CS433/533: Computer Networks

Y. Richard Yang

http://zoo.cs.yale.edu/classes/cs433/

8/29/2013

Outline

- Administrative trivia’s
- What is a network protocol?
- A brief introduction to the Internet: past and present
- Challenges of Internet network and app
- Summary

Personnel

- Instructor
  - Y. Richard Yang, yry@cs.yale.edu, AKW 308A
    - office hours
      - TTh 4:00-5:00 pm or by appointment
      - please feel free to stop by if you see I am in my office

- Teaching assistant
  - Jason Wang, AKW 302
    - office hours: TBP

Textbook

- Textbook
  - Computer Networking: A Top-Down Approach, 6/e by Jim Kurose and Keith Ross

- Reference books
  - Computer Networks by Tanenbaum and Wetherall
  - Computer Networks: A Systems Approach by Larry Peterson and Bruce Davie
  - TCP/IP Illustrated, Volume 1: The Protocols by W. Richard Stevens
  - Java Network Programming, by Elliotte Harold

- Resources
  - http://zoo.cs.yale.edu/classes/cs433

What are the Goals of this Course?

- Learn design principles and techniques of:
  - the Internet infrastructure
  - large-scale Internet applications

- Focus on how the principles and techniques apply and adapt in real world:
  - real examples from the Internet

What Do You Need To Do?

- Please return the class background survey
  - help us determine your background
  - help us determine the depth, topics, and assignments
  - suggest topics that you want to be covered (if you think of a topic later, please send me email)

- Your workload
  - homework assignments
    - written assignments
    - programming assignments
  - two exams
Grading

Exams 30%
Assignments 60%
Class Participation 10%

Subject to change after I know more about your background
More important is what you realize/learn than the grades!!

Outlines

- Administrative trivia’s
  - What is a network protocol?

What is a Network Protocol?

- A network protocol defines the format and the order of messages exchanged between two or more communicating entities, as well as the actions taken on the transmission and/or receipt of a message or other events.

Example Protocol: Simple Mail Transfer Protocol (SMTP)

- Messages from a client to a mail server
  - MAIL FROM: <address>
  - RCPT TO: <address>
  - DATA
    - This is the text and a line with a single .
  - QUIT

- Messages from a mail server to a client
  - The first digit of the response broadly indicates the success, failure, or progress of the previous command.
    - 1 – Informational response
    - 2 – Command ok
    - 3 – Command ok so far, send the rest of it
    - 4 – Command was correct, but couldn’t be performed for some reason.
    - 5 – Command unimplemented, or incorrect, or a serious program error occurred.
  - CONTENT

Example: TCP Protocol Handshakes

Command: Telnet netra.cs.yale.edu smtp

Questions?
Protocol Standardization

- Most widely used protocols are defined in standards
- Why standard?

Internet Standardization Process

- All standards of the Internet are published as RFC (Request for Comments)
  - e.g., the SMTP protocol is specified in RFC821
  - but not all RFCs are Internet Standards: [http://zoo.cs.yale.edu/classes/cs433/cs433-2013-fall/readings/interestingrfcs.html](http://zoo.cs.yale.edu/classes/cs433/cs433-2013-fall/readings/interestingrfcs.html)

Internet Standardization Process

- A typical (but not the only) way of standardization:
  - Internet draft
  - RFC
  - proposed standard
  - draft standard (requires 2 working implementations)
  - Internet standard (declared by Internet Architecture Board)
- David Clark, 1992: We reject: kings, presidents, and voting. We believe in: rough consensus and running code.

Outline

- Administrative trivia’s
- What is a network protocol?
  - A brief introduction to the Internet
  - past (a brief history)
  - present

Prelude: Packet Switching and ARPANET

- 1957
  - USSR launched Sputnik; US DoD formed Advanced Research Projects Agency (ARPA)
- 1961
  - First paper by Len Kleinrock on packet switching theory
- 1964
  - Paul Baran from RAND on design of packet switching networks
- 1965-1968
  - ARPANET plan
  - Bolt Beranek and Newman Inc. (BBN), a small company, was awarded Packet Switch contract to build Interface Message Processors (IMPs)

Internet 1.0: Initial ARPANET

- 1969
  - ARPANET commissioned: 4 nodes, 50kbps

Page 3
Initial Expansion of the ARPANET

1969: Lay the groundwork
1970: ALOHAnet, the first packet radio network, developed by Norman Abramson, Univ of Hawaii, becomes operational
1971: ARPANET, packet radio network, starts operations
1972: Mail network becomes operational
1973: Telnet packet service begins
1974: Telnet and TELNET become operational
1975: X.25 implemented
1976: More services and subnetworks added
1977: NSFnet project begins to provide backbone service
1978: TCP/IP becomes operational
1979: Internet Protocol Suite (IP) becomes operational
1980: Internet Protocol Suite (IP) becomes operational
1981: BITNET between CUNY and Yale
1982: NSFnet backbone becomes operational
1983: NSFnet backbone upgrades to 1.5Mbps
1984: Internet congestion collapse
1985: Internet congestion collapse
1986: Internet congestion collapse
1987: Internet congestion collapse
1988: Internet congestion collapse
1989: Internet congestion collapse
1990: ARPANET ceases to exist
1991: NSF lifts restrictions on the commercial use of the Internet
1992: 1 million hosts (RFC 1300: Remembrances of Things Past)
1993: 5 million hosts
1994: 10 million hosts
1995: 20 million hosts
1996: 50 million hosts
1997: 100 million hosts
1998: Google was founded
1999: 200 million hosts
2000: 500 million hosts
2001: 1 billion hosts
2002: 2 billion hosts
2003: 5 billion hosts
2004: Facebook was founded
2005: 10 billion hosts
2006: Amazon AWS cloud computing
2007: 20 billion hosts
2008: 40 billion hosts
2009: 60 billion hosts
2010: 80 billion hosts
2011: 100 billion hosts
2012: 120 billion hosts
2013: 140 billion hosts
2014: 160 billion hosts
2015: 180 billion hosts
2016: 200 billion hosts
2017: 220 billion hosts
2018: 240 billion hosts
2019: 260 billion hosts
2020: 280 billion hosts
2021: 300 billion hosts
2022: 320 billion hosts
2023: 340 billion hosts
2024: 360 billion hosts
2025: 380 billion hosts
2026: 400 billion hosts
2027: 420 billion hosts
2028: 440 billion hosts
2029: 460 billion hosts
2030: 480 billion hosts
2031: 500 billion hosts
2032: 520 billion hosts
2033: 540 billion hosts
2034: 560 billion hosts
2035: 580 billion hosts
2036: 600 billion hosts
2037: 620 billion hosts
2038: 640 billion hosts
2039: 660 billion hosts
2040: 680 billion hosts
2041: 700 billion hosts
2042: 720 billion hosts
2043: 740 billion hosts
2044: 760 billion hosts
2045: 780 billion hosts
2046: 800 billion hosts
2047: 820 billion hosts
2048: 840 billion hosts
2049: 860 billion hosts
2050: 880 billion hosts
2051: 900 billion hosts
2052: 920 billion hosts
2053: 940 billion hosts
2054: 960 billion hosts
2055: 980 billion hosts
2056: 1 trillion hosts

Growth of the Internet

1981: BITNET (Because It’s Time NETwork) between CUNY and Yale
1986: NSF build NSFNET as backbone, linked 6 supercomputer centers, 56 kbps: this allows an explosion of connections, especially from universities
1987: 10,000 hosts
1988: NSFNET backbone upgrades to 1.5Mbps
1988: Internet congestion collapse, TCP congestion control
1989: 100,000 hosts
RFC 1221: Act One - The Poem
WELCOME by Leonard Kleinrock
We’ve gathered here for two days to examine and debate And reflect on data networks and as well to celebrate To recognize the leaders and recount the path we took. We’ll begin with how it happened, for it’s time to take a look Yet the factory is legend and the pioneers are here. Listen to the story — It’s our job to make it clear We’ll tell you where we are now and where we’ll likely go. So welcome to ACT ONE, folks. Sit back — enjoy the show!!

Internet 2.0: Web, Commercialization, Social Networking of the Internet

1990: ARPANET ceases to exist
1991: NSF lifts restrictions on the commercial use of the Net; Berners-Lee of European Organization for Nuclear Research (CERN) released World Wide Web
1992: 1 million hosts (RFC 1300: Remembrances of Things Past)
1998: Google was founded
2004: Facebook was founded
2006: Amazon AWS cloud computing

For a link of interesting RFCs, please see http://zoo.cs.yale.edu/classes/cs433/cs433-2013-fall/readings/interestingrfcs.html
For more on Internet history, please see http://www.zakon.org/robert/internet/timeline/

Internet 3.0: Always-Connected, Virtualized Life

Office => Virtual workspace
Shopping => Online shopping
Education => Remote education
Entertainment => Online media/games

Growth of the Internet in Terms of Number of Hosts

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of Hosts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug. 1981</td>
<td>213</td>
</tr>
<tr>
<td>Oct. 1984</td>
<td>1,024</td>
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<tr>
<td>Dec. 1987</td>
<td>28,174</td>
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<tr>
<td>Oct. 1990</td>
<td>313,000</td>
</tr>
<tr>
<td>Jul. 1993</td>
<td>1,776,000</td>
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<tr>
<td>Jul. 1996</td>
<td>12,881,000</td>
</tr>
<tr>
<td>Jul. 1999</td>
<td>56,218,000</td>
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<tr>
<td>Jul. 2002</td>
<td>162,128,493</td>
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<tr>
<td>Jul. 2005</td>
<td>353,284,187</td>
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<tr>
<td>Jul. 2008</td>
<td>570,937,778</td>
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<tr>
<td>Jul. 2011</td>
<td>849,869,781</td>
</tr>
<tr>
<td>Jul. 2013</td>
<td>996,230,757</td>
</tr>
</tbody>
</table>

The Internet Becomes a Network of Networks

1970: ALOHAnet, the first packet radio network, developed by Norman Abramson, Univ of Hawaii, becomes operational
1973: Bob Kahn posed the Internet problem—how to connect ARPANET, packet radio network, and satellite network
1974: Vint Cerf, Bob Kahn publish initial design of TCP (NCP) to connect multiple networks
- 1978: TCP (NCP) split to TCP/IP
- 1983: TCP (NCP) converted to TCP/IP (Jan. 1)
Outline

- Administrative trivia’s
- What is a network protocol?
  - A brief introduction to the Internet
    - past
    - present

Internet Physical Infrastructure

- Residential access
  - Cable
  - Fiber
  - DSL
  - Wireless
- Backbone ISP
- ISP

The Internet is a network of networks
- Each individually administrated network is called an Autonomous System (AS)

Access: Fiber to the x

- Access: Fiber to the Premises (FTTP)
  - Deployed by Verizon, AT&T, Google
  - One of the largest comm. construction projects

FTTP Architecture

- Optical Network Terminal (ONT) box outside dwelling or business
- Fiber Distribution Terminal (FDT) in poles or pedestals
- Fiber Distribution Hub (FDH) at street cabinet
- Optical Line Terminal (OLT) at central office

Access: Fiber to the Premises (FTTP)

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FTTP Architecture

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FTTP Architecture: To Home

- Backbone fiber ring on primary arterial streets (brown)
- Local distribution fiber plant (red) meets backbone at cabinet

FTTP Architecture: Central to Fiber Distribution Hub (FDH)

Access: DSL

- Compared with FTTP, copper from cabinet (DSLAM) to home

Access: Cable

- Fiber node: 500 - 2K homes
- Distribution hub: 20K - 40 K homes
- Regional headend: 200 K - 400 K homes

Also called Hybrid Fiber-coaxial Cable (HFC)

Campus Network
Recall: Internet Physical Infrastructure

The Internet is a network of networks. Each individually administrated network is called an Autonomous System (AS).

Cable
Fiber
DSL
Wireless
ISP
ISP
ISP
ISP
ISP
ISP

Yale Internet Connection

Try traceroute from Yale to:
- microsoft.com
- facebook.com
- google.com
- amazon.com

Internet2

http://atlas.grnoc.iu.edu/atlas.cgi?map_name=Internet2%20IP%20Layer

Quest Backbone Map

http://www.qwest.com/largebusiness/enterprisesolutions/networkMaps/preloader.swf
Internet ISP Connectivity

- Roughly hierarchical
  - Divided into tiers
  - Tier-1 ISPs are also called backbone providers, e.g., AT&T, Verizon, Sprint, Level 3, Qwest
- An ISP runs (private) Points of Presence (PoP) where its customers and other ISPs connect to it
- ISPs also connect at (public) Internet Exchange Point (IXP) where public peering occurs

http://en.wikipedia.org/wiki/List_of_Internet_exchange_points_by_size

Outline

- Administrative trivia's
- What is a network protocol?
  - A brief introduction to the Internet
    - Past
    - Present
      - Topology
      - Traffic

Internet (Consumer) Traffic

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<tbody>
<tr>
<td>Total (Tbps/month)</td>
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<td>Fixed</td>
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<td>Mobile</td>
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<td>Internet access</td>
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<td>Internet sales</td>
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<td>Data, video, and voice</td>
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<td>F2L sharing</td>
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<td>Online gaming</td>
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<td>By geography (Tbps/month)</td>
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<td>Asia Pacific</td>
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<td>North America</td>
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<td>Western Europe</td>
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<td>Central and Eastern Europe</td>
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<td>Latin America</td>
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<td>Middle East and Africa</td>
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<td>Total (Tbps/month)</td>
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</table>

Internet Traffic in Perspective

Developers who have worked at the small scale might be asking themselves why we need to bother when we could just use some kind of out-of-the-box solution. For small-scale applications, this can be a great idea. We save time and money up front and get a working and serviceable application. The problem comes at larger scales—there are no off-the-shelf kits that will allow you to build something like Amazon... There's a good reason why the largest applications on the Internet are all bespoke creations: no other approach can create massively scalable applications within a reasonable budget.

http://www.evontech.com/symbian/55.html

Outline

- Administrative trivia's
- What is a network protocol?
  - A brief introduction to the Internet
    - Past
    - Present
      - Challenges of Internet network and app

Scale

"Developers who have worked at the small scale might be asking themselves why we need to bother when we could just use some kind of out-of-the-box solution. For small-scale applications, this can be a great idea. We save time and money up front and get a working and serviceable application. The problem comes at larger scales—there are no off-the-shelf kits that will allow you to build something like Amazon... There’s a good reason why the largest applications on the Internet are all bespoke creations: no other approach can create massively scalable applications within a reasonable budget."
Increasing QoE Demand

- 20 ms increase in latency
  \[\Rightarrow \] 1% drop in click-through rate

Politics: Sharing a Shared Infrastructure

- question: how to allocate network resources among users?

Poor App and Network Interaction

- Network Providers change routing to shift traffic away from highly utilized links
- Adaptive/decentralized apps direct traffic to lower latency paths
  - Equilibrium points can be inefficient

Autonomous (“Selfish”) App

- Assume each link has a latency function \(l_e(x)\): latency of link \(e\) when \(x\) amount of traffic goes through \(e\):

  \[
  \text{total traffic} = x
  \]

  \[
  \log = 1
  \]
**App and Network Interaction**

![Graph showing network latency and link utilization](image)

**Decentralized (“Selfish”) Users**

![Network diagram](image)

**Fast Wireless Data Growth**

![Data growth chart](image)

**Decentralized (“Selfish”) Users**

![Network diagram](image)

**Flexibility vs Performance**

![Balance scale diagram](image)

**What Will We Cover?**

- A tentative schedule will be posted at class schedule page
- Network architecture and design principles
  - Layered network architecture principle
- Application architecture and design principles
  - Application paradigms; high performance network app.
  - HTTP/Web, Email, DNS, Content distribution
- Transport
  - Transport services
  - Reliability; distributed resource allocation; primal-dual
  - Transport protocols: TCP/UDP
What Will We Cover?

- Network
  - network services
  - distributed, asynchronous, autonomous routing algorithms; scalable router design
  - IP/IPv6; mobile IP; cellular networks
- Link and physical
  - multiple access; queuing analysis; capacity analysis
  - Ethernet, 802.11, CDMA, Bluetooth
- Data center design
- Network security
  - security primitives; BAN logic, SSL

Summary

- Course administration
  - A protocol defines the format and the order of messages exchanged between two or more communicating entities, as well as the actions taken on the transmission and/or receipt of a message or other events.
- The past:
  - Facts:
    - The Internet started as ARPANET in the 1960s
    - The initial link bandwidth was 50 kbps
    - The number of hosts at the end of 1969 was 4
  - Some implications of the past:
    - ARPANET is sponsored by ARPA — design should survive failures
    - The initial IMPs were very simple — keep the network simple
    - Many networks need a network to connect networks
- Current:
  - The number of hosts connected to the Internet is around 1 billion.
  - The backbone speed of the current Internet is about 40/100 Gbps.
  - The Internet is roughly hierarchical where ISPs interconnect at PoPs and IXPs.
  - Needs to handle scale, decentralization, mobility, security

Preview

- We have only looked at the topology/connectivity of the Internet
  - A communication network is a mesh of interconnected devices
- A fundamental question: how is data transferred through a network?

Backup Slides

Challenge of the Internet: Characterizing Internet Topology

Challenge of the Internet: Power Law?

- Some researchers found that the Internet AS connectivity graph satisfies Power Law.
- Does it really satisfy power law? If so, why?

Note that the plot is a line in log-log scale.
An Example: Network News Transport Protocol (NNTP)

Messages from a client to a news server
- help
- list active <pattern>
- group <group_name>
- article <article_number>
- next
- post

Messages from a news server to a client
- status code
  - The first digit of the response broadly indicates the success, failure, or progress of the previous command.
    - 1xx - Informative message
    - 2xx - Command ok
    - 3xx - Command ok so far, send the rest of it.
    - 4xx - Command was correct, but couldn't be performed for some reason.
    - 5xx - Command unimplemented, or incorrect, or a serious program error occurred.
- content

Internet (Global) Traffic

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Rate (Gbps) per Month</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consumer</td>
<td>45.375</td>
<td>58.850</td>
<td>74.480</td>
</tr>
<tr>
<td>Business</td>
<td>112.025</td>
<td>120.885</td>
<td>141.265</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>By Geography (Gbps) per Month</th>
</tr>
</thead>
<tbody>
<tr>
<td>Americas</td>
</tr>
<tr>
<td>Europe</td>
</tr>
<tr>
<td>Global Traffic</td>
</tr>
</tbody>
</table>

Yale Internet Connectivity: Qwest

cindy.cs.yale.edu% /usr/sbin/traceroute www.synopsis.com

1. anger.net.yale.edu (128.36.229.1)  0.767 ms  1.740 ms  1.452 ms
2. bifrost.net.yale.edu (130.132.1.100)  0.489 ms  0.473 ms  0.472 ms
3. bos-edge-02.inet.qwest.net (63.145.0.13)  4.897 ms  5.270 ms  5.384 ms
4. bos-core-01.inet.qwest.net (205.171.28.13)  4.918 ms  5.405 ms  4.898 ms
5. ewr-core-02.inet.qwest.net (205.171.8.114)  11.998 ms  11.688 ms  11.647 ms
6. ewr-brdr-02.inet.qwest.net (205.171.17.130)  11.432 ms  12.036 ms  11.474 ms
7. 205.171.1.98 (205.171.1.98)  7.547 ms  7.727 ms  7.632 ms
9. ae-1-54.bbr2.NewYork1.Level3.net (4.68.97.97)  7.585 ms  7.585 ms  7.585 ms
10. ge-0-1-0.bbr2.SanJose1.Level3.net (64.159.1.130)  75.468 ms  82.720 ms  86.392 ms
11. so-0-0-0.bbr1.SanJose1.Level3.net (64.159.1.133)  75.630 ms  75.630 ms  75.630 ms
12. ge-9-0.hsa1.SanJose1.Level3.net (4.68.123.40)  75.499 ms  76.429 ms  76.431 ms
13. h1.synopsysmv.bbnplanet.net (4.25.120.46)  86.414 ms  85.996 ms  85.896 ms
14. 198.182.56.45 (198.182.56.45)  88.705 ms  92.585 ms  90.412 ms

Note: which link Yale will use depends on its current load balancing. It may not be qwest.

Yale Internet Connectivity: AT&T

cindy.cs.yale.edu% /usr/sbin/traceroute www.amazon.com

1. anger.net.yale.edu (128.36.229.1)  0.906 ms  1.028 ms  0.784 ms
2. bifrost.net.yale.edu (130.132.1.100)  0.798 ms  0.722 ms  0.836 ms
3. 12.175.96.1 (12.175.96.1)  0.861 ms  0.869 ms  0.804 ms
4. 12.124.179.65 (12.124.179.65)  2.279 ms  2.276 ms  2.223 ms
5. gbr5-p80.n54ny.ip.att.net (12.123.1.202)  2.524 ms  2.314 ms  2.169 ms
6. tbr1-p013201.n54ny.ip.att.net (12.122.11.9)  3.212 ms  3.203 ms  3.560 ms
7. ggr2-p310.n54ny.ip.att.net (12.123.3.105)  3.045 ms  2.468 ms  2.419 ms
8. sl-bb20-nyc-12-0.sprintlink.net (144.232.8.49)  3.518 ms  2.748 ms  2.951 ms
9. sl-bb26-nyc-6-0.sprintlink.net (144.232.13.9)  4.690 ms  4.466 ms  4.531 ms
10. sl-bb23-pen-12-0.sprintlink.net (144.232.20.9)  7.181 ms  7.292 ms  7.033 ms
11. sl-amazon-4-0.sprintlink.net (144.223.246.18)  10.562 ms  10.572 ms  10.816 ms

Network Access Point

ATT Global Backbone IP Network

From http://www.business.att.com
Present Internet: Likely Web-based

- The Internet infrastructure has better support for HTTP than other protocols
- A trend of software applications:
  - From the desktop to the browser
  - SaaS == Web-based applications
  - Examples: Google Maps/Doc, Facebook
- How do we deliver highly-interactive Web-based applications?
  - AJAX (asynchronous JavaScript and XML)
  - For better, or for worse...

Evolving Computing Models

- Do it yourself (build your own data centers)
- Utility computing
  - Why buy machines when you can rent cycles?
  - Examples: Amazon's EC2, GoGrid, AppNexus
- Platform as a Service (PaaS)
  - Give me nice API and take care of the implementation
  - Example: Google App Engine
- Software as a Service (SaaS)
  - Just run it for me!
  - Example: Gmail; MS Exchange; MS Office Online

Data centers

- [http://www.youtube.com/watch?v=WBIl0curTxU](http://www.youtube.com/watch?v=WBIl0curTxU)
- [http://www.youtube.com/watch?v=PBx7rqq6G68](http://www.youtube.com/watch?v=PBx7rqq6G68)
- Google
  - [http://www.youtube.com/watch?v=ZRwPSFpLX8I](http://www.youtube.com/watch?v=ZRwPSFpLX8I)