CS433/533: Computer Networks

Y. Richard Yang

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

1/20/2016

Outline

- *Administrative trivia's*
- What is a network protocol?
- A brief introduction to the Internet: past and present
- Challenges of Internet networks and apps
- Summary

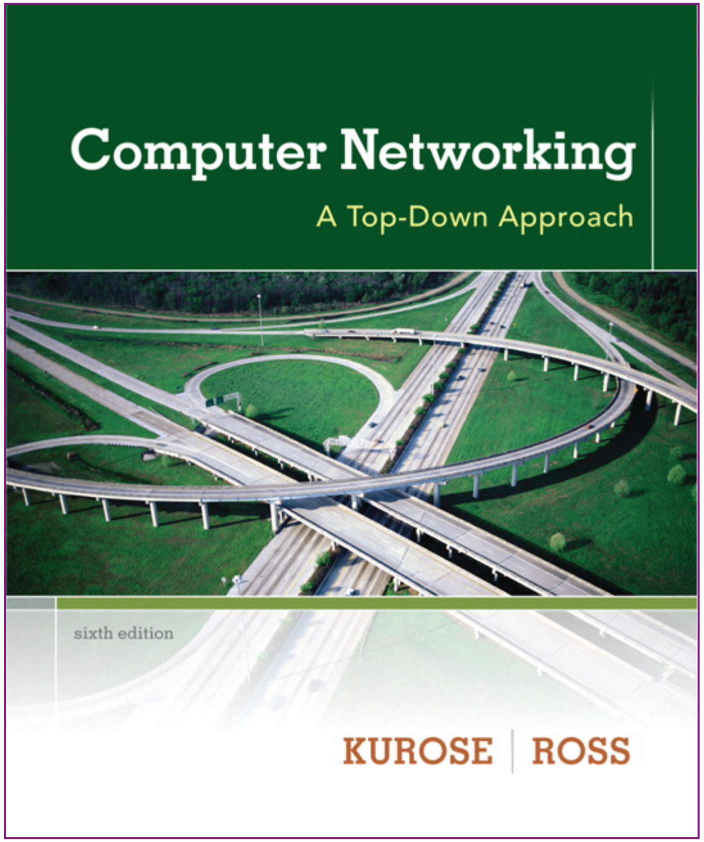
Personnel

- Instructor
  - Y. Richard Yang, yry@cs.yale.edu, AKW 208A
    - office hours
      - WM 2:00-3:00 pm or by appointment
      - please feel free to stop by if you see I am in my office

- Teaching assistants
  - Qiao Xiang, AKW 214
    - office hours TBA
  - Dan Peng, AKW 214
    - office hours TBA

Textbook

- Textbook
  - *Computer Networking: A Top-Down Approach, 6/e*
    by Jim Kurose and Keith Ross
    (7/e will become available in Apr)
- Reference books
  - *Computer Networks*
    by Tanenbaum and Wetherall on
  - *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 (ISP, data center, cloud)
  - 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
    - three programming assignments
      - one HTTP 1.1 server, one TCP, and one OpenStack network orchestrator [still debating]
  - one exam
  - one project

Grading

Exam	20%
Assignments and project	70%
Class Participation	10%

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

Questions?

Outline

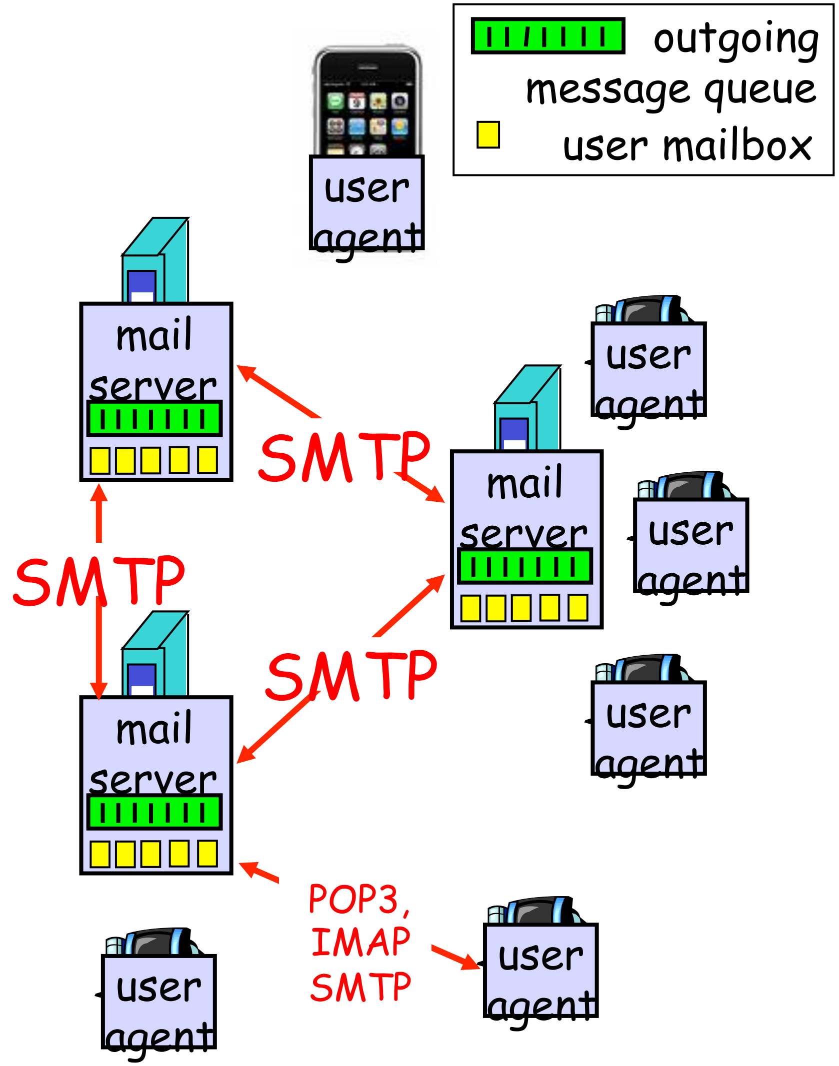
- Administrative trivia's
- *What is a network protocol?*

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.

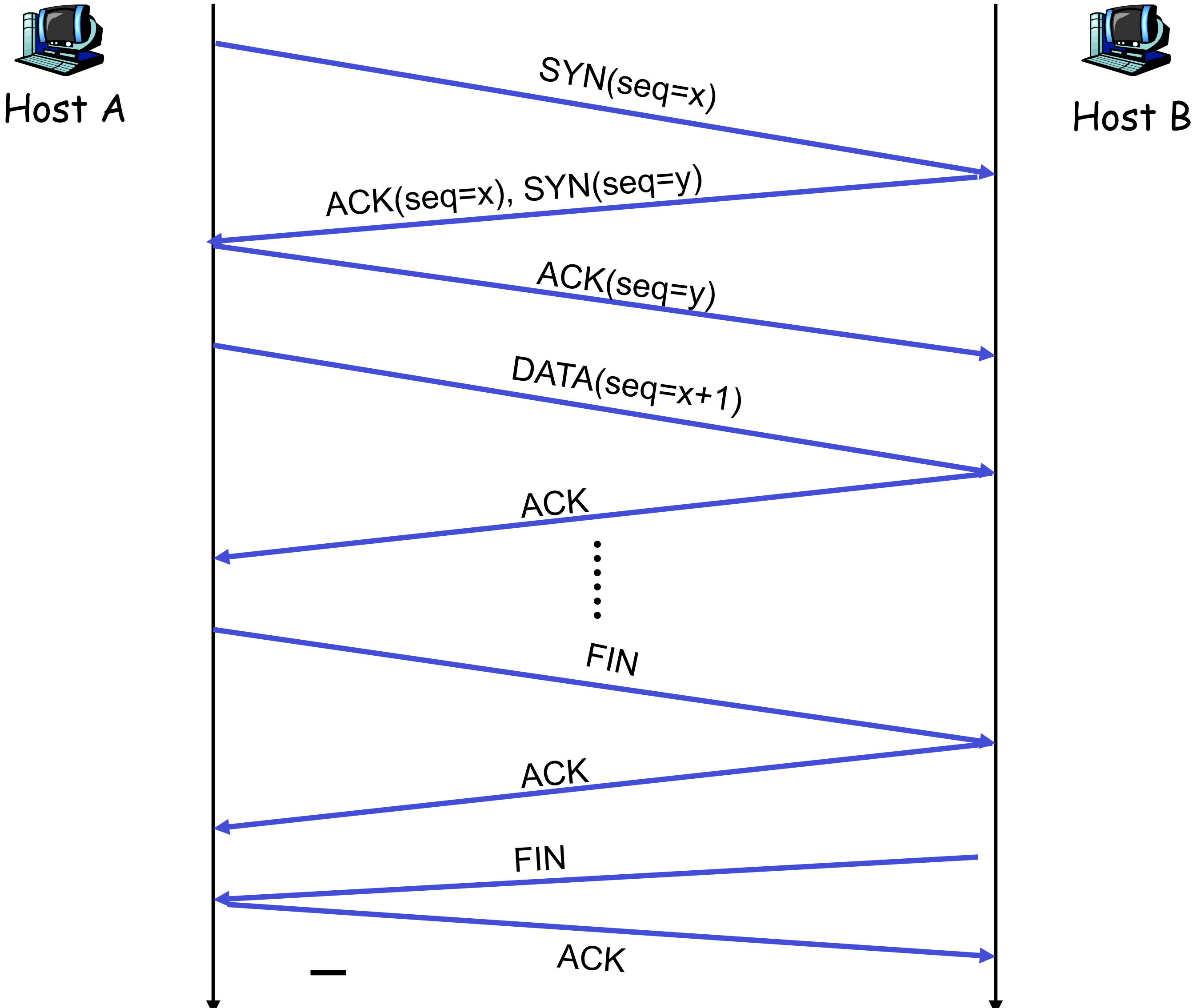
Example Protocol: Simple Mail Transfer Protocol (SMTP)

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



Command: %telnet netra.cs.yale.edu smtp

Example: TCP Protocol Handshakes



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/cs433-2016-spring/readings/interestingrfcs.html

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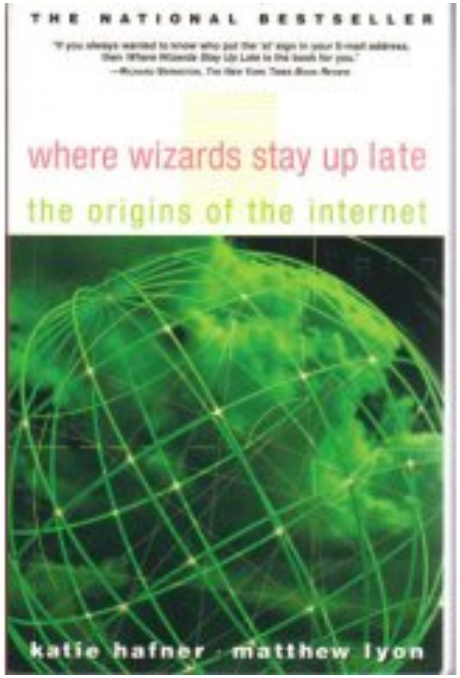
  - but not all RFCs are Internet Standards: http://zoo.cs.yale.edu/classes/cs433/cs433-2016-spring/readings/interestingrfcs.html
- A typical (but not the only) way of standardization:
  - Internet draft
  - RFC
  - proposed standard
  - draft standard (requires 2 working implementations)
  - Internet standard (declared by Internet Architecture Board)
- David Clark, 1992:

  We reject: kings, presidents, and voting. We believe in: rough consensus and running code.

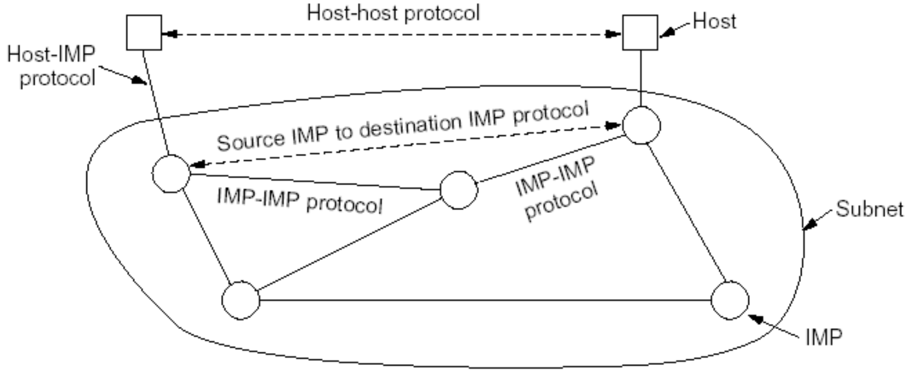
Outline

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



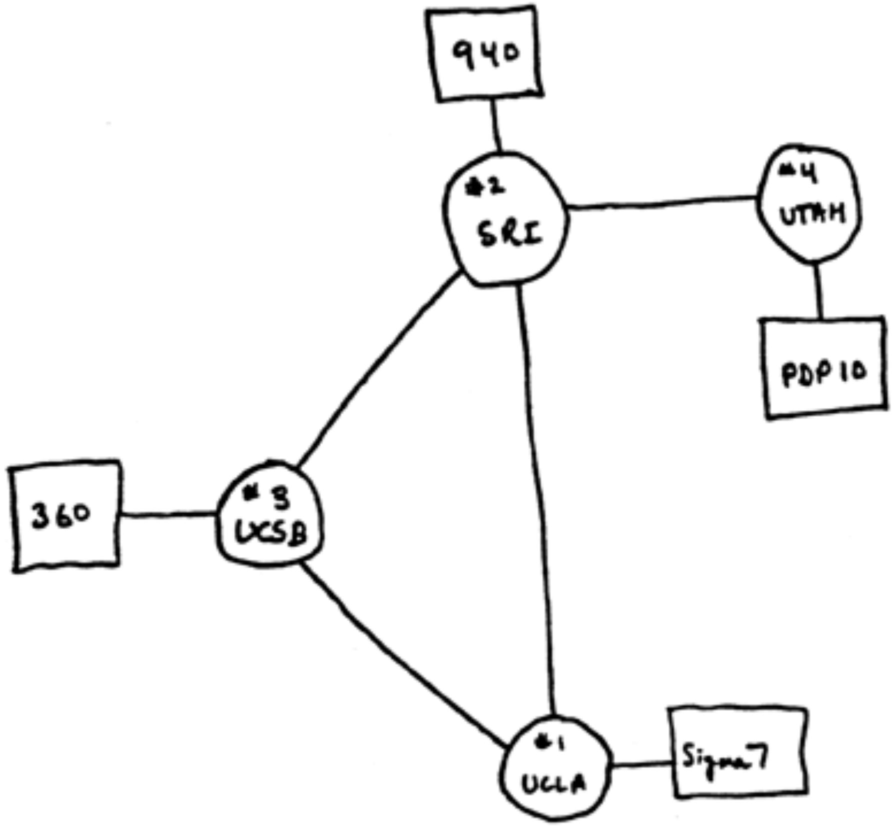
Prelude:
Packet Switching and ARPANET

- **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)

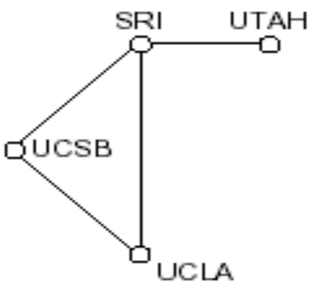


Internet 1.0: Initial ARPANET

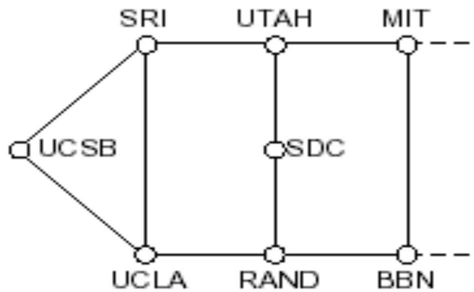
- 1969
  - ARPANET commissioned: 4 nodes, 50kbps



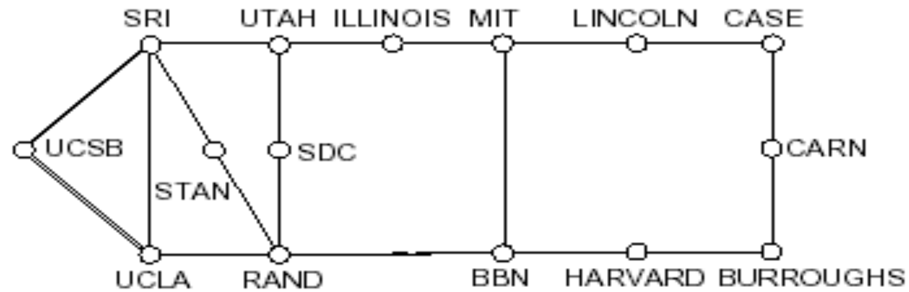
Initial Expansion of the ARPANET



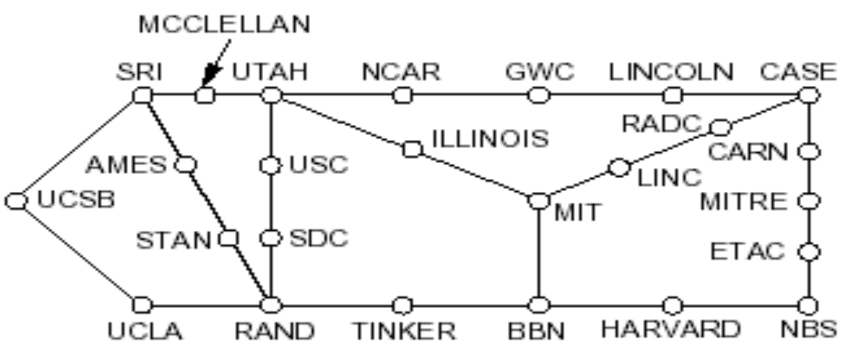
Dec. 1969

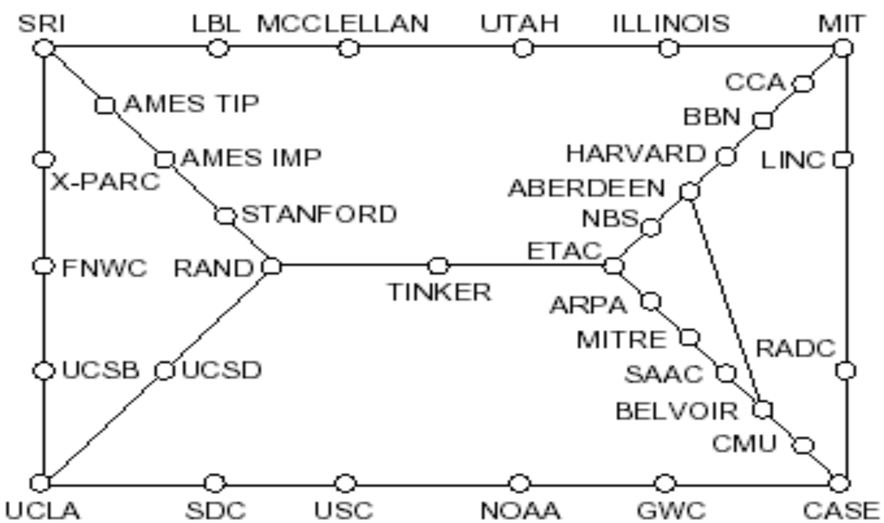


July 1970



Mar. 1971





Apr. 1972

Sept. 1972

RFC 527: ARPAWOCKY; RFC 602: The Stockings Were Hung by the Chimney with Care

The Internet Becomes a Network of Networks

- 1970: ALOHAnet, the first packet radio network, developed by Norman Abramson, Univ of Hawaii, becomed operational

- 1973: Bob Kahn posed the Internet problem---how to connect ARPANET, packet radio network, and satellite network

- 1974: Vint Cerf, Bob Kahn published 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)

Growth of the Internet

- 1981: BITNET (Because It's Time NETwork) between CUNY and Yale
- 1986: NSF builds NSFNET as backbone, links 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 1121: 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.
Yes, the history 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!!

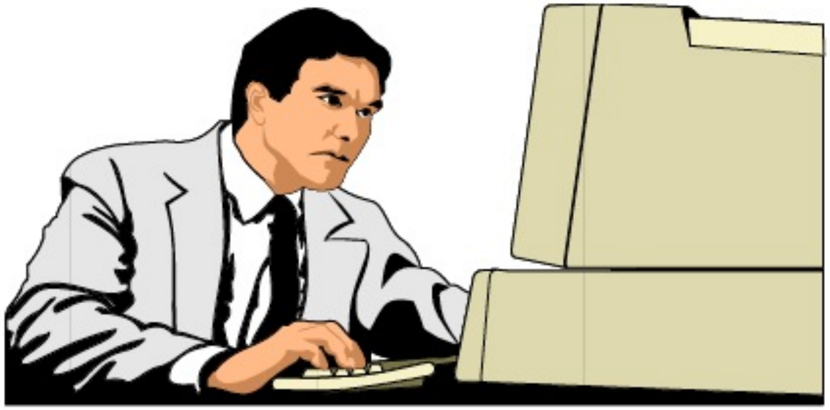
Internet 2.0: Web, Commercialization, Social Networking of the Internet

- 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/cs433-2016-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

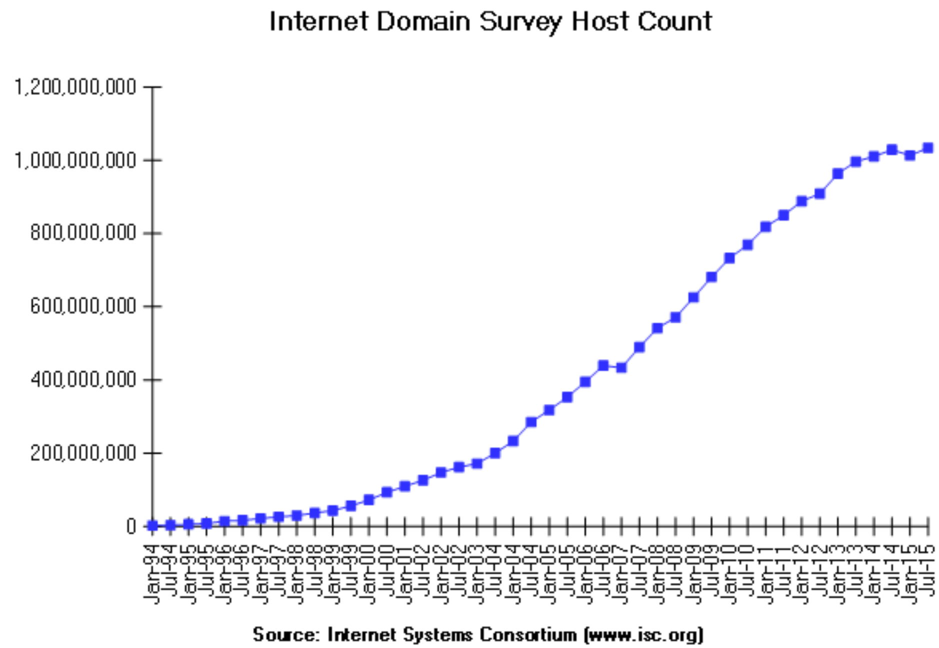


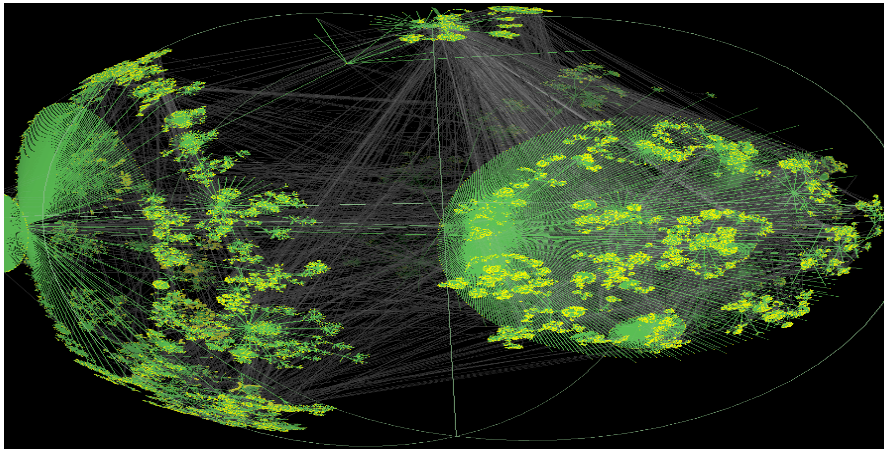
- Office => Virtual workspace
- Shopping => Online shopping
- Education => Remote education
- Entertainment $\Rightarrow$ Online media/games
- Environment $\Rightarrow$ Internet of things

Growth of the Internet in Terms of Number of Hosts

Number of Hosts on the Internet:

Aug.	1981	213
Oct.	1984	1,024
Dec.	1987	28,174
Oct.	1990	313,000
Jul.	1993	1,776,000
Jul.	1996	12,881,000
Jul.	1999	56,218,000
Jul.	2002	162,128,493
Jul.	2005	353,284,187
Jul.	2008	570,937,778
Jul.	2011	849,869,781
Jul.	2013	996,230,757
Jul.	2015	1,033,836,245





CAIDA router level view

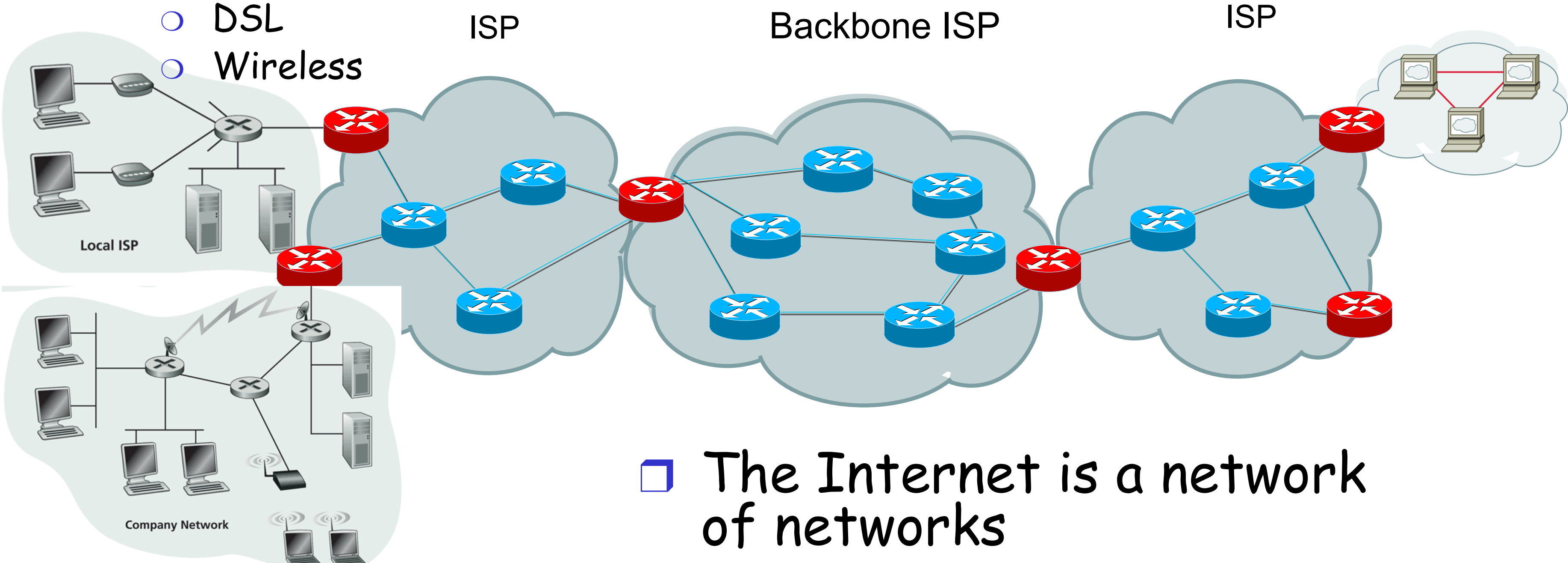
http://ftp.isc.org/www/survey/reports/current/

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

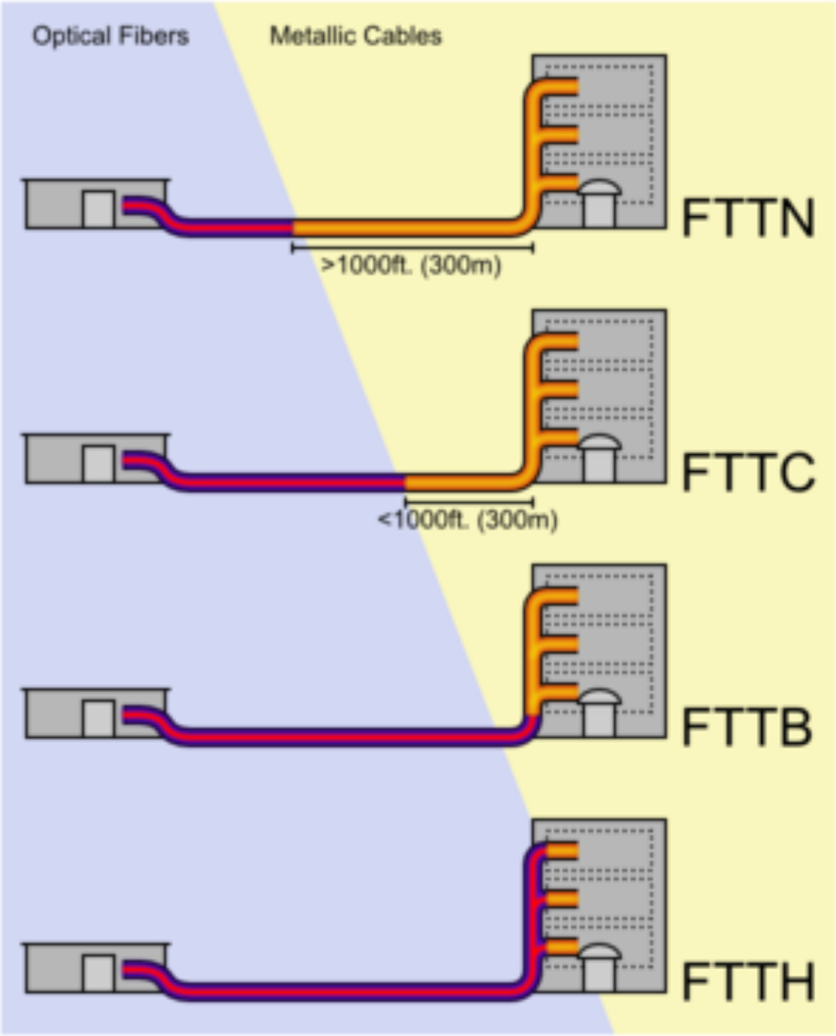


Campus access, e.g.,
- Ethernet
- Wireless

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

https://www.google.com/loon/how/

Access: Fiber to the x

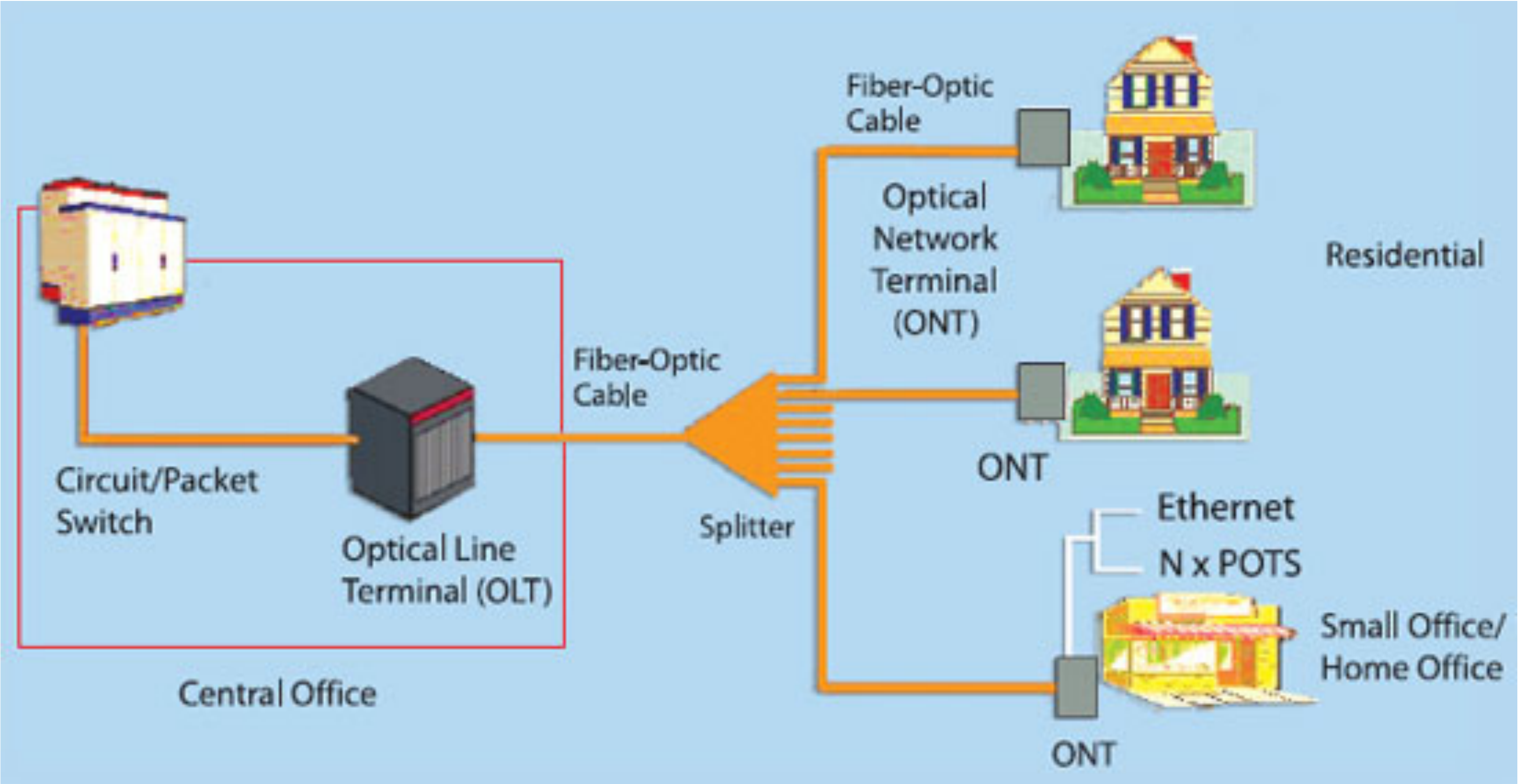


http://en.wikipedia.org/wiki/Fiber_to_the_x

Access: Fiber to the Premises (FTTP)

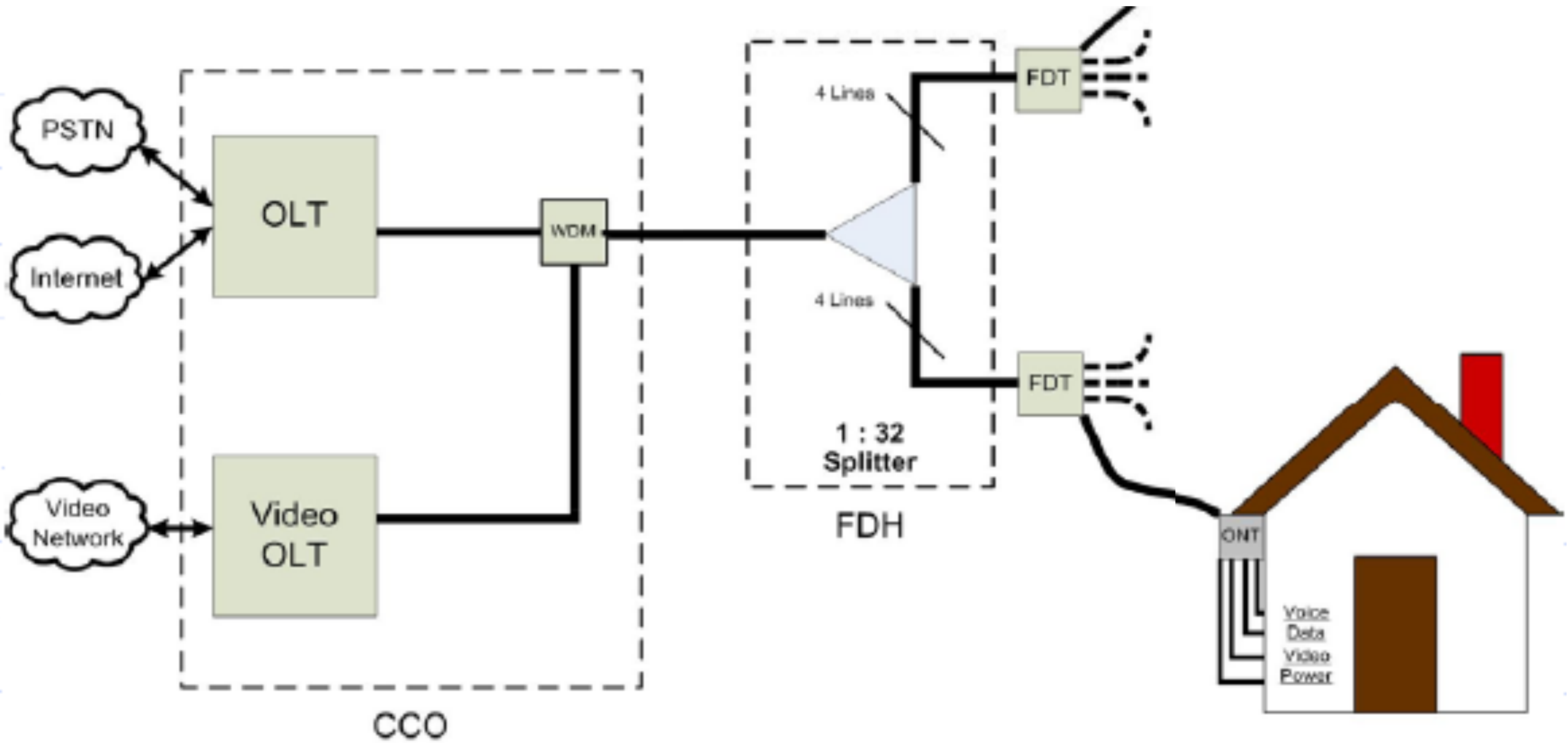
- Deployed by Verizon, AT&T, Google
- One of the largest comm. construction projects

FTTP Architecture

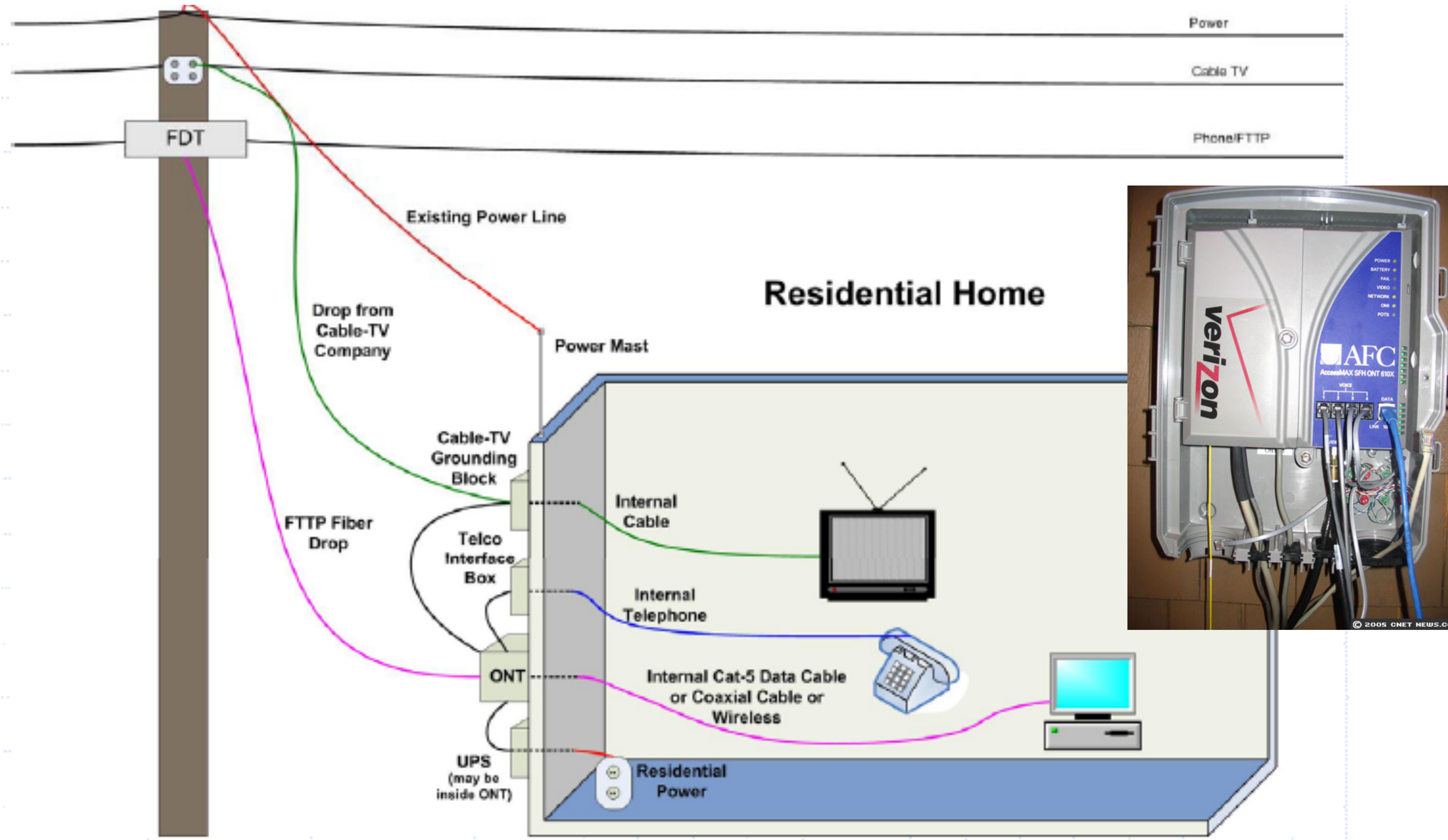


FTTP Architecture

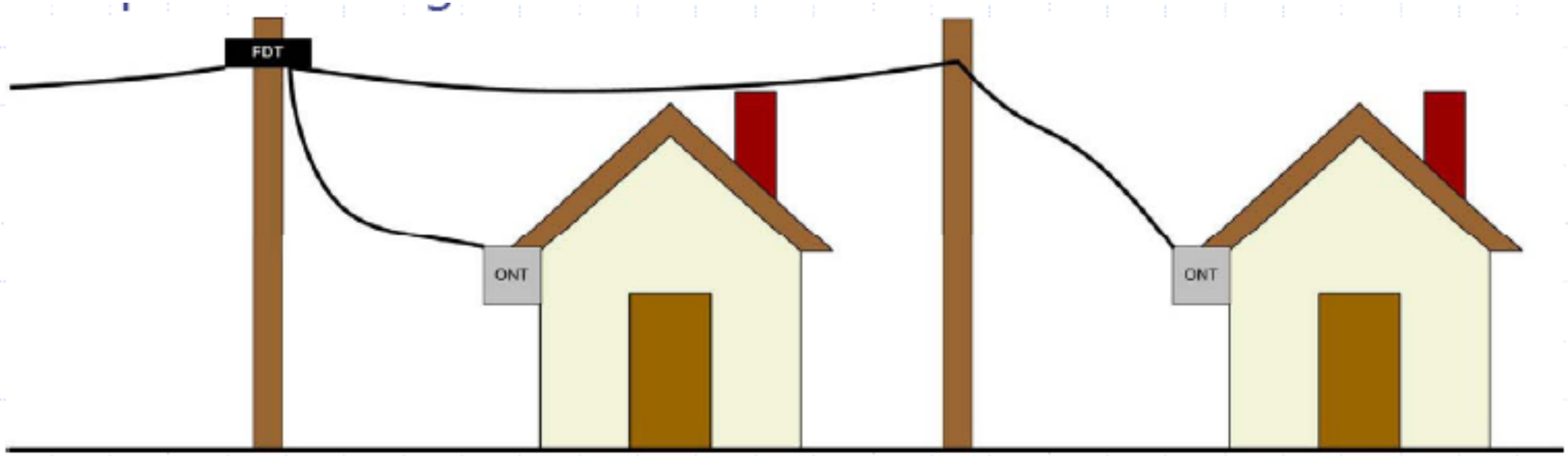
- Optical Network Terminal (ONT) box outside dwelling or business
- Fiber Distribution Terminal (FDT) in poles or pedestals
- Fiber Distribution Hub (FDH) at street cabinet
- Optical Line Terminal (OLT) at central office



FTTP Architecture: To Ho



FTTP Architecture: Fiber Distribution Terminal (FDT)



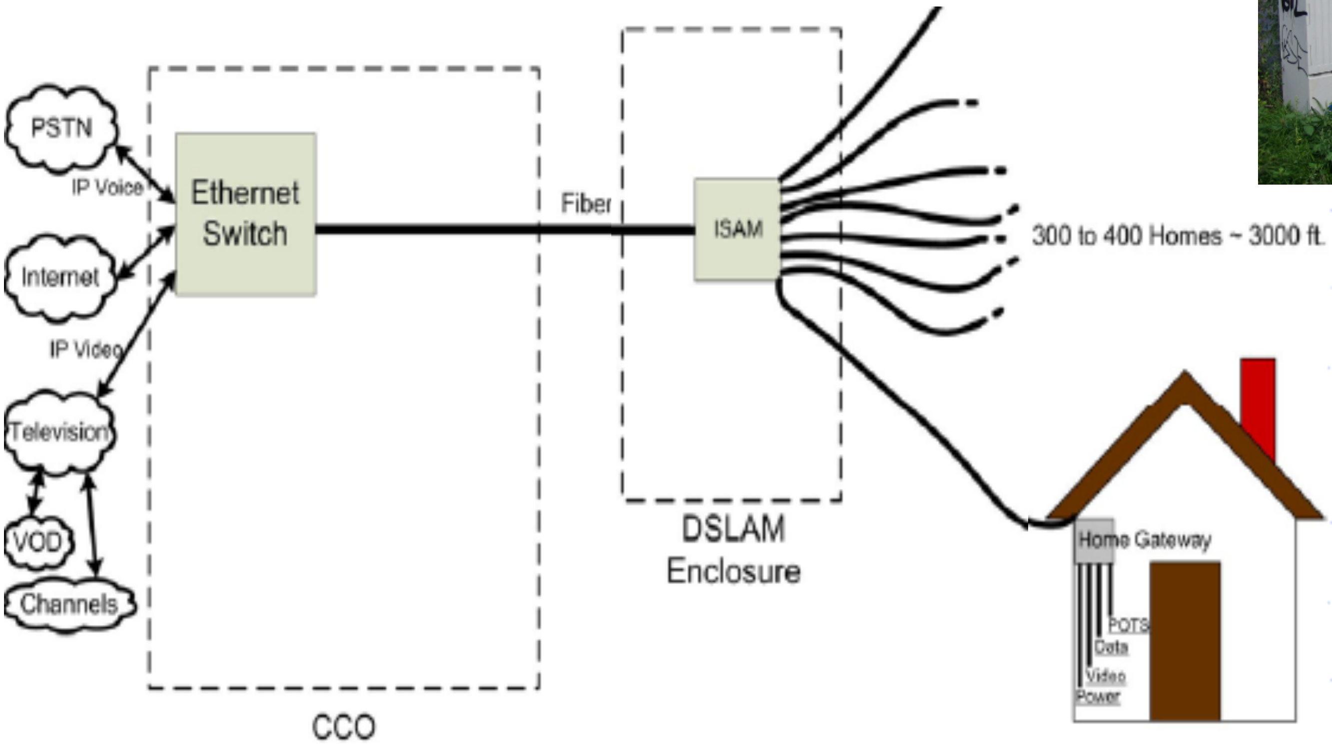
FTTP Architecture: Central to Fiber Distribution Hub (FDH)

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

FDH

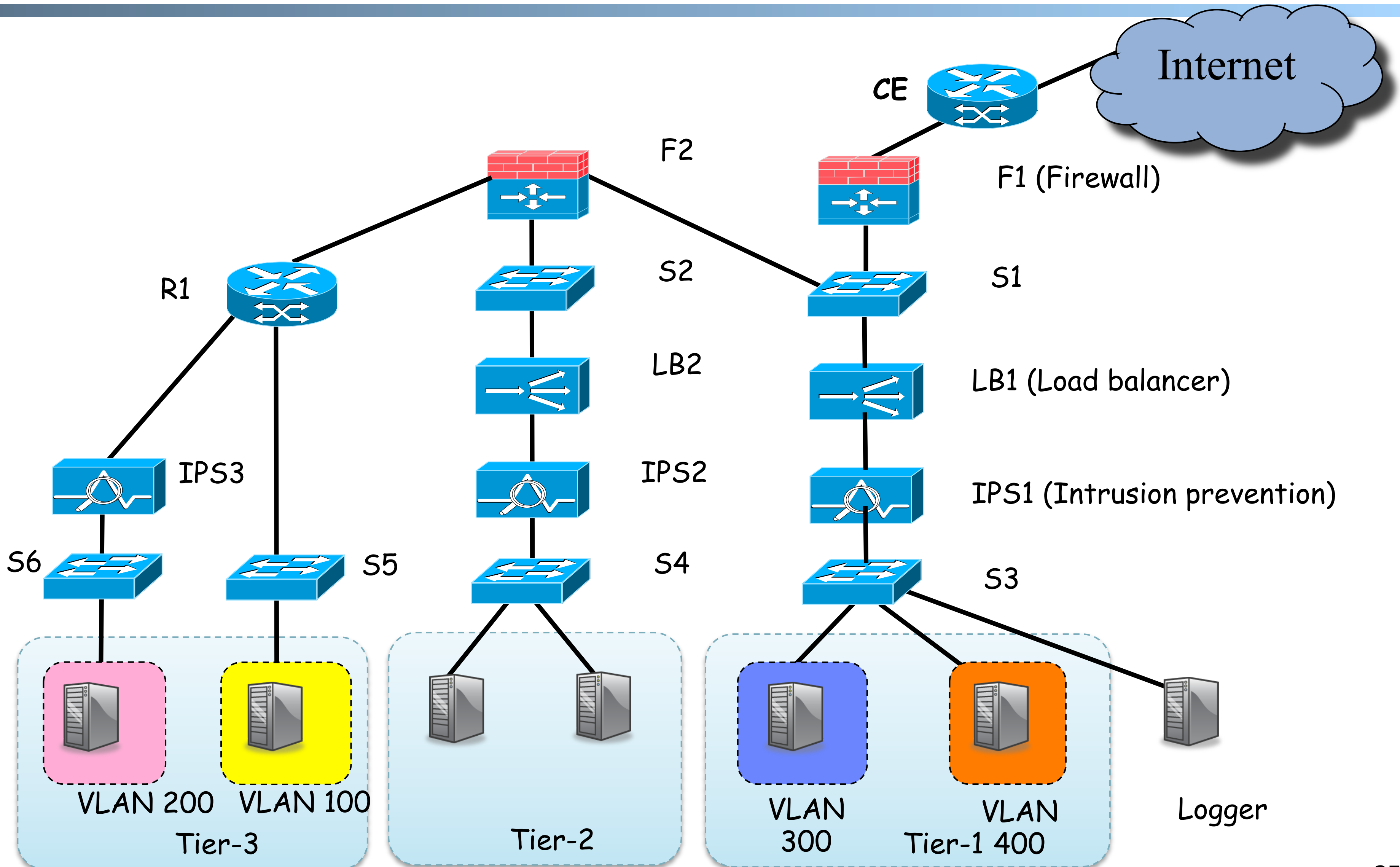
Access: DSL

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

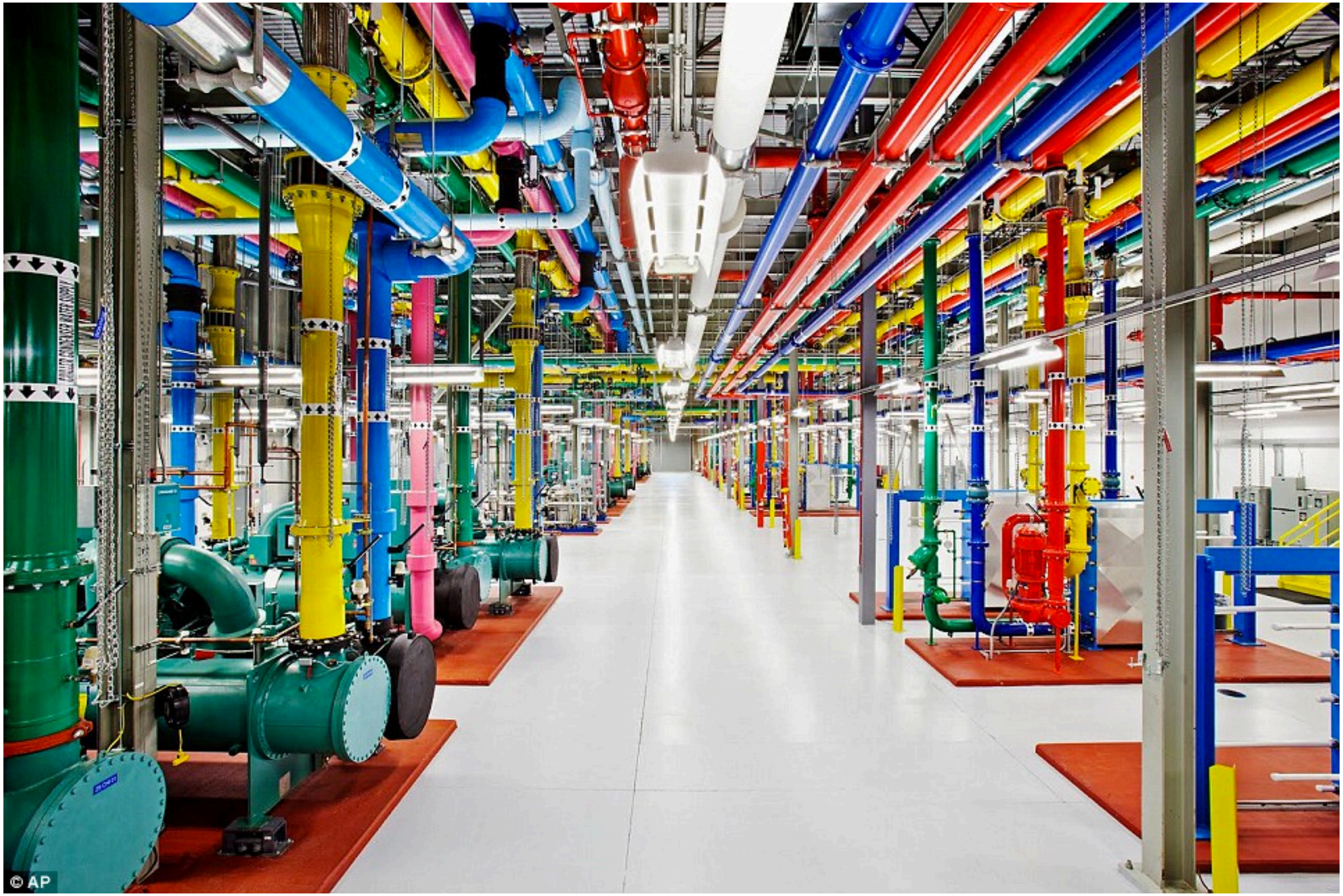


DSLAM

Campus Network

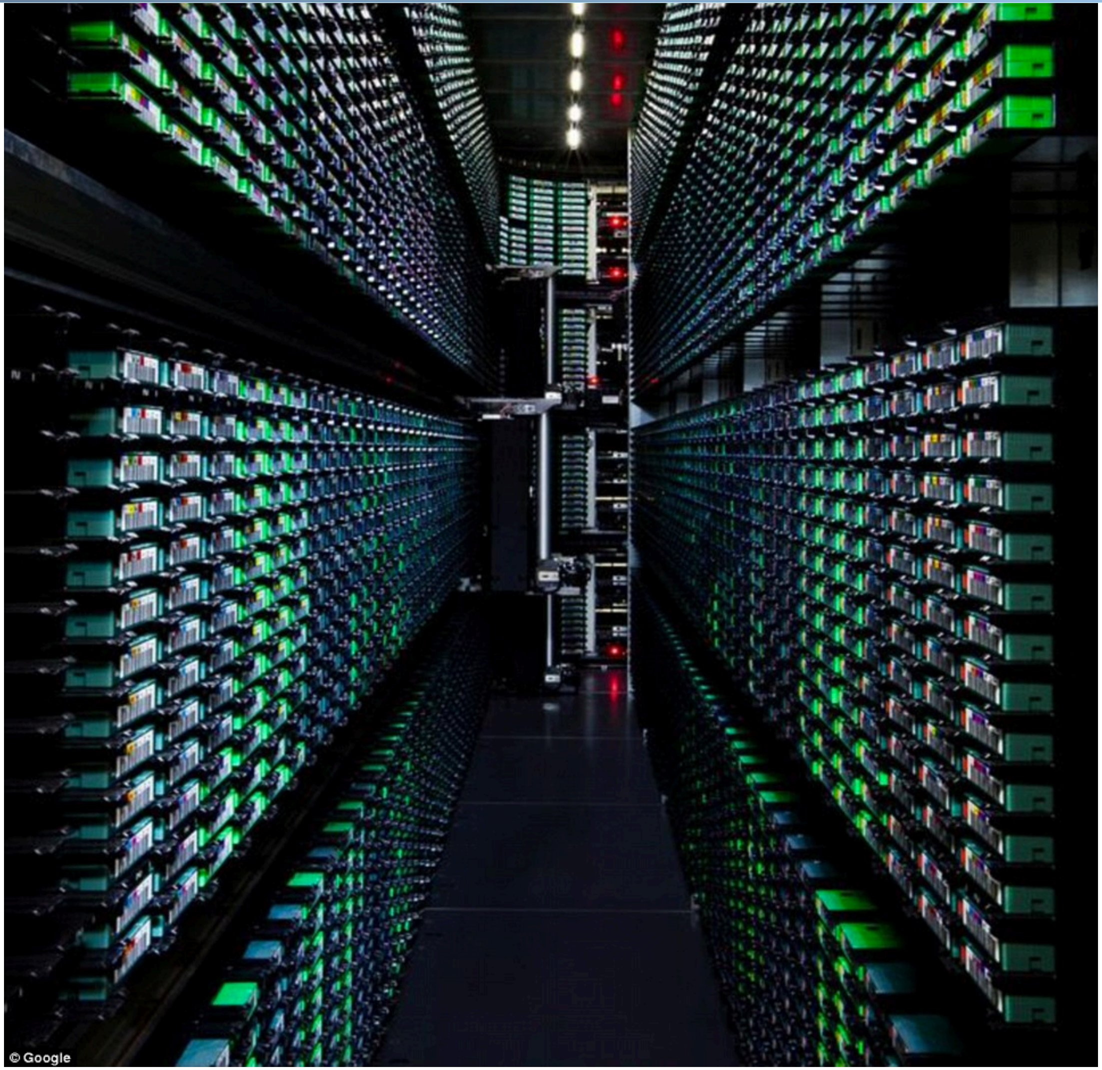


Data Center Networks



http://www.dailymail.co.uk/sciencetech/article-3369491/Google-s-plan-world-Search-engine-build-half-billion-dollar-data-center-US.html

Data Center Networks



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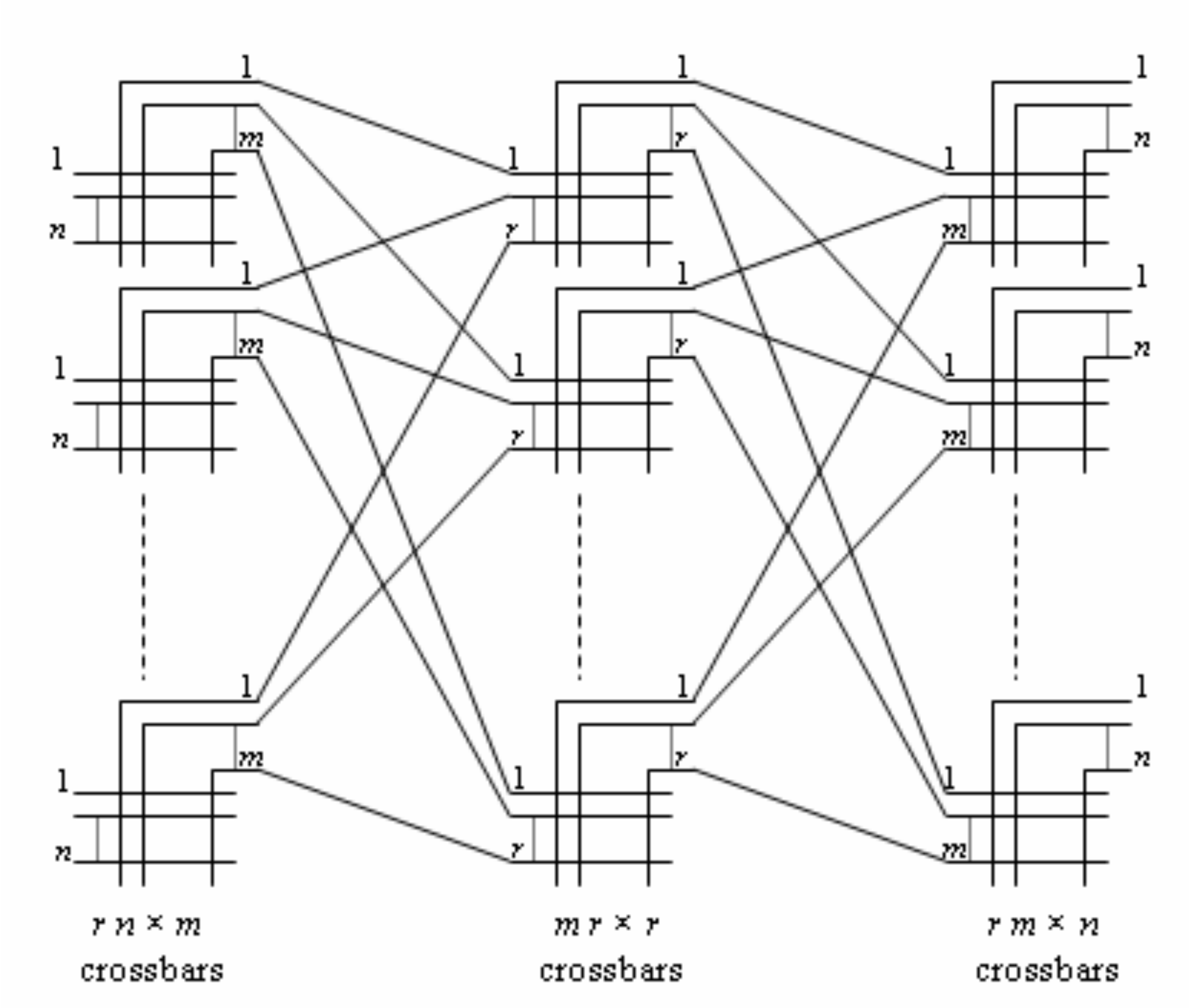
Foundation of Data Center Networks: Clos Networks



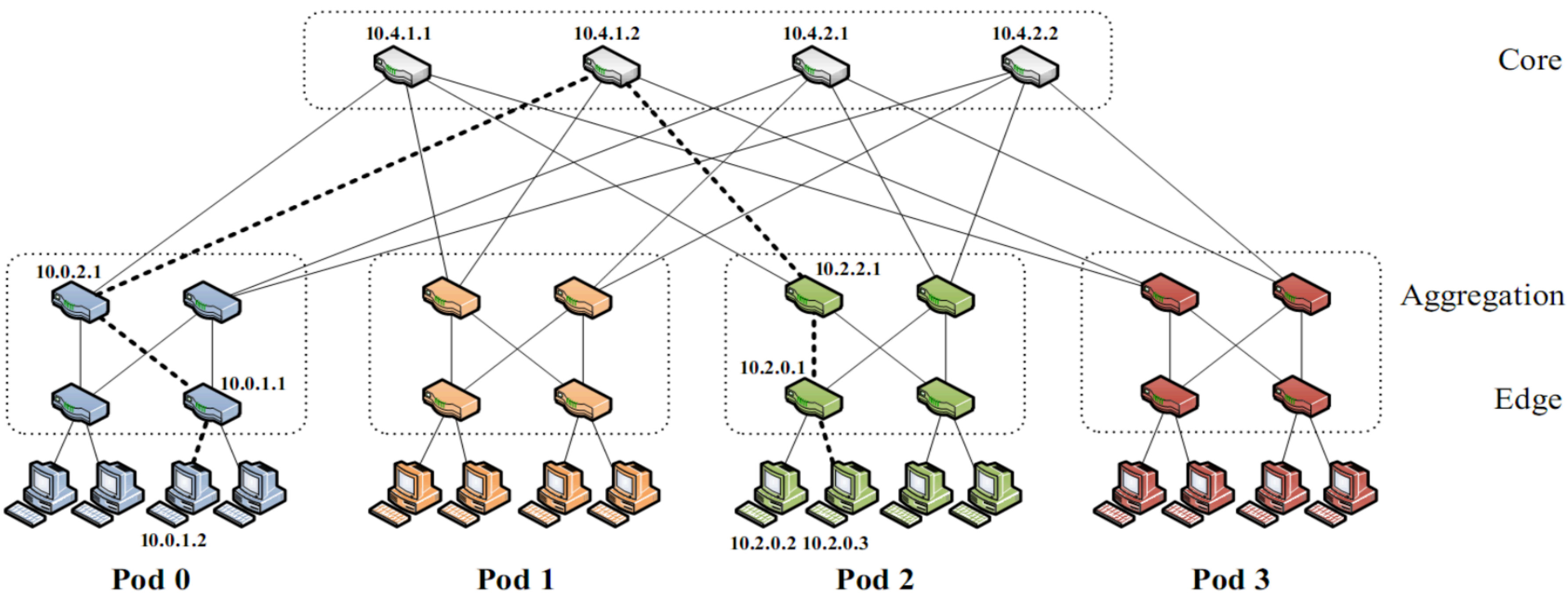
Q: How big is m so that each new call can be established w/o moving current calls?

Homework: If you can move existing calls, it is only m >= n.

https://en.wikipedia.org/wiki/Clos_network

Data Center Networks: Fat-tree Networks

- K-ary fat tree: three-layer topology (edge, aggregation and core)
  - k pods w/ each pod consists of $(k/2)^2$ servers & 2 layers of k/2 k-port switches
    - each edge switch connects to k/2 servers & k/2 aggr. switches
    - each aggr. switch connects to k/2 edge & k/2 core switches
  - $(k/2)^2$ core switches: each connects to k pods



http://www.cs.cornell.edu/courses/cs5413/2014fa/lectures/08-fattree.pdf

Data Center Networks

- For example, Google Jupiter at 1 Pbits/sec bisection bw: 100,000 servers at 10G each

Datacenter Generation	First Deployed	Merchant Silicon	ToR Config	Aggregation Block Config	Spine Block Config	Fabric Speed	Host Speed	Bisection BW
Four-Post CRs	2004	vendor	48x1G	-	-	10G	1G	2T
Firehose 1.0	2005	8x10G 4x10G (ToR)	2x10G up 24x1G down	2x32x10G (B)	32x10G (NB)	10G	1G	10T
Firehose 1.1	2006	8x10G	4x10G up 48x1G down	64x10G (B)	32x10G (NB)	10G	1G	10T
Watchtower	2008	16x10G	4x10G up 48x1G down	4x128x10G (NB)	128x10G (NB)	10G	nx1G	82T
Saturn	2009	24x10G	24x10G	4x288x10G (NB)	288x10G (NB)	10G	nx10G	207T
Jupiter	2012	16x40G	16x40G	8x128x40G (B)	128x40G (NB)	10/40G	nx10G/ nx40G	1.3P

http://googlecloudplatform.blogspot.com/2015/06/A-Look-Inside-Googles-Data-Center-Networks.html

http://conferences.sigcomm.org/sigcomm/2015/pdf/papers/p183.pdf

Recall: Internet Physical Infrastructure

Residential access
- Cable
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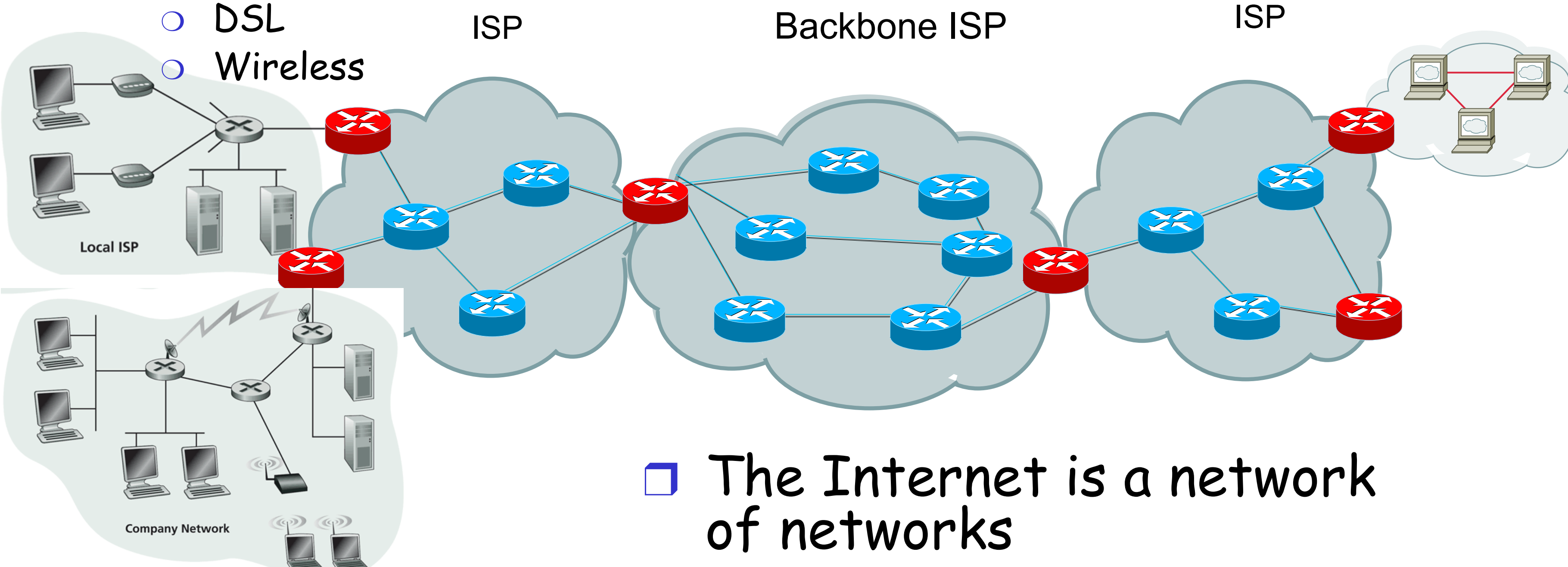

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https://www.google.com/loon/how/

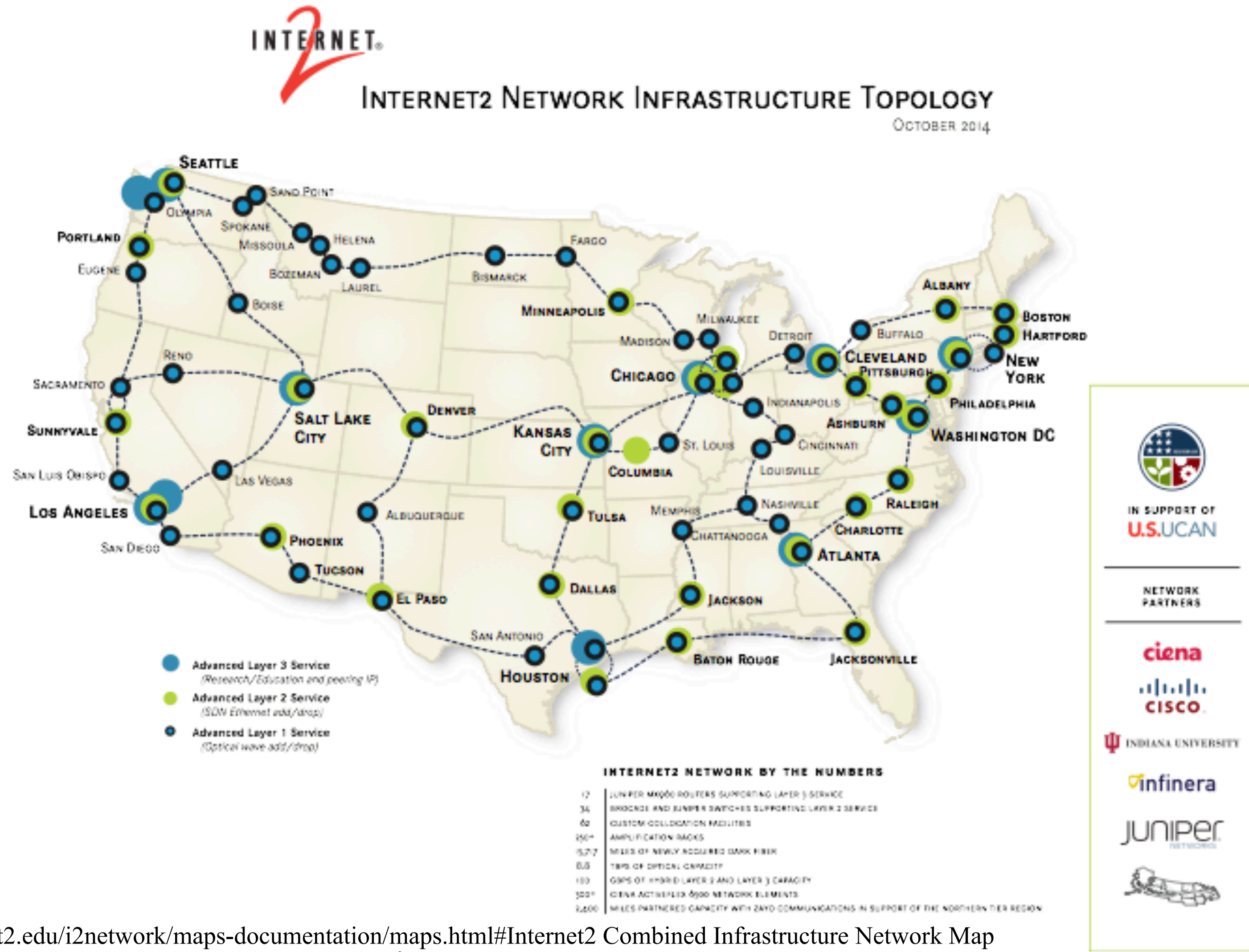
Yale Internet Connection

```
cicada:~% traceroute www.tsinghua.edu.cn
traceroute to www.d.tsinghua.edu.cn (166.111.4.100), 64 hops max, 52 byte packets
 1  college.net.yale.internal (172.28.201.1)  10.310 ms  147.298 ms  3.948 ms
 2  10.1.1.13 (10.1.1.13)  3.846 ms  1.721 ms  1.603 ms
 3  level3-10g-asr.net.yale.internal (10.1.4.40)  2.830 ms  3.641 ms  126.830 ms
 4  cen-10g-yale.net.yale.internal (10.1.3.102)  3.116 ms  2.904 ms  2.843 ms
 5  * * *
 6  enrt064hhh-9k-te0-3-0-5.net.cen.ct.gov (67.218.83.254)  43.064 ms  3.999 ms  3.701 ms
 7  198.71.46.215 (198.71.46.215)  10.636 ms  3.819 ms  3.893 ms
 8  et-5-0-0.1180.rtr.newy32aoa.net.internet2.edu (198.71.46.214)  6.510 ms  6.686 ms  9.789 ms
 9  et-10-0-0.118.rtr.atla.net.internet2.edu (198.71.46.174)  26.527 ms  24.777 ms  24.925 ms
10  et-10-2-0.105.rtr.hous.net.internet2.edu (198.71.45.13)  49.217 ms  48.551 ms  48.667 ms
11  et-5-0-0.111.rtr.losa.net.internet2.edu (198.71.45.21)  81.462 ms  81.486 ms  82.688 ms
12  210.25.189.133 (210.25.189.133)  85.624 ms  84.093 ms  83.087 ms
...
```

Yale Internet Connection

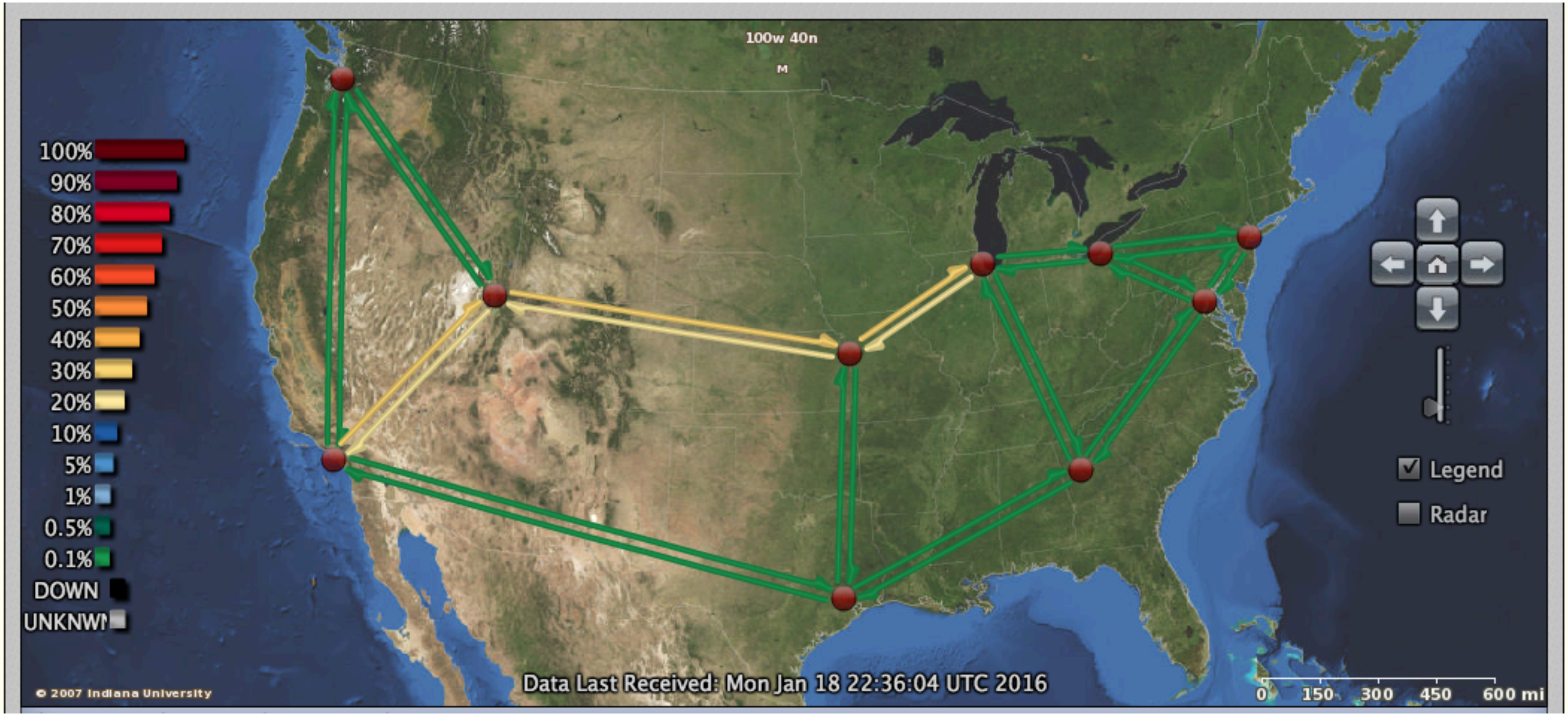
cicada:~% traceroute www.tsinghua.edu.cn

Internet2



http://noc.net.internet2.edu/i2network/maps-documentation/maps.html#Internet2 Combined Infrastructure Network Map

Internet2



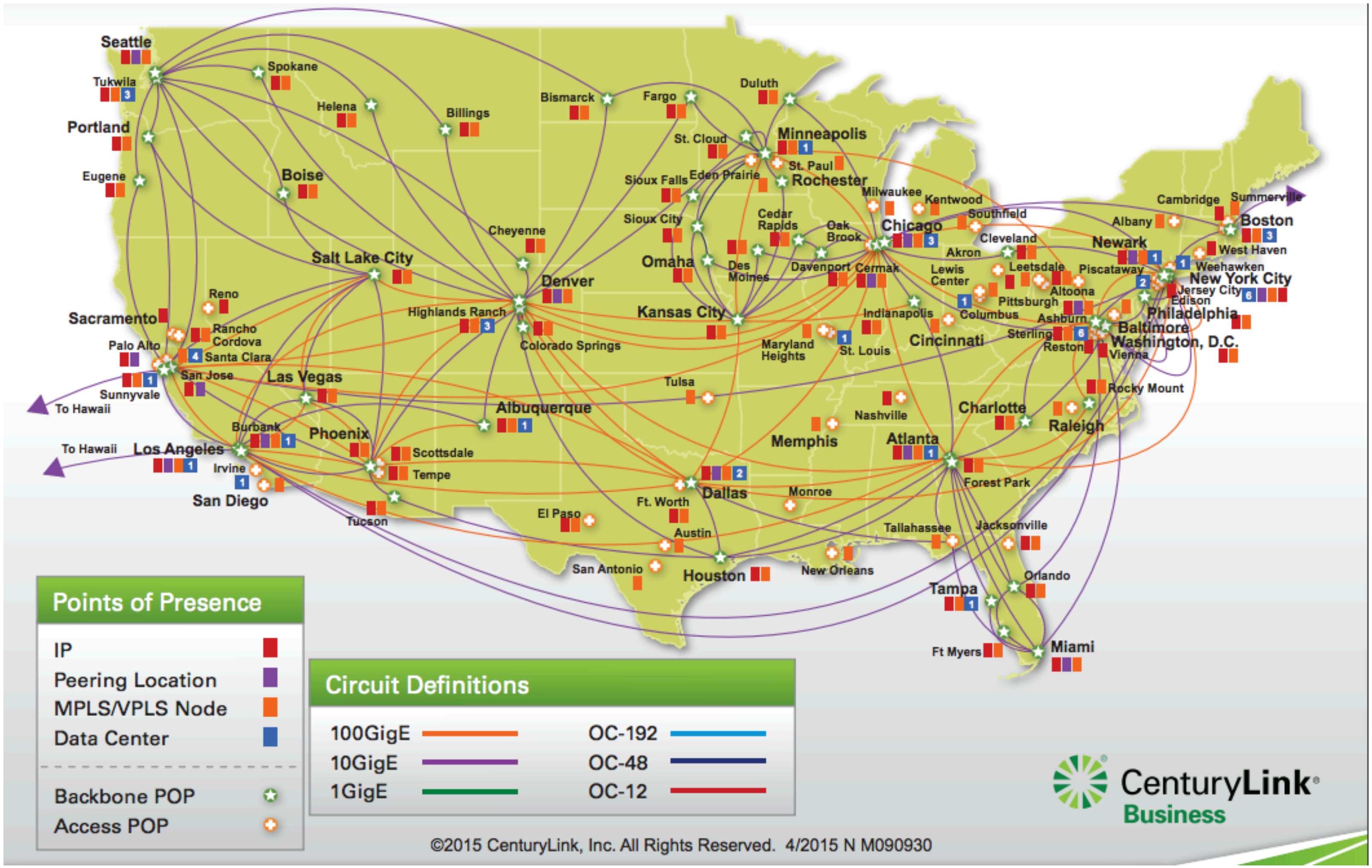
http://atlas.grnoc.iu.edu/atlas.cgi?map_name=Internet2%20IP%20Layer

Yale Internet Connection

Try traceroute from Yale to

- www.microsoft.com
- www.facebook.com
- www.amazon.com
- www.google.com

Qwest (CentryLink) Network Maps



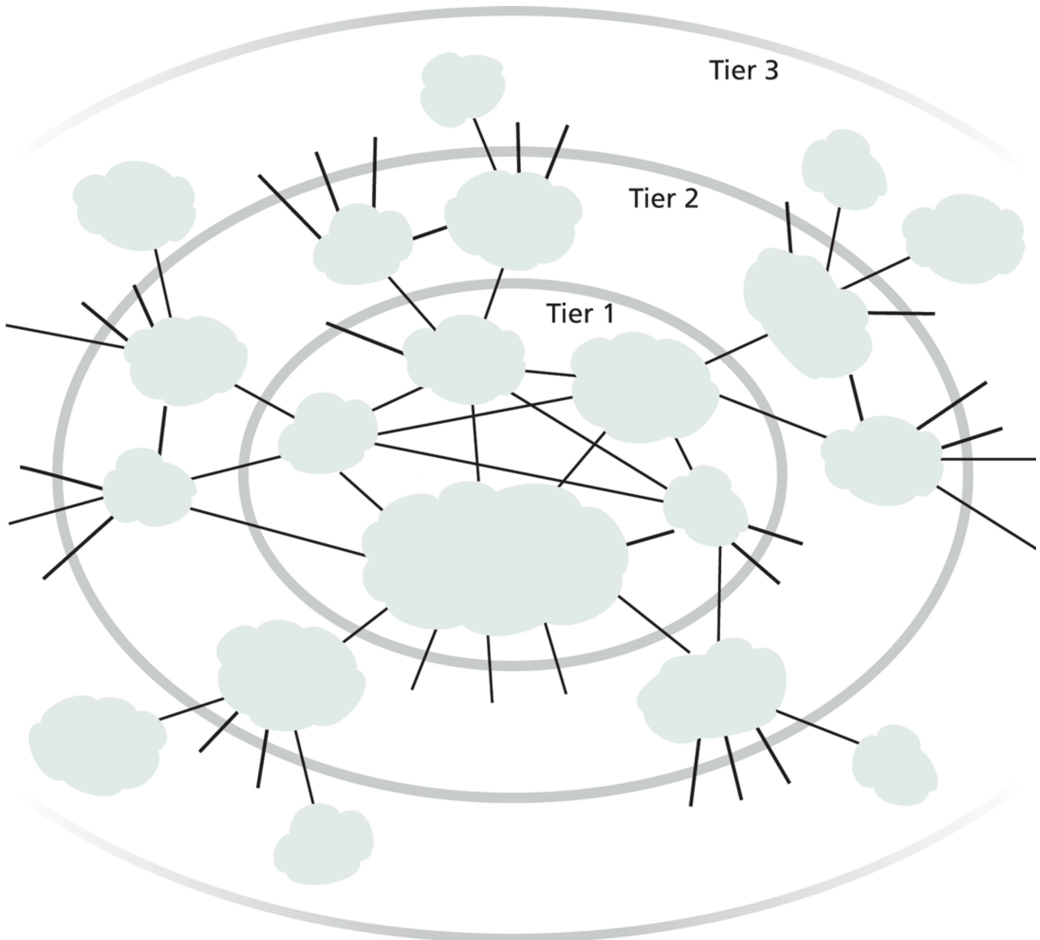
http://www.centurylink.com/business/asset/network-map/ip-mpls-network-nm090930.pdf

Qwest Backbone Map

http://www.centurylink.com/business/resource-center/network-maps/

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)
  - public peering



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

Consumer Internet Traffic, 2012–2017	2012	2013	2014	2015	2016	2017	CAGR 2012–2017
By Network (PB per Month)							
Fixed	25,529	32,097	39,206	47,035	56,243	66,842	21%
Mobile	684	1,239	2,223	3,774	6,026	9,131	68%
By Subsegment (PB per Month)							
Internet video	14,818	19,855	25,800	32,962	41,916	52,752	29%
Web, email, and data	5,173	6,336	7,781	9,542	11,828	14,494	23%
File sharing	6,201	7,119	7,816	8,266	8,478	8,667	7%
Online gaming	22	26	32	39	48	59	22%
By Geography (PB per Month)							
Asia Pacific	9,033	11,754	14,887	18,707	23,458	29,440	27%
North America	6,834	8,924	11,312	14,188	17,740	21,764	26%
Western Europe	5,086	5,880	6,804	7,810	9,197	10,953	17%
Central and Eastern Europe	2,194	2,757	3,433	4,182	5,015	5,897	22%
Latin America	2,656	3,382	4,049	4,588	5,045	5,487	16%
Middle East and Africa	410	640	944	1,334	1,816	2,432	43%
Total (PB per Month)							
Consumer Internet traffic	26,213	33,337	41,429	50,809	62,269	75,973	24%

Internet Traffic in Perspective

640K ought to be enough for anybody.

1 Petabyte
1,000 Terabytes or 250,000 DVDs

1 Exabyte
1,000 Petabytes or 250 million DVDs

1 Zettabyte
1,000 Exabytes or 250 billion DVDs

1 Yottabyte
1,000 Zettabytes or 250 trillion DVDs

480 Terabytes
A digital library of all of the world's catalogued books in all languages

100 Petabytes
The amount of data produced in a single minute by the new particle collider at CERN

5 Exabytes
A text transcript of all words ever spoken†

100 Exabytes
A video recording of all the meetings that took place last year across the world

400 Exabytes
The amount of data that crossed the Internet in 2012 alone

1 Zettabyte
The amount of data that has traversed the Internet since its creation

300 Zettabytes
The amount of visual information conveyed from the eyes to the brain of the entire human race in a single year‡

20 Yottabytes
A holographic snapshot of the earth's surface

† Roy Williams, "Data Powers of Ten," 2000
‡ Based on a 2006 estimate by the University of Pennsylvania School of Medicine that the retina transmits information to the brain at 10 Mbps.

All other figures are Cisco estimates.
Source: Cisco, 2013

Outline

- Administrative trivia's
- What is a network protocol?
- A brief introduction to the Internet: past and present
- *Challenges of Internet networks and apps*

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."

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

Largest Internet Sites in U.S. (Jan. 2016)

RANK	SITE	MONTHLY PEOPLE	DIRECTLY MEASURED
1	google.com	232,288,144	
2	youtube.com	208,776,272	
3	msn.com	165,291,680	
4	facebook.com	130,319,464	
5	bing.com	93,572,256	
6	yahoo.com	86,557,024	
7	amazon.com	82,737,184	
8	yelp.com	78,720,336	✓
9	microsoft.com	68,743,296	
10	buzzfeed.com	63,977,968	✓
11	ebay.com	63,353,208	
12	pinterest.com	63,027,644	
13	answers.com	62,870,684	✓
14	twitter.com	60,161,296	
15	wikia.com	48,973,188	✓
16	wikipedia.org	47,630,496	
17	live.com	44,831,308	
18	aol.com	42,879,008	
19	linkedin.com	40,406,232	
20	paypal.com	40,279,492	
21	netflix.com	38,836,980	
22	about.com	37,114,640	

RANK	SITE	MONTHLY PEOPLE	DIRECTLY MEASURED
51	stackexchange.com	21,869,768	✓
52	adobe.com	21,779,906	
53	Hidden profile	—	✓
54	Hidden profile	—	✓
55	healthline.com	20,552,928	✓
56	nytimes.com	20,219,290	
57	usmagazine.com	19,856,848	✓
58	imgur.com	19,683,136	✓
59	comcast.net	18,676,528	
60	Hidden profile	—	✓
61	wellsfargo.com	18,444,774	
62	vice.com	17,967,660	✓
63	rollingstone.com	17,771,256	✓
64	fandango.com	17,282,236	✓
65	babycenter.com	17,052,306	✓
66	247sports.com	16,997,532	✓
67	viralands.com	16,939,364	✓
68	goodreads.com	16,925,204	✓
69	apple.com	16,837,476	
70	yourdailydish.com	16,275,180	✓
71	Hidden profile	—	✓
72	gizmodo.com	16,140,121	✓

https://www.quantcast.com/top-sites

General Complexity

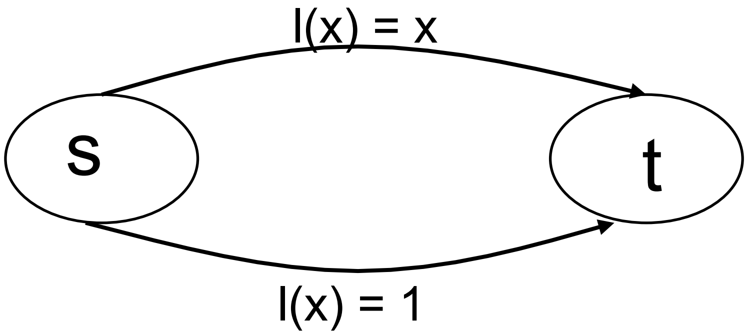
- Complexity in highly organized systems arises primarily from design strategies intended to create robustness to uncertainty in their environments and component parts.
  - Scalability is robustness to changes to the size and complexity of a system as a whole.
  - Evolvability is robustness of lineages to large changes on various (usually long) time scales.
  - Reliability is robustness to component failures.
  - Efficiency is robustness to resource scarcity.
  - Modularity is robustness to component rearrangements.

David Meyer

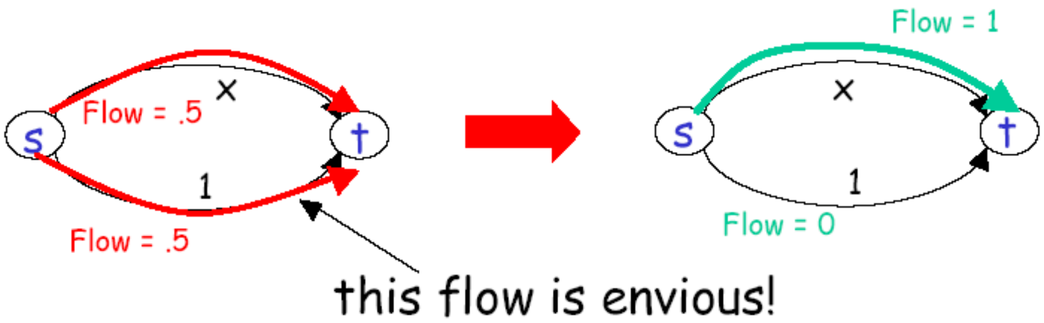
Centralized vs Decentralized (Price of Anarchy)

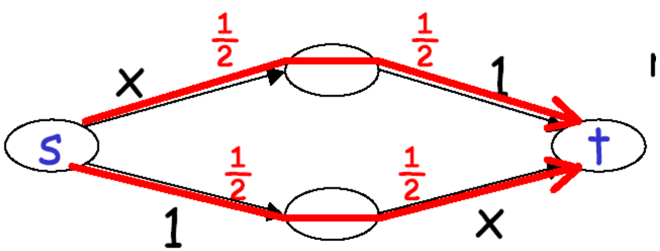
- Autonomous ("Selfish") App: Assume each link has a latency function $l_e(x)$: latency of link e when x amount of traffic goes through e:

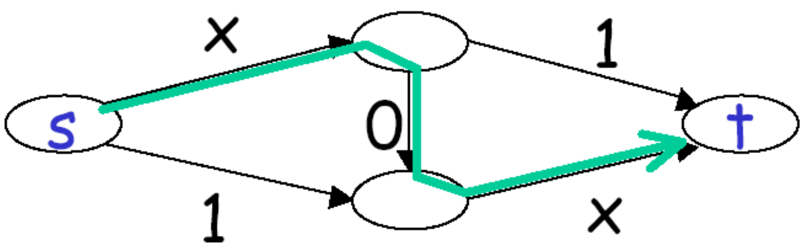
total traffic



Autonomous ("Selfish") App

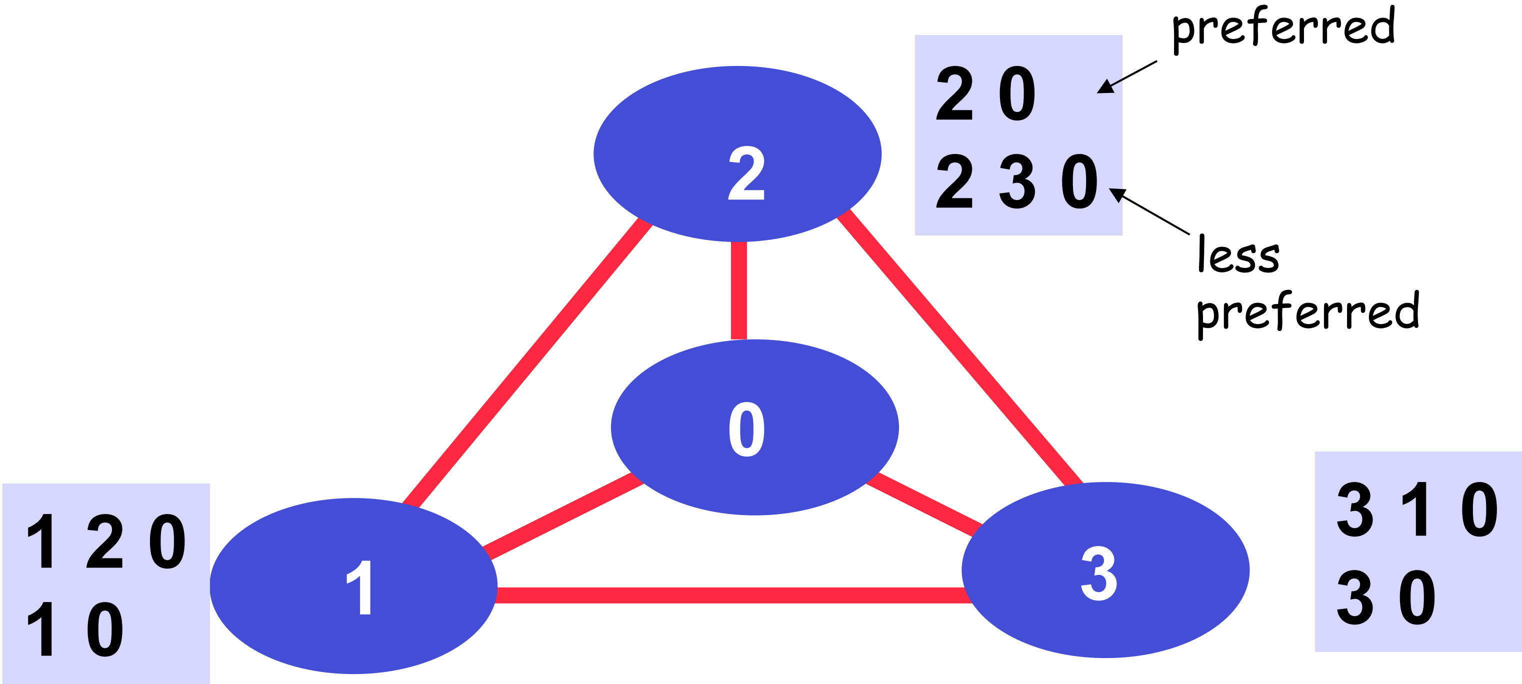




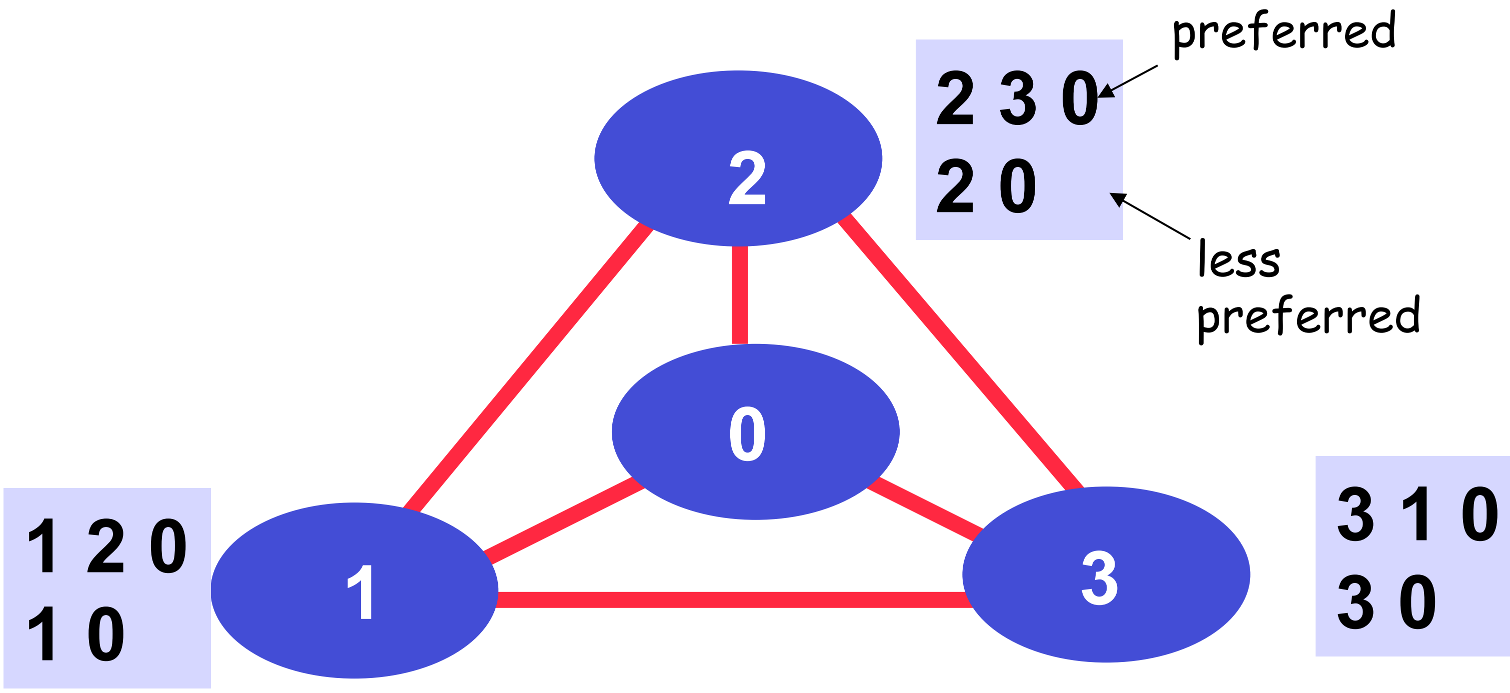


Braess's paradox

Decentralized ("Selfish") Users



Decentralized ("Selfish") Users



Distributed vs Centralized

- Distributed computing is hard, e.g.,
  - FLP Impossibility Theorem
  - Arrow's Impossibility Theorem

- Achieved good design for only few specific tasks (e.g., state distribution, leader election). Hence, a trend in networking is Software Defined Networking, which is a way of moving away from generic distributed computing, by focusing on utilizing the few well-understood primitives, in particular logically centralized state.

What Will We Cover?

- A tentative schedule is posted at class schedule page

- Network architecture and design principles
  - Layered network arch; e2e 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; queueing analysis; capacity analysis
  - Ethernet, 802.11, CDMA, bluetooth

- Cloud and data center design

- Network security
  - security primitives; BAN logic, SSL

Summary

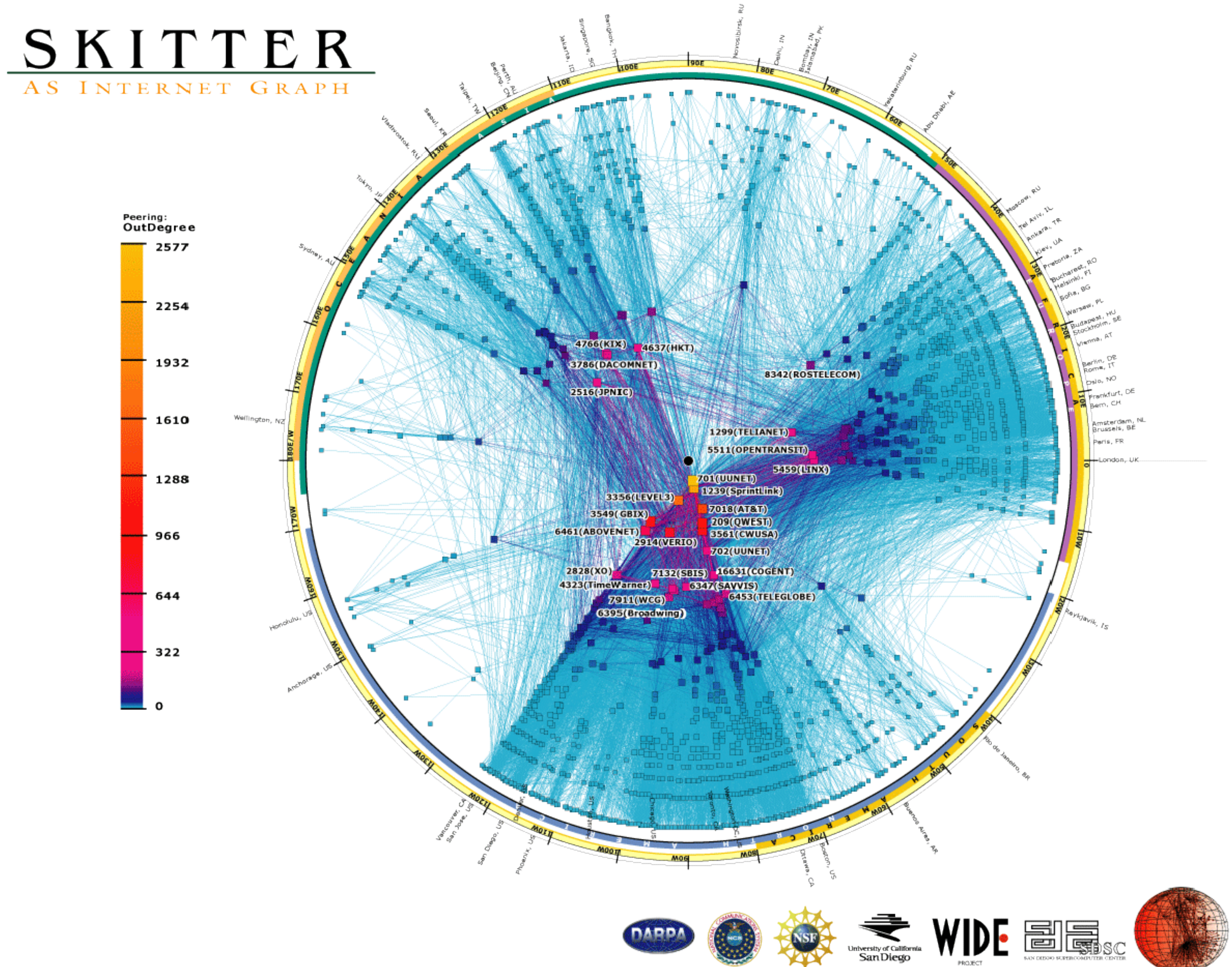
- Course administration
- A protocol defines the format and the order of messages exchanged between two or more communicating entities, as well as the actions taken on the transmission and/or receipt of a message or other events.
- The past:
  - facts:
    - The Internet started as ARPANET in late 1960s
    - 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 billions
  - The backbone speed of the current Internet is about 40/100 Gbps
  - The Internet is roughly hierarchical where ISPs interconnect at PoP and IXP
  - Needs to handle scale, complexity, decentralization, 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



cooperative association for internet data analysis ○ san diego supercomputer center ○ university of california, san diego

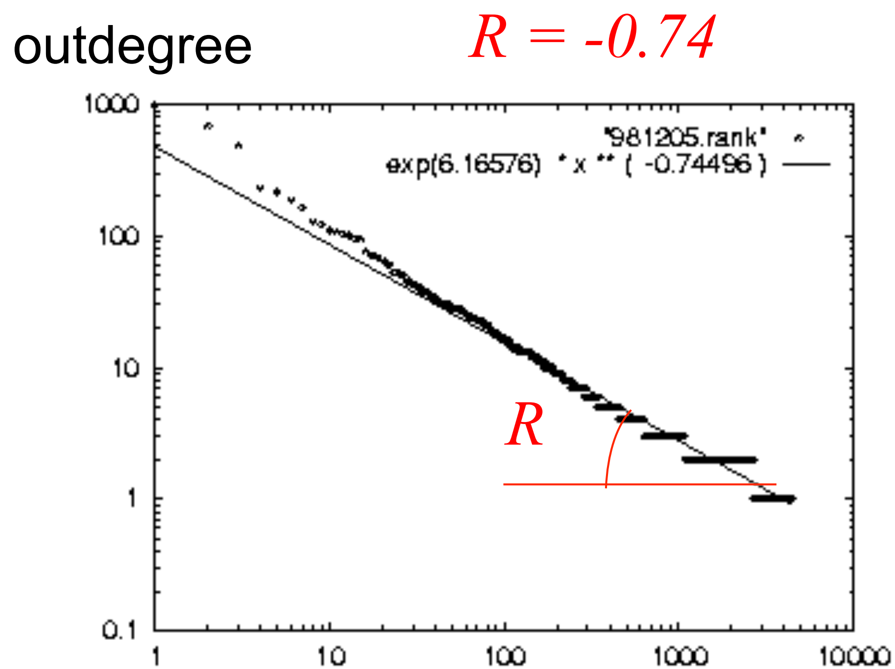
9500 gilman drive, mc0505 ○ la jolla, ca 92093-0505 ○ tel. 858-534-5000 ○ http://www.caida.org/

CAIDA is a program of the University of California's San Diego Supercomputer Center (UCSD/SDSC)
CAIDA's topology mapping projects are supported by DARPA, NCS, NSF, WIDE and CAIDA members

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?

Exponent = slope



Dec' 98

Rank: nodes in decreasing outdegree order

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

IP Traffic, 2012–2017	2012	2013	2014	2015	2016	2017	CAGR 2012–2017
By Type (PB per Month)							
Fixed Internet	31,339	39,295	47,987	57,609	68,878	81,818	21%
Managed IP	11,346	14,679	18,107	21,523	24,740	27,668	20%
Mobile data	885	1,578	2,798	4,704	7,437	11,157	66%
By Segment (PB per Month)							
Consumer	35,047	45,023	56,070	68,418	82,683	98,919	23%
Business	8,522	10,530	12,822	15,417	18,372	21,724	21%
By Geography (PB per Month)							
Asia Pacific	13,906	18,121	22,953	28,667	35,417	43,445	26%
North America	14,439	18,788	23,520	28,667	34,457	40,672	23%
Western Europe	7,722	9,072	10,568	12,241	14,323	16,802	17%
Central and Eastern Europe	3,405	4,202	5,167	6,274	7,517	8,844	21%
Latin America	3,397	4,321	5,201	5,975	6,682	7,415	17%
Middle East and Africa	701	1,049	1,483	2,013	2,659	3,465	38%
Total (PB per Month)							
Total IP traffic	43,570	55,553	68,892	83,835	101,055	120,643	23%

Source: Cisco VNI, 2013

Yale Internet Connectivity: Qwest

cyndra.cs.yale.edu% /usr/sbin/traceroute www.synopsis.com
traceroute to www.synopsis.com (198.182.60.11), 30 hops max, 38 byte packets

- 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) 0.680 ms 0.597 ms 0.567 ms
- 3 bos-edge-02.inet.qwest.net (63.145.0.13) 4.897 ms 5.257 ms 5.294 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
- 8 ae-1-56.bbr2.NewYork1.Level3.net (4.68.97.161) 7.513 ms 7.466 ms
  ae-1-54.bbr2.NewYork1.Level3.net (4.68.97.97) 7.585 ms
- 9 ge-0-1-0.bbr2.SanJose1.Level3.net (64.159.1.130) 75.468 ms
  so-0-0-0.bbr1.SanJose1.Level3.net (64.159.1.133) 75.630 ms
  ge-0-1-0.bbr2.SanJose1.Level3.net (64.159.1.130) 75.126 ms
- 10 ge-9-0.hsa1.SanJose1.Level3.net (4.68.123.40) 75.499 ms
  ge-8-0.hsa1.SanJose1.Level3.net (4.68.123.8) 76.429 ms 76.431 ms
- 11 h1.synopsysmv.bbnplanet.net (4.25.120.46) 86.414 ms 85.996 ms 85.896 ms
- 12 198.182.56.45 (198.182.56.45) 88.705 ms 92.585 ms 90.412 ms

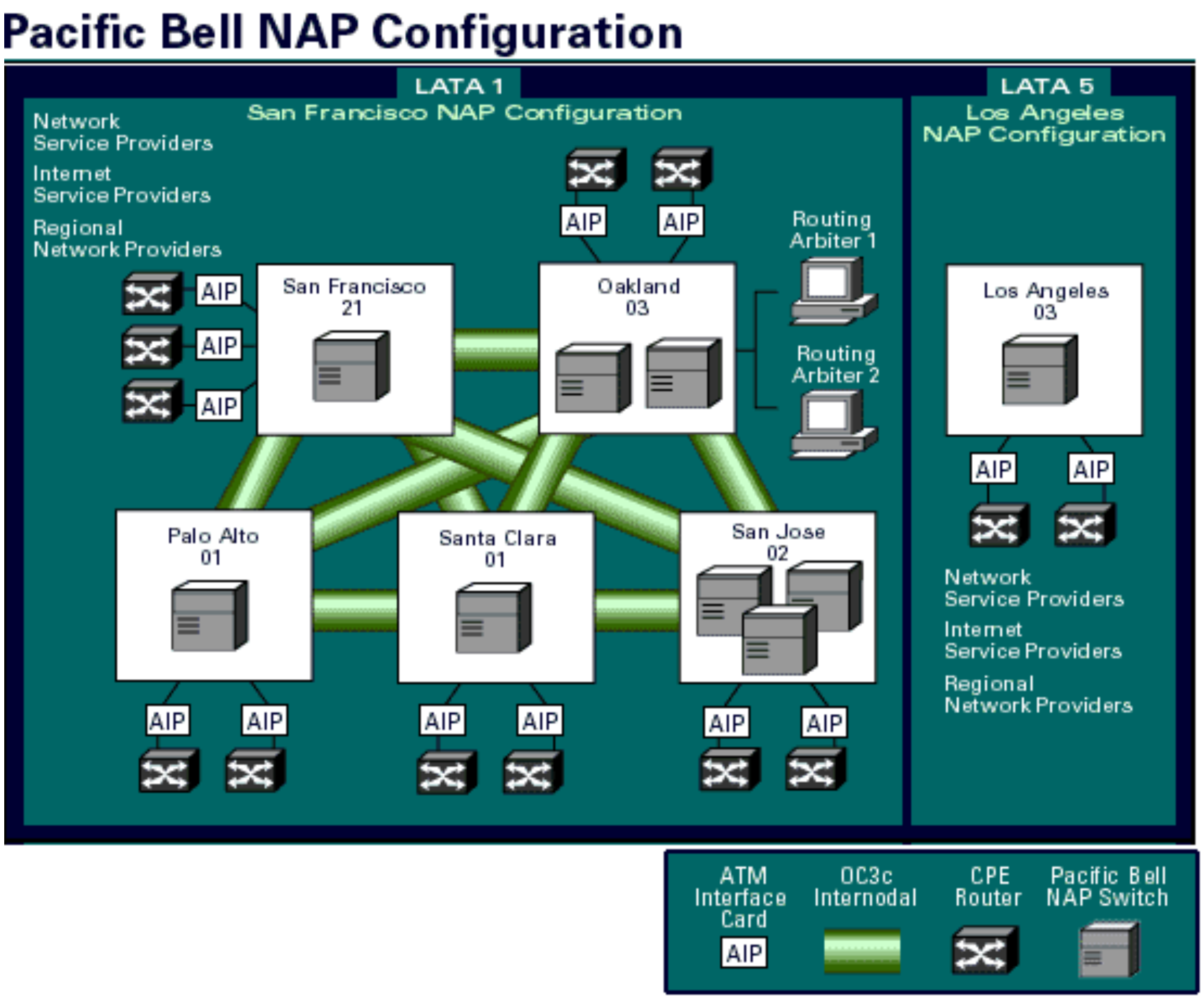
Note: which link Yale will use depends on its current load balancing. It may not be qwest.

Yale Internet Connectivity: AT&T

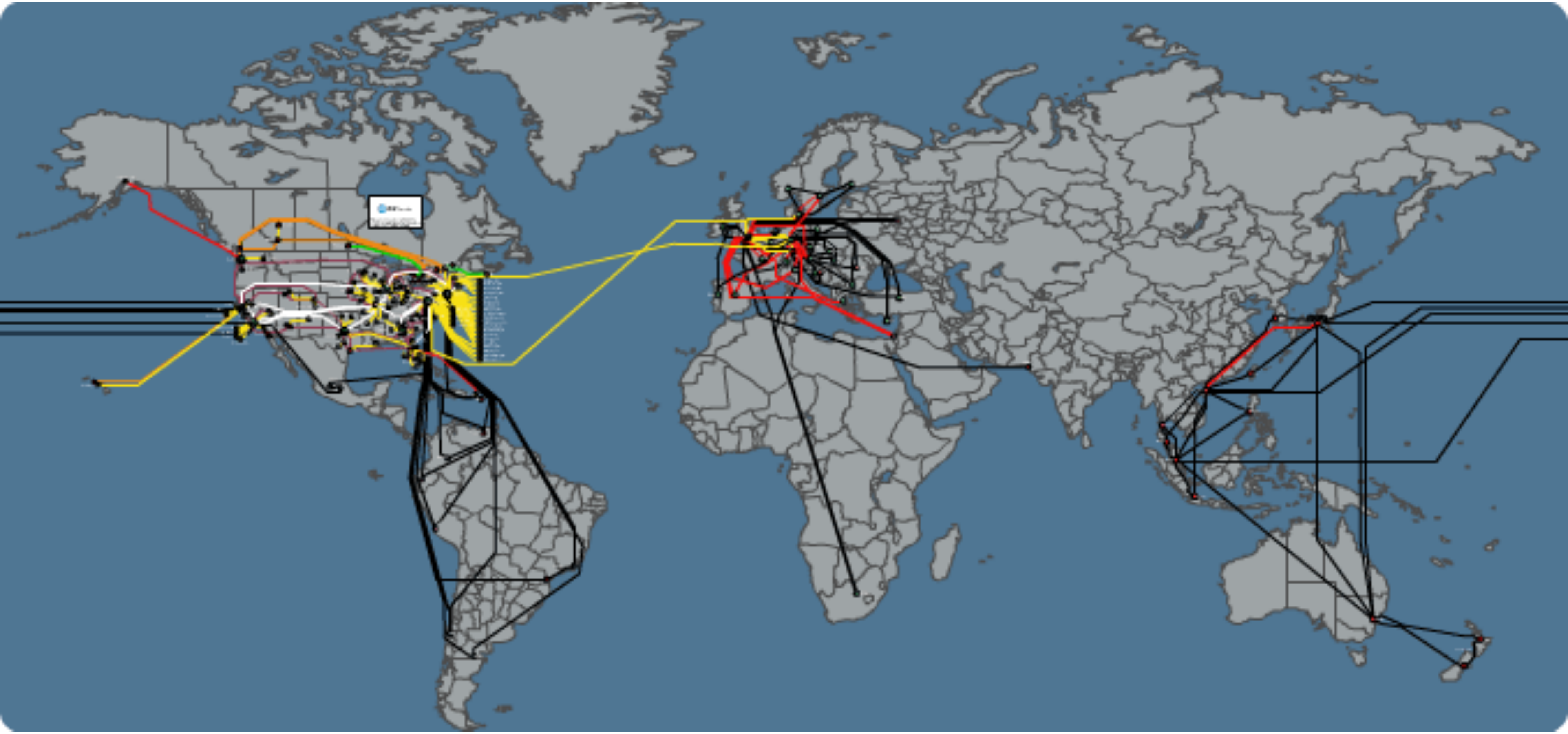
cicada.cs.yale.edu% /usr/sbin/traceroute www.amazon.com

- 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) 2.278 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 4.460 ms 49.531 ms
- 10 sl-bb23-pen-12-0.sprintlink.net (144.232.20.95) 7.191 ms 7.202 ms 7.033 ms
- 11 sl-bb22-pen-14-0.sprintlink.net (144.232.8.178) 7.131 ms 7.245 ms 7.096 ms
- 12 sl-bb21-pen-15-0.sprintlink.net (144.232.16.29) 7.100 ms 7.423 ms 8.049 ms
- 13 sl-bb23-rly-0-0.sprintlink.net (144.232.20.32) 10.777 ms 10.826 ms 11.049 ms
- 14 sl-st20-ash-11-0.sprintlink.net (144.232.20.150) 11.281 ms 10.948 ms 10.730 ms
- 15 sl-amazon-4-0.sprintlink.net (144.223.246.18) 10.562 ms 10.572 ms 11.381 ms

Network Access Point

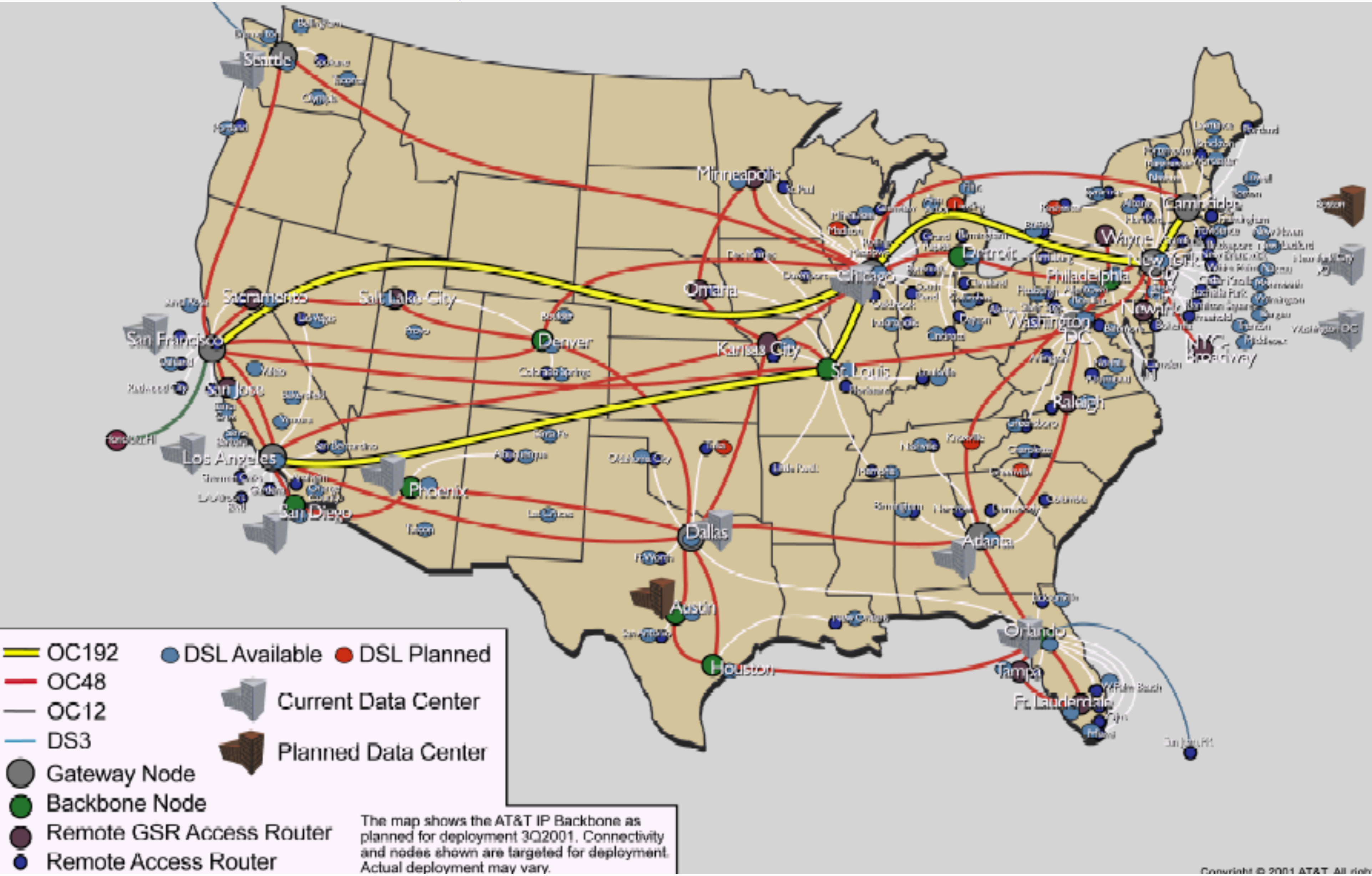


ATT Global Backbone IP Network



From http://www.business.att.com

AT&T USA Backbone Map



From AT&T web site.

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=PBx7rgqeGG8
- Google
- http://www.youtube.com/watch?v=zRwPSFpLX8I

Yale Internet Connection

```
cicada:~% traceroute www.cs.utexas.edu
traceroute to www.cs.utexas.edu (128.83.139.21), 30 hops max, 60 byte packets

 1  anger.net.yale.edu (128.36.232.1)  3.735 ms  3.731 ms  3.729 ms
 2  10.1.2.81 (10.1.2.81)  0.359 ms  0.370 ms  0.416 ms
 3  10.1.2.113 (10.1.2.113)  2.584 ms  2.603 ms  2.657 ms
 4  CEN10G-ASR.net.yale.internal (10.1.4.30)  1.841 ms  2.316 ms  2.124 ms
 5  level3-10g-yale.net.yale.internal (10.1.3.103)  1.850 ms  2.265 ms  2.137 ms
 6  te-4-1.car1.Stamford1.Level3.net (4.26.48.81)  40.900 ms  40.651 ms  40.723 ms
 7  * * *
 8  4.71.198.54 (4.71.198.54)  37.201 ms  37.202 ms  37.184 ms
 9  aust-utnoc-core-ae2-765.tx-bb.net (192.124.227.126)  45.004 ms  45.049 ms  45.045 ms
10  ser2-v60.gw.utexas.edu (192.12.10.2)  49.800 ms  49.751 ms  49.770 ms
11  nocb10-e10-2-noca2.gw.utexas.edu (128.83.8.9)  50.359 ms  50.686 ms  50.644 ms
12  cs-nocb10-v690.gw.utexas.edu (146.6.10.34)  50.533 ms  52.657 ms  52.546 ms
13  cs65k-cs45k-po1-p2p.gw.utexas.edu (128.83.37.66)  50.552 ms  49.816 ms  49.813 ms
14  net9.cs.utexas.edu (128.83.139.21)  49.755 ms  49.792 ms  49.851 ms
```

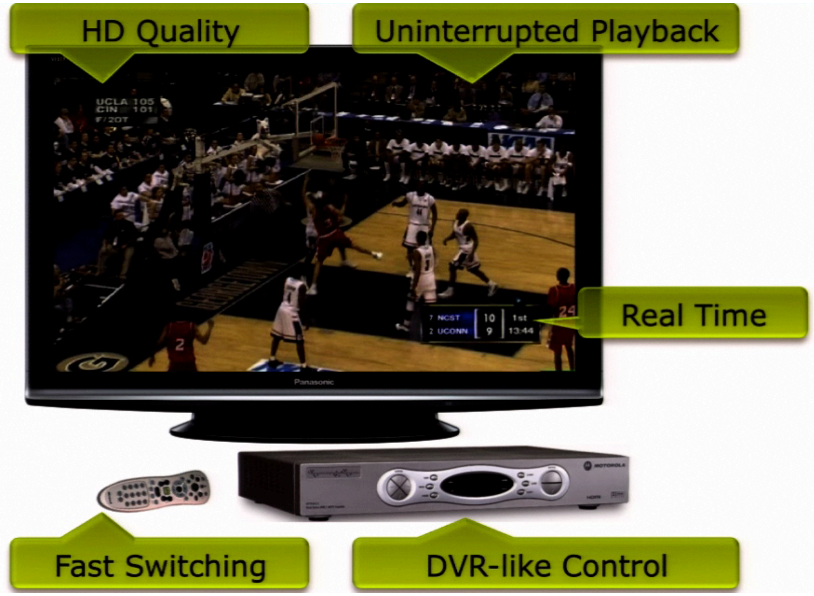
Yale Internet Connection

August 2013

```
cicada:~% traceroute www.cs.utexas.edu
traceroute to net6.cs.utexas.edu (128.83.120.139), 64 hops max, 52 byte packets
 1  arubacentral-vlan30-router.net.yale.internal (172.28.204.129)  1.540 ms  1.200 ms  1.344 ms
 2  10.1.1.13 (10.1.1.13)  2.854 ms  1.072 ms  1.237 ms
 3  qwest-asr.net.yale.internal (10.1.4.5)  1.139 ms  1.327 ms  1.281 ms
 4  10.1.3.99 (10.1.3.99)  2.120 ms  1.343 ms  1.874 ms
 5  cen-yale.net.yale.edu (130.132.251.74)  1.558 ms  1.634 ms  1.592 ms
 6  nox300gw1-vl-706-nox-yale.nox.org (207.210.143.89)  5.570 ms  6.367 ms  5.208 ms
 7  nox300gw1-vl-706-nox-yale.nox.org (207.210.143.89)  5.000 ms  5.008 ms  5.663 ms
 8  nox1sumgw1-vl-803-nox.nox.org (192.5.89.237)  5.765 ms  5.909 ms  5.145 ms
 9  nox1sumgw1-peer-nox-internet2-192-5-89-18.nox.org (192.5.89.18)  27.455 ms  27.232 ms
    27.344 ms
10  64.57.28.36 (64.57.28.36)  38.111 ms  126.638 ms  37.985 ms
11  xe-1-1-0.0.rtr.hous.net.internet2.edu (64.57.28.57)  51.982 ms  106.096 ms  51.817 ms
12  rt1-hardy-hstn-xe-0-1-0-3018.tx-learn.net (74.200.187.6)  52.988 ms  52.937 ms  53.307 ms
13  tx-bb-i2-hstn.tx-learn.net (74.200.187.26)  53.444 ms  53.515 ms  53.288 ms
14  aust-utnoc-core-ge-5-0-0-706.tx-bb.net (192.88.12.50)  54.636 ms  54.703 ms  55.054 ms
15  192.88.12.26 (192.88.12.26)  55.056 ms  74.044 ms  54.926 ms
16  ser10-v702.gw.utexas.edu (128.83.10.1)  55.208 ms  54.803 ms  55.117 ms
17  cs-nocb10-v690.gw.utexas.edu (146.6.10.34)  55.013 ms  55.099 ms  55.045 ms
18  cs65k-cs45k-po1-p2p.aces.utexas.edu (128.83.37.66)  54.960 ms  55.005 ms  55.551 ms
19  net6.cs.utexas.edu (128.83.120.139)  55.015 ms  54.956 ms  54.847 ms
```

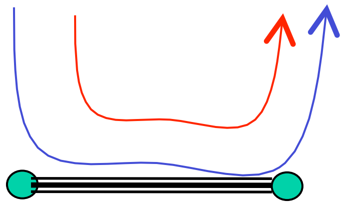
Increasing QoE Demand

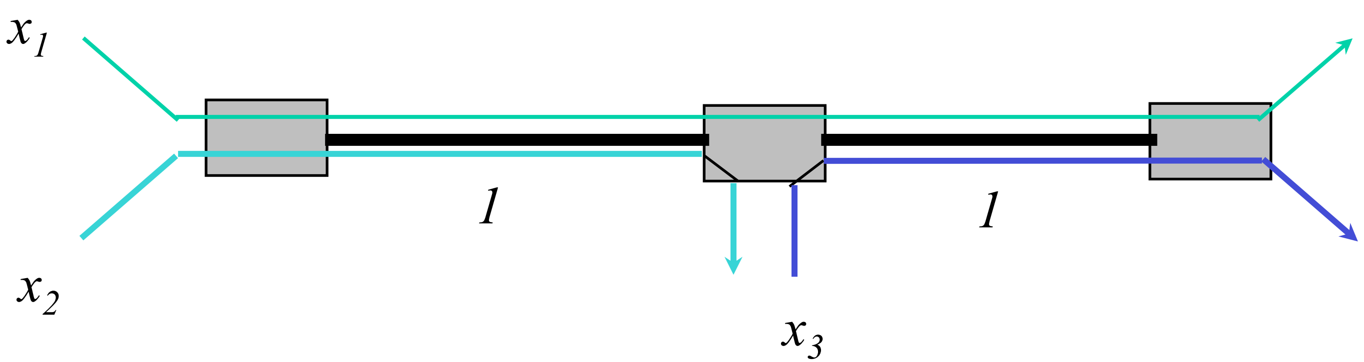
- 20 ms increase in latency
  =>
  1% drop in click-through rate



Politics: Sharing a Shared Infrastructure

- question: how to allocate network resources among users?



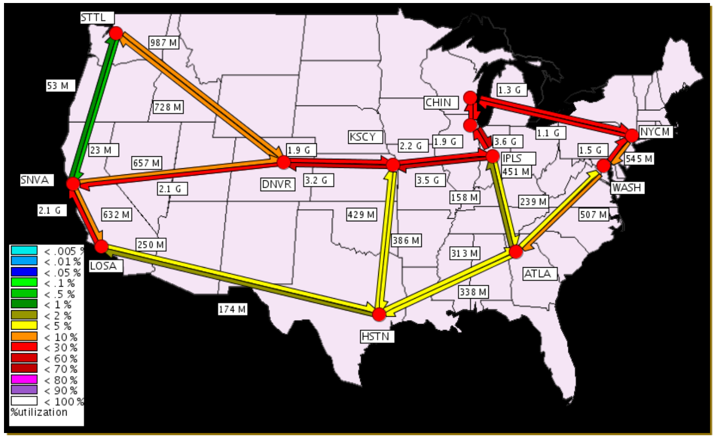


Poor App and Network Interaction

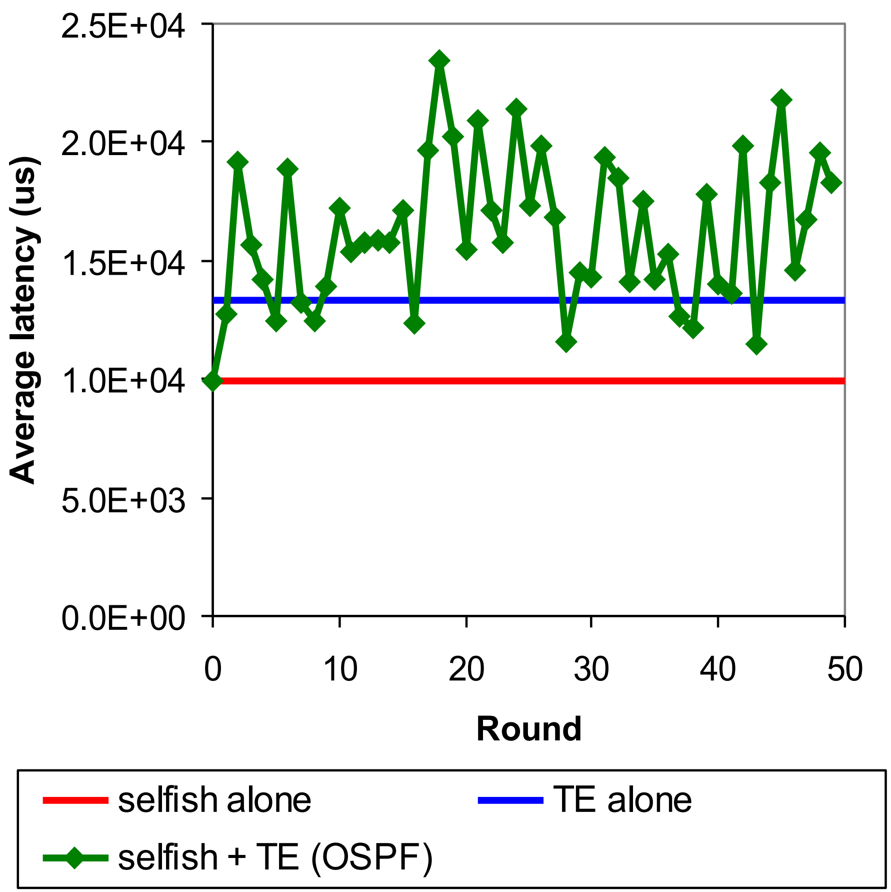
- Network Providers change routing to shift traffic away from highly utilized links

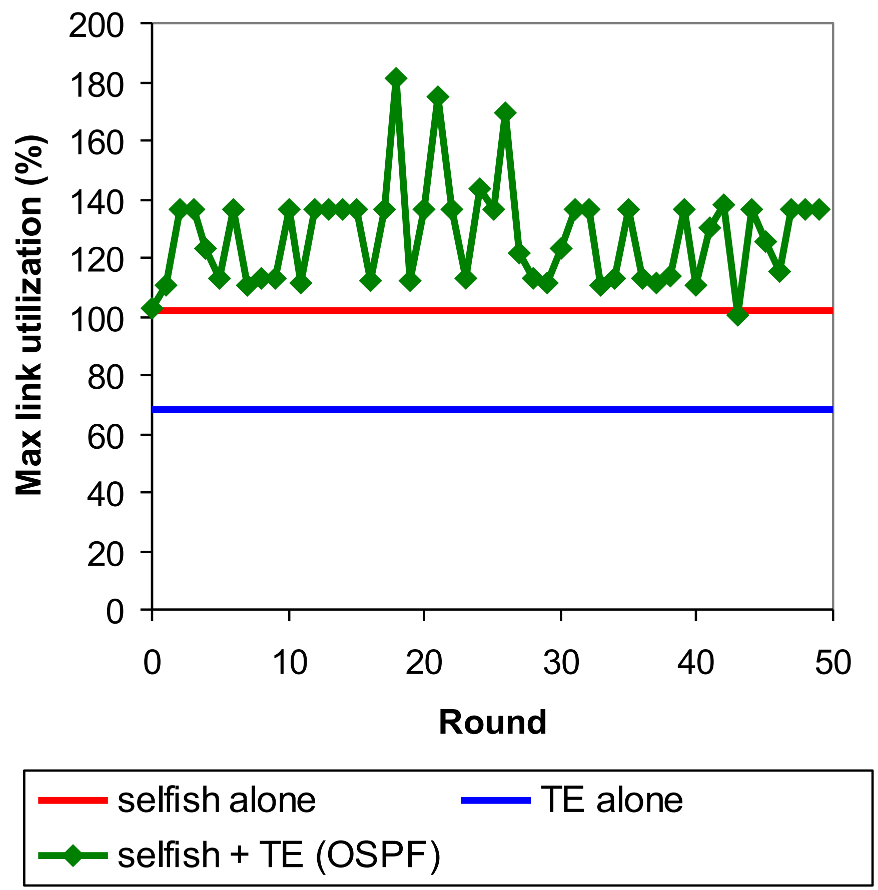
- Adaptive/decentralized apps direct traffic to lower latency paths

- Equilibrium points can be inefficient



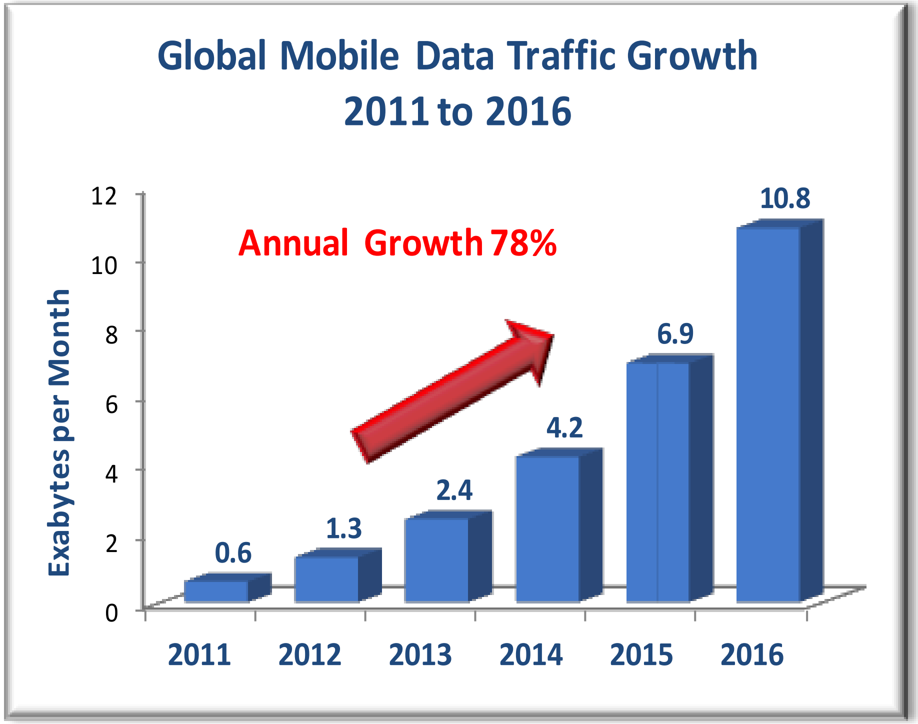
App and Network Interaction





Fast Wireless Data Growth

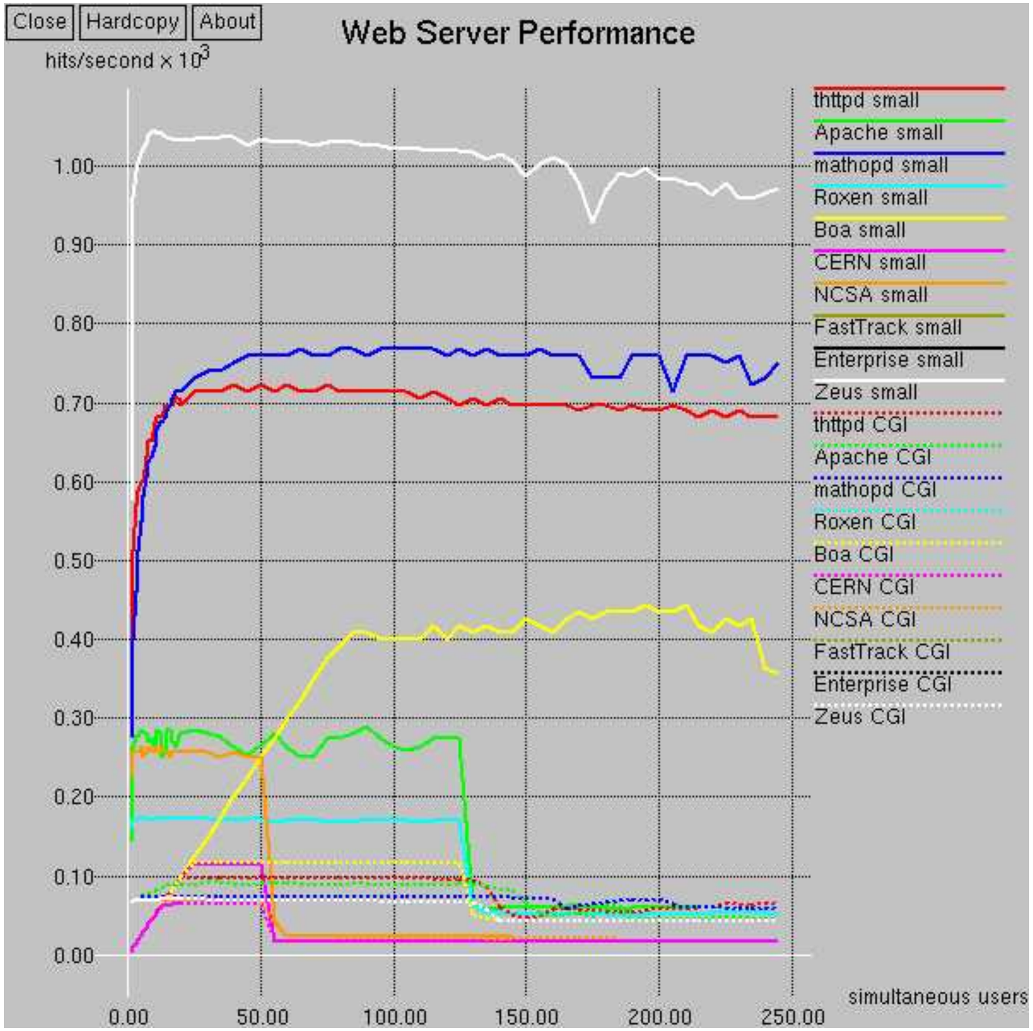
- AT&T
  - Wireless data growth 20,000% in the past 5 years



Problems: Bandwidth limitations and poor TCP performance.

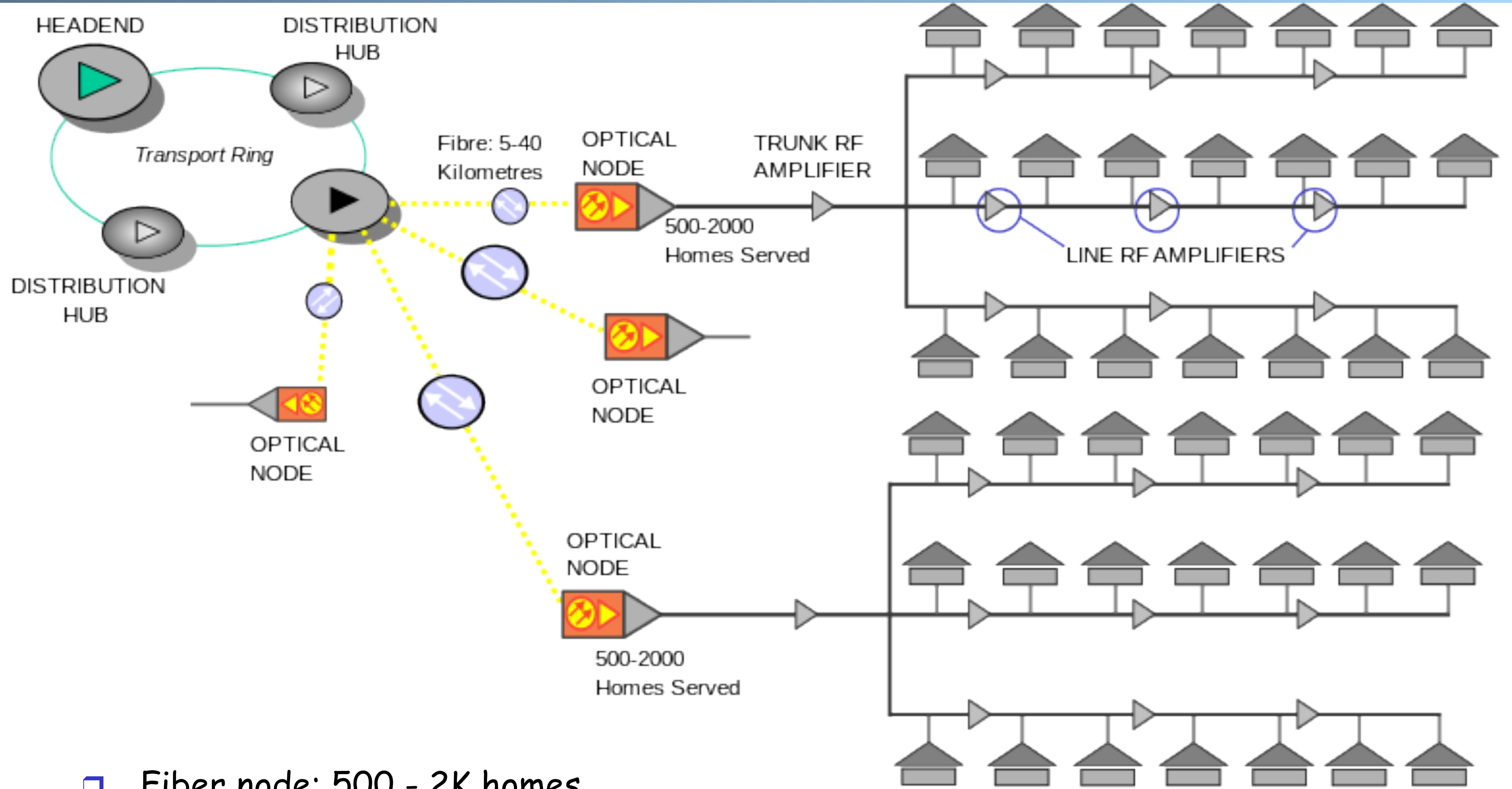
Source: CISCO Visual Networking Index (VNI) Global Mobil Data Traffic Forecast 2011 to 2016

Flexibility vs Performance



Access: Cable

Also called Hybrid Fiber-coaxial Cable (HFC)



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