivable comms systems; "hot potato routing" and decentralized architecture, paper on packet switching over *digital* links

Donald Davies (UK), early 1960s

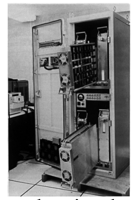
- Coins the term "packet"

Len Kleinrock (MIT thesis): "Information flow in large communication nets", 1961

J. Licklider & W. Clark (MIT), *On-line Man Computer Communication* (1962) & Licklider's vision of a "galactic network"

L. Roberts (MIT then ARPA), first ARPANET plan for time-sharing remote computers

ARPANET



BBN team that implemented the *interface message processor* (IMP)

- 1967: Connect computers at key research sites across the US using telephone lines
- Interface Message Processors (IMP) ARPA contract to BBN
- Sen. Ted Kennedy sends a somewhat confused telegram to BBN on winning the contract
  "Congratulations … on **interfaith** message processor"

Initial Baby Steps

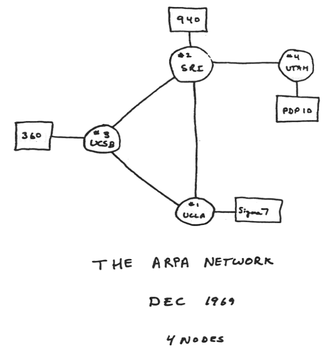


FIGURE 6.2 Drawing of 4 Node Network (Courtesy of Alex McKenzie)

In the Beginning…

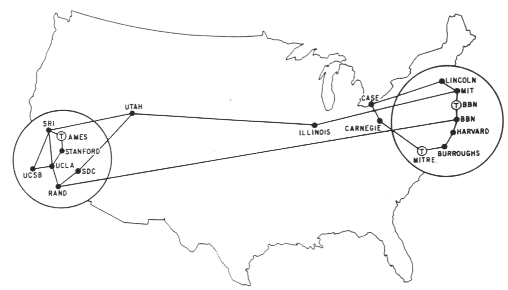
- Kleinrock's group at UCLA tried to log on to SRI computer: His recollection of the event…
- "We set up a telephone connection between us and the guys at SRI…
- We typed the L and we asked on the phone…
  - "Do you see the L?"
  - "Yes, we see the L," came the response
- We typed the O, and we asked…
  - "Do you see the O?"
  - "Yes, we see the O."
- Then we typed the G…
  - …and the system crashed!

September 1971

1970, ARPANET hosts start using NCP; first two cross-country lines (BBN-UCLA and MIT-Utah)

"Hostile overlay" atop telephone network

Ran a distance-vector routing protocol



MAP 4 September 1971

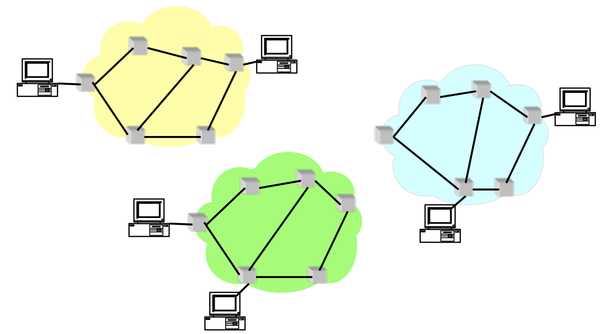
1970s: Packet networks → Internetworking

- 1972: successful ARPANET demo at conference (except it failed when demo'd to skeptics from AT&T!)
- 1972: modified ARPANET email program
- 1972: CYCLADES network (Louis Pouzin et al.): best-effort "datagrams"; *sliding window* protocol; distance-vector routing; time sync; congestion control ideas
- 1973: Ethernet (MAC protocol inspired by Aloha -- CSMA)
- 1973-74: Xerox PUP (used distance-vector protocol)
- 1973: ARPANET becomes international
- 1973-75: Internetworking effort (Cerf, Kahn, et al.)
  - Developed TCP and IP (originally intertwined) – TCP uses *sliding window*

6.02 Spring 2012 Lecture 25, Slide #29

The Problem

- Many different packet-switching networks
- Only nodes on the same network could communicate



Slide: Scott Shenker, UC Berkeley

6.02 Spring 2012 Lecture 25, Slide #30

Kahn's Rules for Interconnection

- Each network is independent and must not be required to change
- Best-effort communication
- Boxes (then called *gateways*) connect networks
- No global control at operations level (why?)

Original TCP paper


A Protocol for Packet Network Intercommunication
VINTON G. CERF AND ROBERT E. KAHN

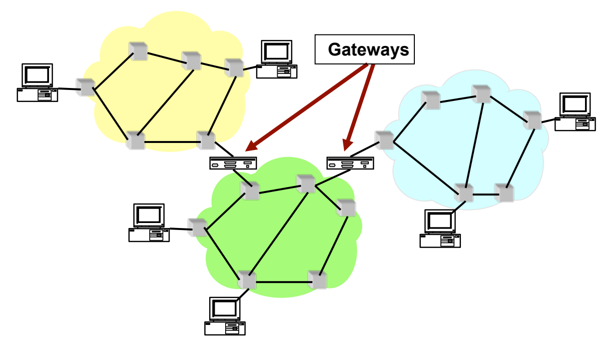
Cerf RFC 968

```
Twas the night before start-up and all through the net,
  not a packet was moving; no bit nor octet.
The engineers rattled their cards in despair,
  hoping a bad chip would blow with a flare.
The salesmen were nestled all snug in their beds,
  while visions of data nets danced in their heads.
And I with my datascope tracings and dumps
  prepared for some pretty bad bruises and lumps.
When out in the hall there arose such a clatter,
  I sprang from my desk to see what was the matter.

There stood at the threshold with PC in tow,
  An ARPANET hacker, all ready to go.
I could see from the creases that covered his brow,
  he'd conquer the crisis confronting him now.
More rapid than eagles, he checked each alarm
  and scrutinized each for its potential harm.
```

6.02 Spring 2012

Solution



Slide: Scott Shenker, UC Berkeley

6.02 Spring 2012 Lecture 25, Slide #32

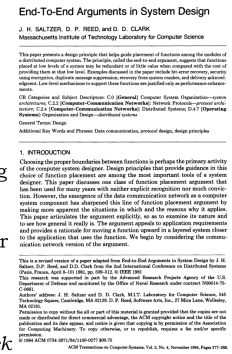
The Internetworking Vision

- Bob Kahn & Vint Cerf imagined there would be only a few networks and thus only a few gateways
  - *"The choice for network identification (8 bits) allows up to 256 distinct networks. This size seems sufficient for the foreseeable future."*
  - They were a little wrong!
- Gateways would "translate" between networks
  - Evolved in the 1974 Cerf/Kahn paper as a universal network layer, later called the *Internet Protocol,* or IP
  - We now think of it as all routers supporting IP

33

1970s: Internetworking

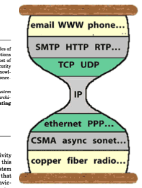
- 1978: **Layering**! TCP and IP split; TCP at end points, IP in the network
- IP network layer: simple best-effort delivery
- In retrospect: Packet switching (& TCP/IP) won because it is good enough for almost every application (though optimal for nothing!)
- Competitor to TCP/IP: ISO, standardizing 7-layer *OSI stack*


End-To-End Arguments in System Design

J. H. SALTZER, D. P. REED, and D. D. CLARK
Massachusetts Institute of Technology Laboratory for Computer Science

1. INTRODUCTION

Classic Internet layering "hourglass" model



Most Useful Lessons

One should architect systems for flexibility – you'll almost never know what apps make it succeed.

(Even if it means sacrificing some performance!)

Il semble que la perfection soit atteinte non quand il n'y a plus rien à ajouter, mais quand il n'y a plus rien à retrancher.

Perfection is achieved, not when there is nothing more to add, but when there is nothing left to take away

-- Antoine de Saint-Exupery

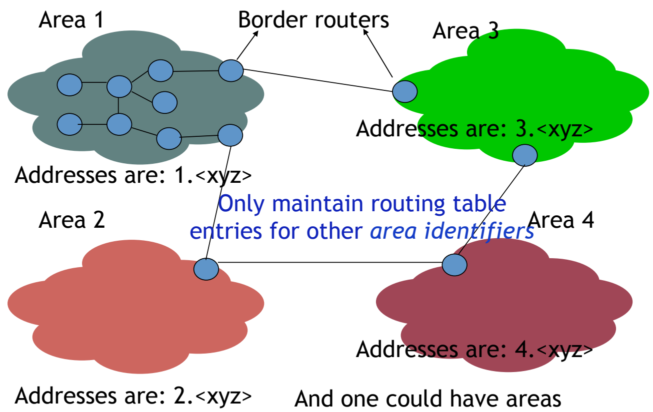
Or,

When in doubt, leave it out

1980s: Handling Growth with Topological Addressing

- 1978-79: ARPANET moves to link-state routing
- Per-node routing entries don't scale well
- Solution: Organize network hierarchically
  - Into "areas" or "domains"
  - Similar to how the postal system works
  - Hide detailed information about remote areas
- For this approach to work, node addresses must be *topological*
  - Address should tell network *where* in the network the node is
  - I.e., address is a *location* in the network
- Three classes of addresses in the 80s: "Class A", "Class B", and "Class C"
  - Not used any more, though the dotted decimal notation of IPv4 addresses makes it look like the dots matter

Ideal Case: Classic "Area Routing"



And one could have areas within areas, etc.

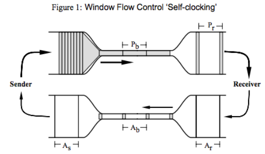
1980s: Rapid Growth

- 1981-89: Dave Clark of MIT is Internet's "Chief Architect"
  - Co-author of the end-to-end arguments (w/ Saltzer/Reed)
  - Ensures consistency of design and vision
  - *"We reject kings, presidents, and voting. We believe in rough consensus and running code."*
- 1982: US DoD standardizes on TCP/IP
  - Berkeley's computer systems research group produces BSD & sockets
- 1983: MIT Project Athena – large-scale campus-area networking
- 1984: Domain Name System (DNS) introduced
- 1985: NSFNet picks TCP/IP as standard

Growth Problems: Congestion

- 1986: Congestion collapse episodes on the Internet
  - Problems with bad timeout settings
  - Window size not appropriate for network state
  - Athena network file system congestion problems (bad timeout settings)
- *Congestion avoidance and control*
  - *RTT estimation using EWMA + new timeout method*
  - TCP congestion control by Van Jacobson (parallel work on DECBit scheme by Ramakrishnan & Jain)
  - Adapt the window size to congestion: If congested, decrease window; else increase. Use exponential back-offs on timeouts
  - By the end of the 1980s, essentially all running TCPs had congestion control

Figure 1: Window Flow Control 'Self-clocking'

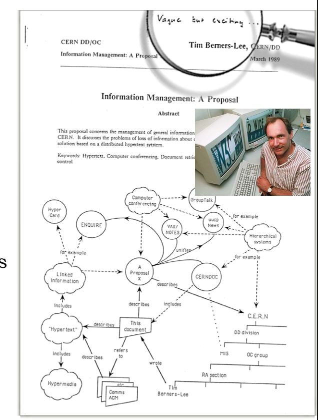


Jacobson

Jain

1990s

- 1990: no more ARPANET
- 1991: Tim Berners-Lee releases "WorldWideWeb
- Mid-1990s: NSFNet backbone ends
  - Commercial ISPs take off
- "Classless" addressing for scale
  - And the rise of NATs
- BGP4: *Path vector protocol* between competing ISPs, who must yet cooperate
- 1991-1994: IPng & IPv6 design starts
- 1993: search engines (Excite)
- Mid-1990s: E-commerce starts
- 1998: Google reinvents search
- 1998: Content distribution networks like Akamai
- 1996-2001: .com bubble starts & bursts



1990s: Handling Growth with CIDR IPv4 Addresses & Address Prefixes

- 18.31.0.82 is actually the 32 bit string 00010010000111110000000001010010
- Routers have forwarding table entries corresponding to an address **prefix** (a range of addrs w/ common prefix bitstring)
- 18.0.0.0/8 stands for all IP addresses in the range 00010010 00…0 to 00010010 11…1 (i.e., 2^{24} addresses of the form 00010010*)
- 18.31.0.0/17 stands for a range of 2^{15} consecutive IP addresses of the form 00010010001111100* (1st 17 bits are the same for each address in that range)
- Hence, *subnetworks* may be of size 1, 2, 4, 8, … (maxing out at 2^{24} usually), and may be recursively divided further
- Forwarding uses **longest prefix match**
  - At each router, routes are of the form "For this range of addresses, use this route"
  - Pick the route that has the longest matching prefix w/ dest addr

2000s: The Internet Matures (Top 5 List)

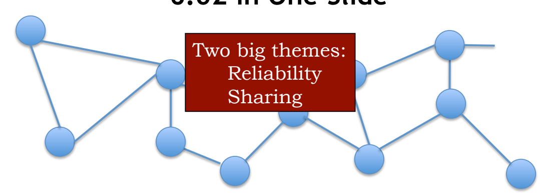
- 2000-2001: .com bust
  - And 9/11 happens
  - Power of content distribution networks to handle load
1. The rise of peer-to-peer networks
   - Gnutella, Freenet, distributed hash tables (e.g., Chord), BitTorrent, and of course, Napster
2. Security threats and defenses
   - 2000: Large-scale distributed denial-of-service (DDoS) attacks start
   - 2003: SQL slammer worm
   - Spam → phishing and pharming → complex ecosystem
   - Route hijacking by errors or malice
3. User-generated content & social networks
   - Blogs, Youtube, Facebook, and Twitter (UGC-meets-social)
4. The rise of wireless and mobile data
5. Cloud computing and large-scale datacenters (Amazon, Google, Microsoft, Facebook, etc.)

- *Almost* everything moves to the Internet: telephony, video, entertainment

2010s: The Decade Ahead

- Even more massive growth (largely from video, entertainment, and collaboration) & internationalization
- Combating complexity: new methods to make things simpler ("software-defined networks")
- Wireless: the spectrum challenge and mobility
- Physical embedding & embodiment: sensors & actuators over the network, mobile robots and autonomous agents, …
- And, surely, new applications that I'm incapable of imagining!

6.02 in One Slide



How to design digital communication networks.
Three layers of abstraction: bits, signals, packets.
A unique storyline: vertical study across all layers

Bits: Binary representation. Compression (source coding). Bit errors and error correction codes (channel coding)

Signals: Noise. LTI models. Frequency-domain analysis. Modulation & demodulation.

Packets: MAC protocols for shared media. Packet-switching & queues. Routing protocols. Reliable transport.

What Next?

- Many UROP opportunities!
- Networks and computer systems
  - 6.033 (computer systems), 6.829 (computer networks), 6.824 (distributed systems), 6.263 (analysis of networks), 6.266 (network algorithms)
- Security/privacy
  - 6.857 (computer and network security), 6.858 (computer systems security)
- Signal processing & digital communications
  - 6.003 (signals and systems), 6.011 (communications, control, and signal processing)
- Advanced communication & information theory
  - 6.450 & 6.451 (digital communications), 6.441 (info theory)

Thank you!

- Lectures
  - Hari Balakrishnan
  - Vladimir Stojanovic
- Recitations
  - Vincent Chan
  - Katrina LaCurts
  - Sidhant Misra
- TAs
  - Omid Aryan
  - Sungwon Chung
  - Nathan Lachenmyer
  - Jared Monnin
  - Muyiwa Ogunnika
  - Sunghyun Park
  - Anirudh Sivaraman

- This week
  - Tu rec: mulligan review
  - Th rec: Quiz 3 review
  - W: no lecture (office hrs)
- Quiz 3: May 22 at 1.30 pm in Johnson (conflict quiz May 22 at 9 am in 34-301)
  - Mulligan: one hour; *right after* the two-hour Quiz 3