CS433/533: Computer Networks

Y. Richard Yang

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

8/31/2017

Outline

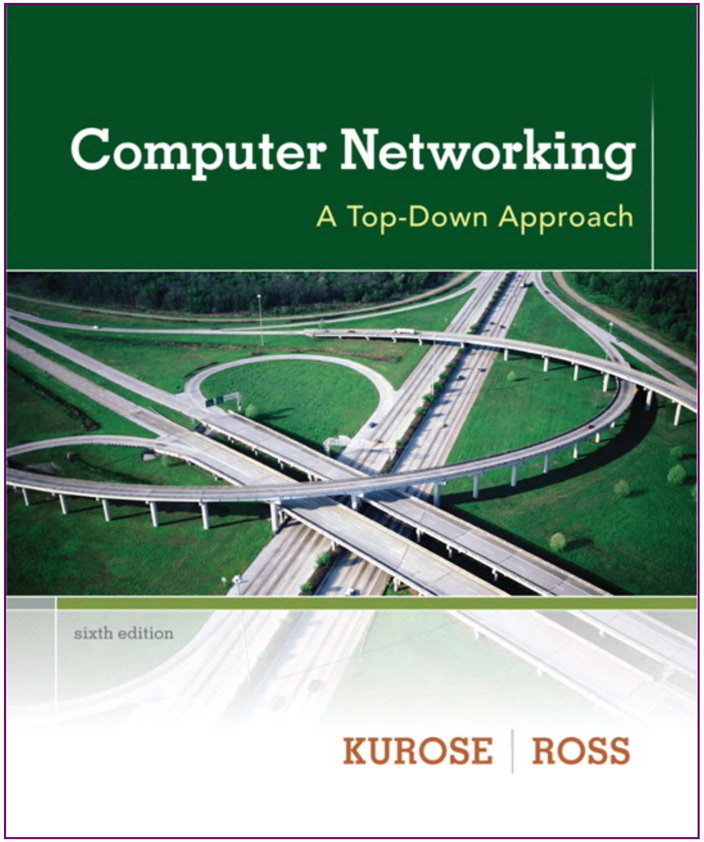
- *Administrative trivia's*
- What is a network protocol?
- A brief introduction to the Internet: past and present
- Challenges of Internet networks and apps
- Summary

Personnel

- Instructor
  - Y. Richard Yang, yry@cs.yale.edu, AKW 208A
    - office hours
      - TTh 4:00-5:00 pm or by appointment
      - please feel free to stop by if you see I am in my office
- Teaching assistants
  - Qiao Xiang, AKW 204
    - office hours TBA
  - Geng Li, AKW 204
    - office hours TBA

Textbook

- Textbook
  - *Computer Networking: A Top-Down Approach, 7/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 (Internet service provider, 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

CPSC433/533 or EENG 452

- CPSC433/533: More from a computer science's view, emphasizing more on programming

- EENG 452: More from an engineering's view, emphasizing more on analysis

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
      - one HTTP 1.1 server, one TCP, and one robot network using Raspberry Pi or BeagleBone
      - 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 !!

Questions?

Outline

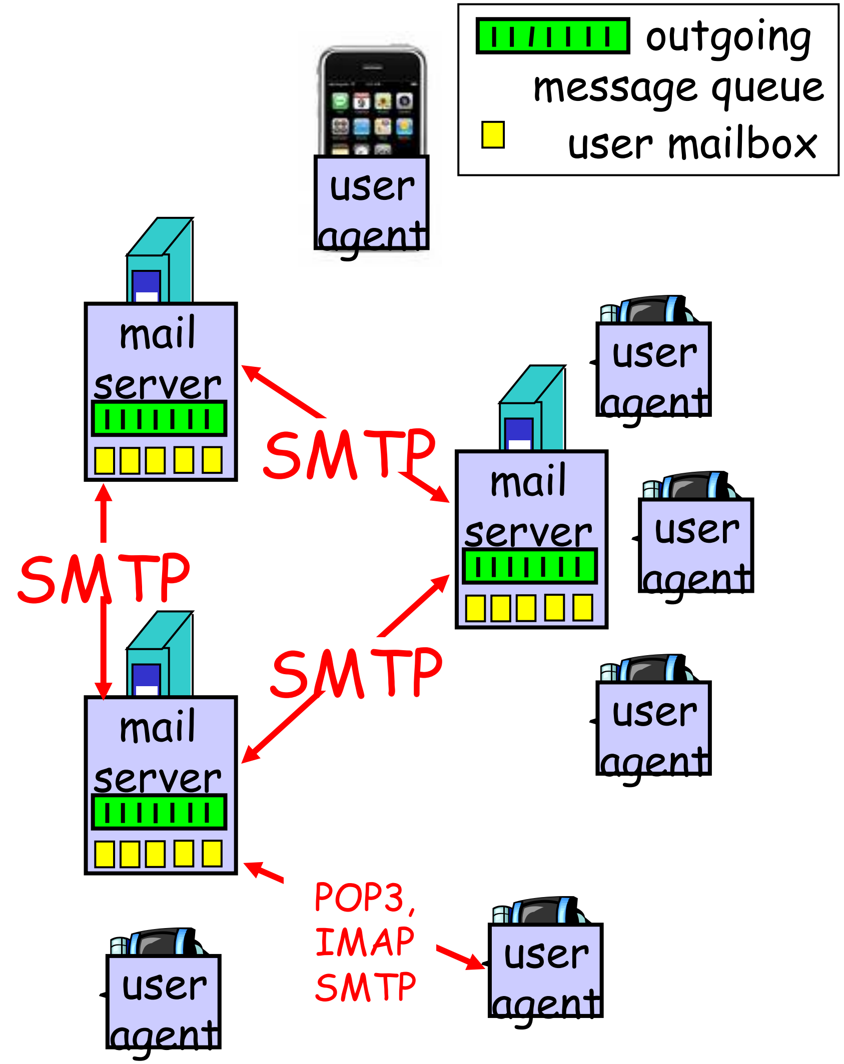
- Administrative trivia's
- *What is a network protocol?*

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)

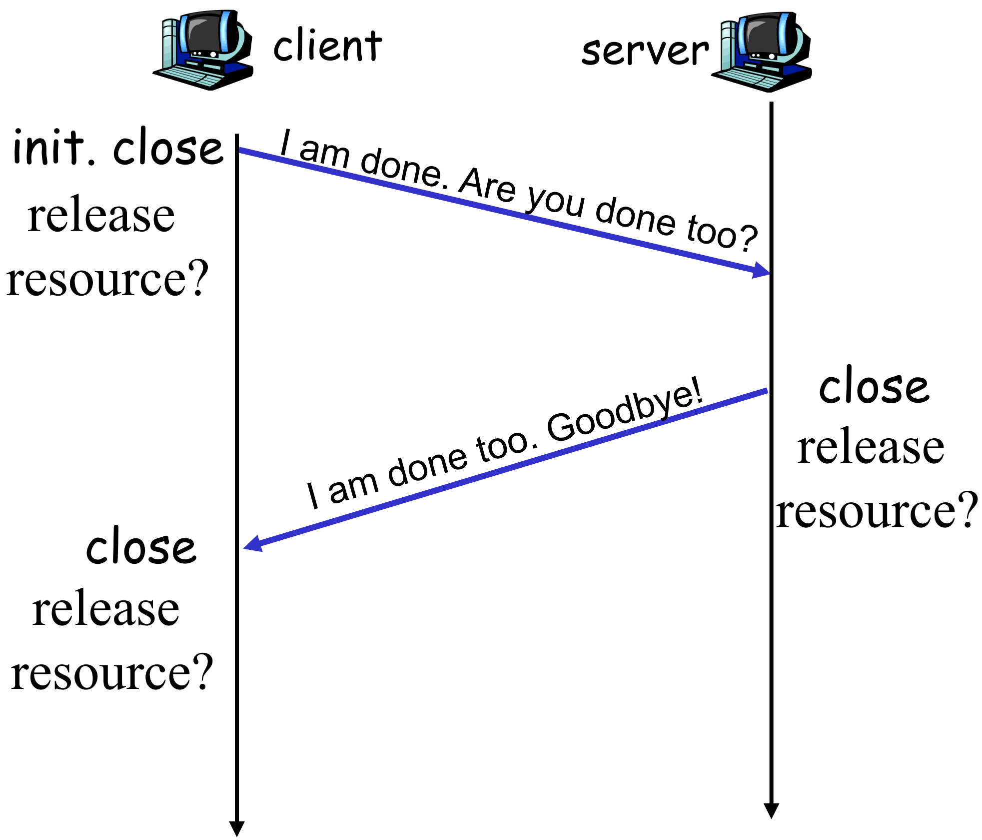
- Messages from a client to a mail server
  - HELO
  - MAIL FROM: <address>
  - RCPT TO: <address>
  - DATA
    <This is the text end with a line with a single .>
  - QUIT
- Messages from a mail server to a client
  - status code
    - The first digit of the response broadly indicates the success, failure, 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



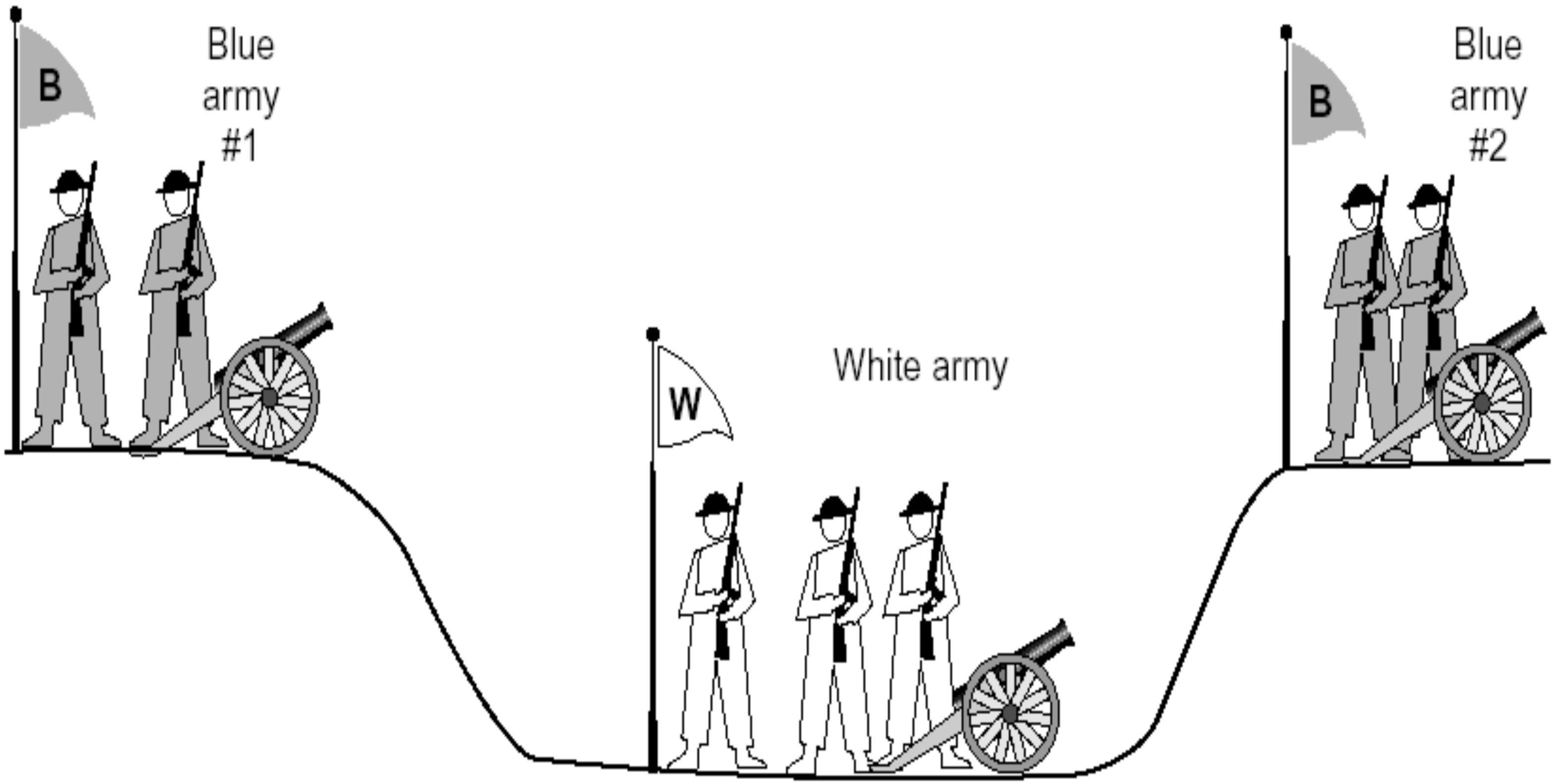
Command: %telnet netra.cs.yale.edu smtp

Example Protocol: TCP Connection Close Protocol

- Why connection close?
  - so that each side can release resource and remove state about the communication

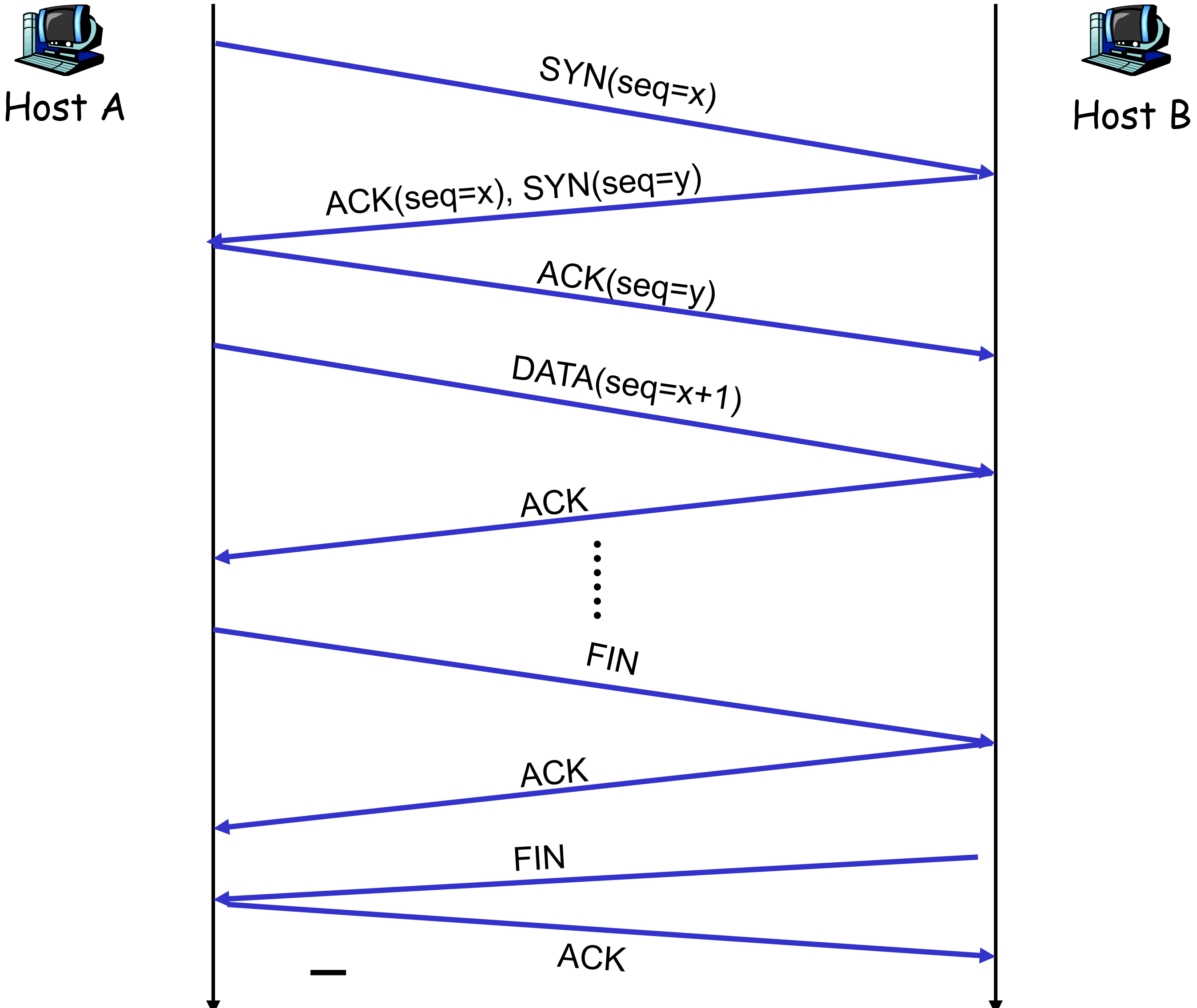


General Case: The Two-Army Problem



The gray (blue) armies need to agree on whether or not they will attack the white army. They achieve agreement by sending messengers to the other side. If they both agree, attack; otherwise, no. Note that a messenger can be captured!

Example: TCP Protocol Handshakes



Example: Google' new QUIC

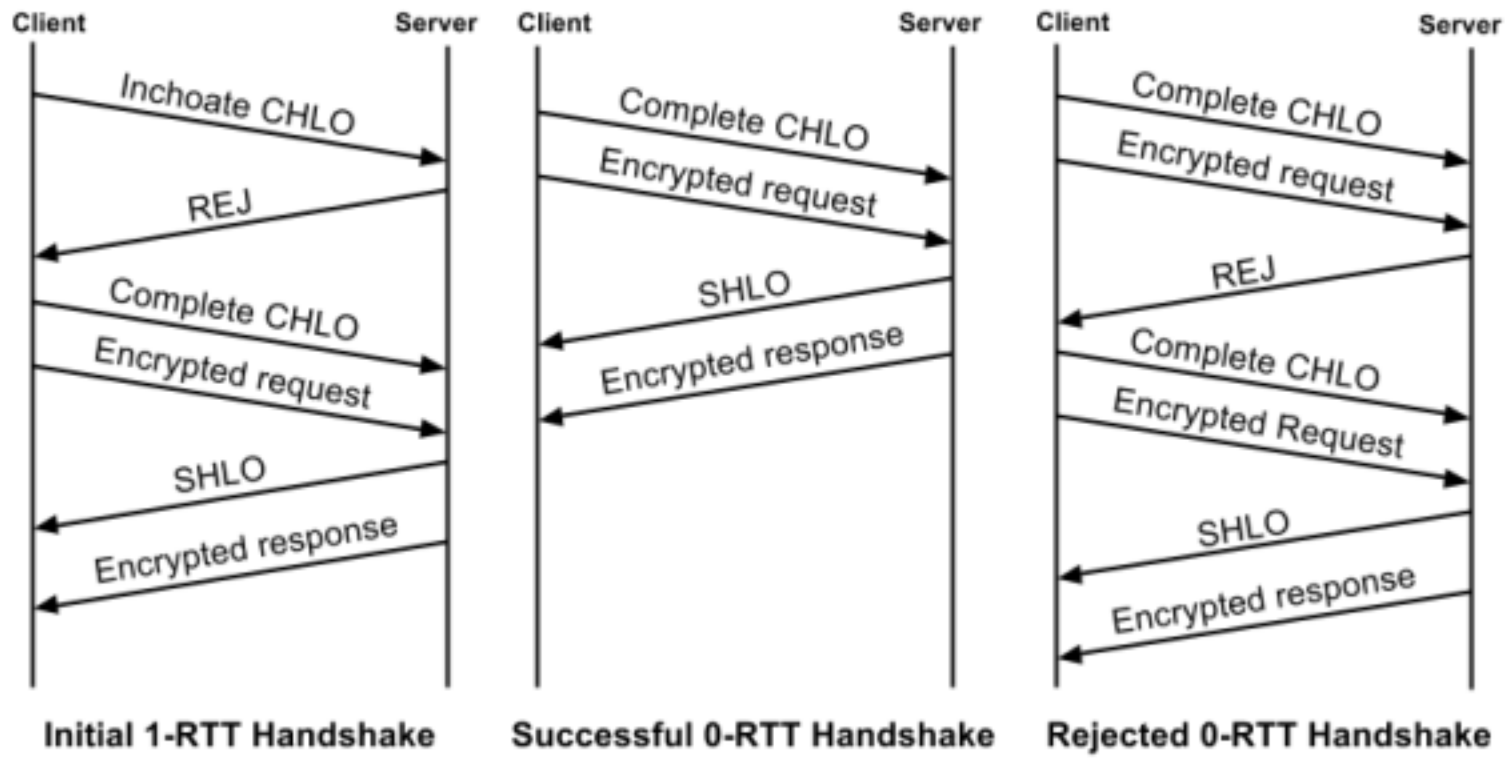


Figure 4: Timeline of QUIC's initial 1-RTT handshake, a subsequent successful 0-RTT handshake, and a failed 0-RTT handshake.

http://conferences.sigcomm.org/sigcomm/2017/files/program/ts-5-1-QUIC.pdf

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

Internet Standardization Process

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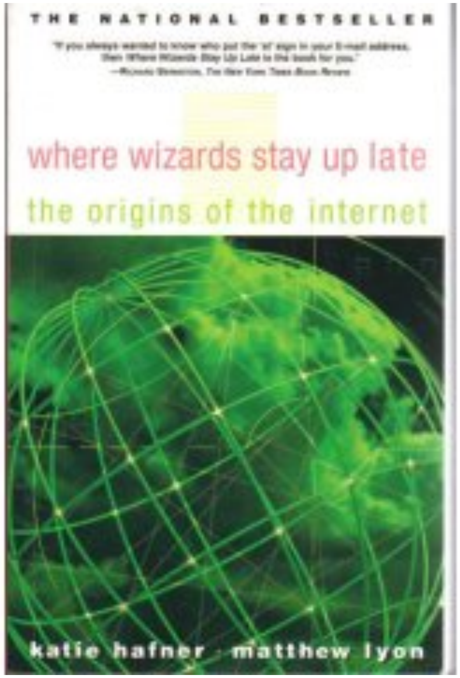
- A typical (but not the only) way of standardization:
  - Internet draft
  - RFC
  - proposed standard
  - draft standard (requires 2 working implementations)
  - Internet standard (declared by Internet Architecture Board)
- David Clark, 1992:

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

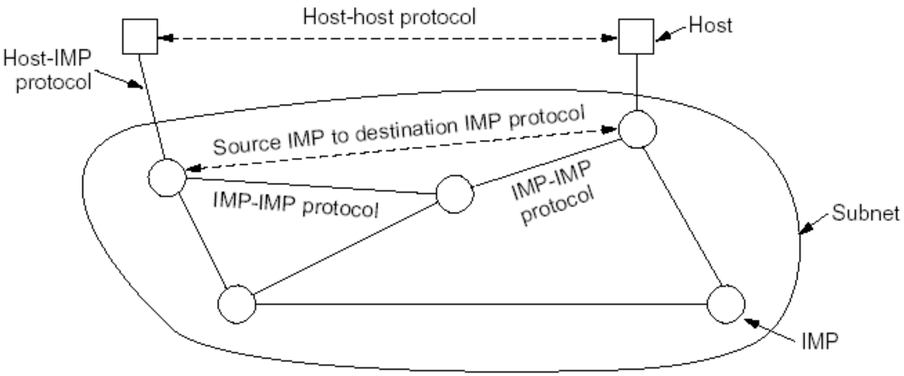
Outline

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



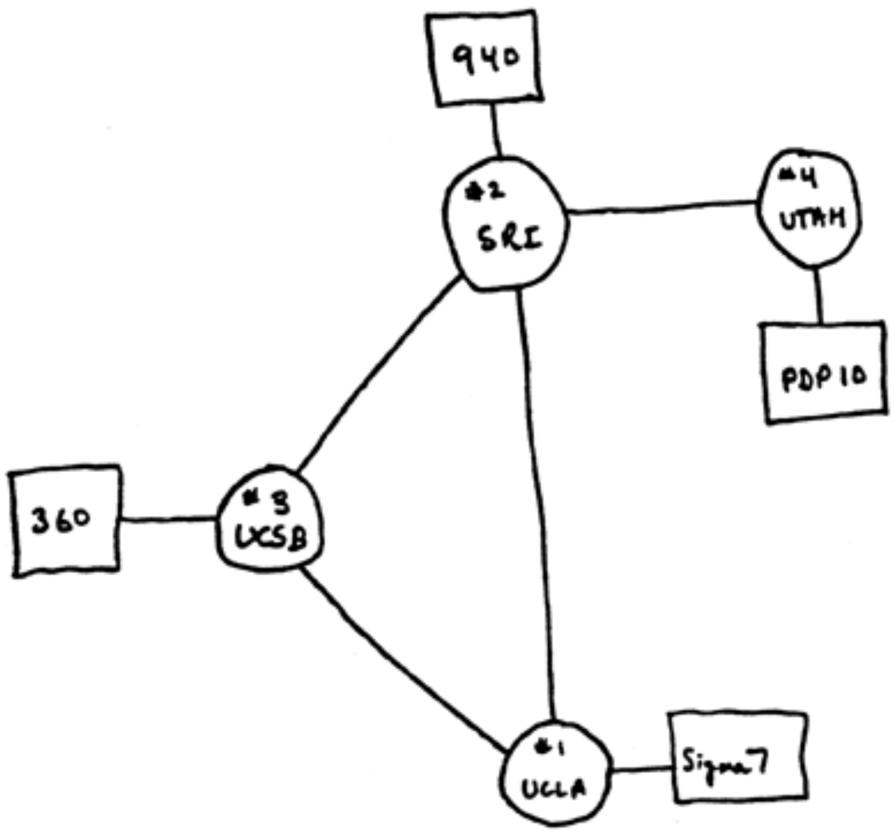
Prelude: Packet Switching and ARPANET

- **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)

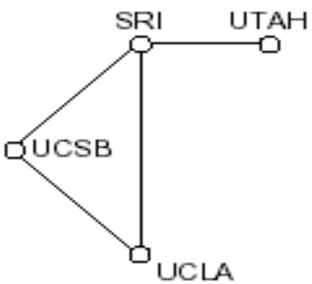


Internet 1.0: Initial ARPANET

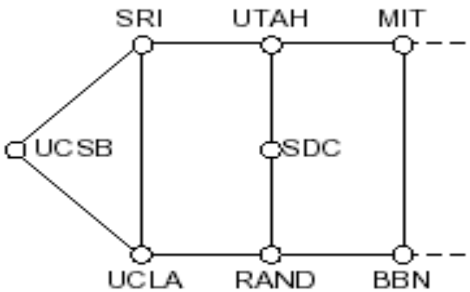
- 1969
  - ARPANET commissioned: 4 nodes, 50kbps



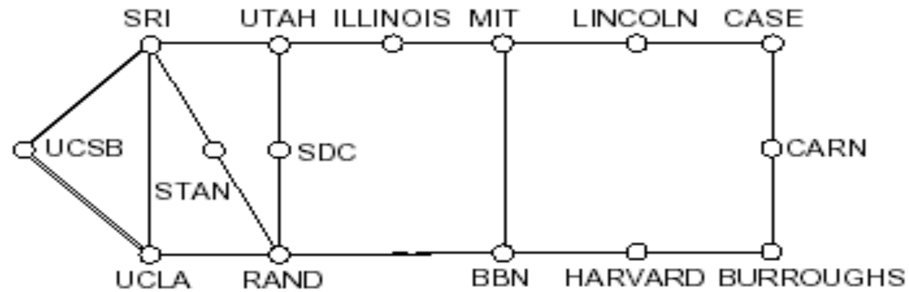
Initial Expansion of the ARPANET



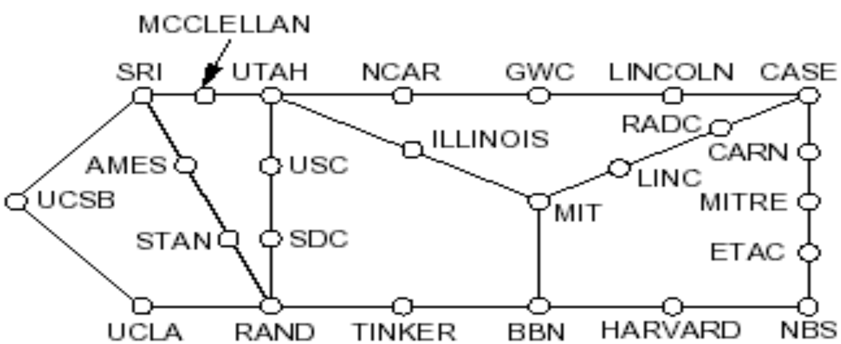
Dec. 1969



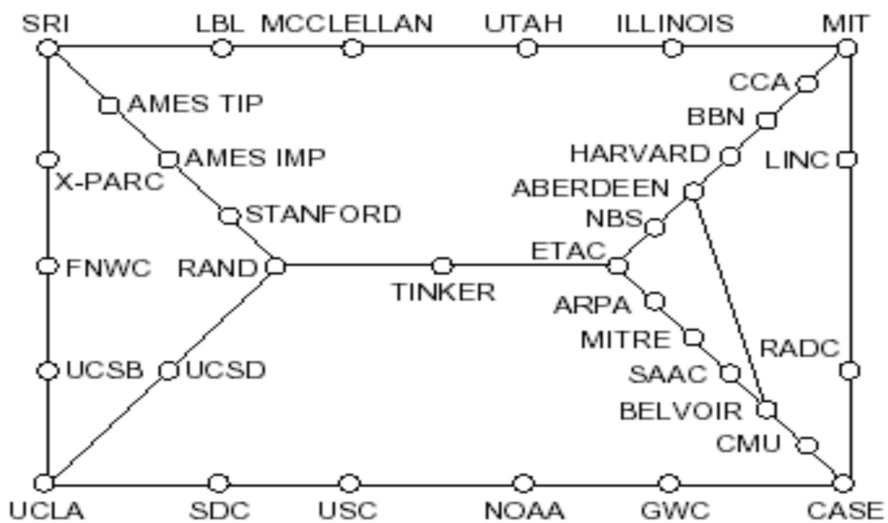
July 1970



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: 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

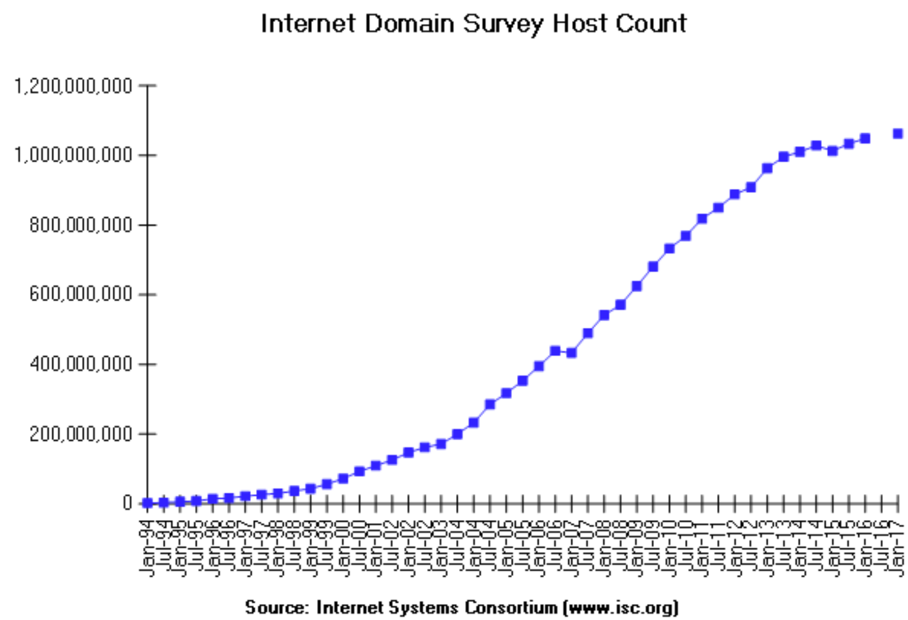
For a link of interesting RFCs, please see
http://zoo.cs.yale.edu/classes/cs433/cs433-2017-fall/readings/interestingrfcs.html

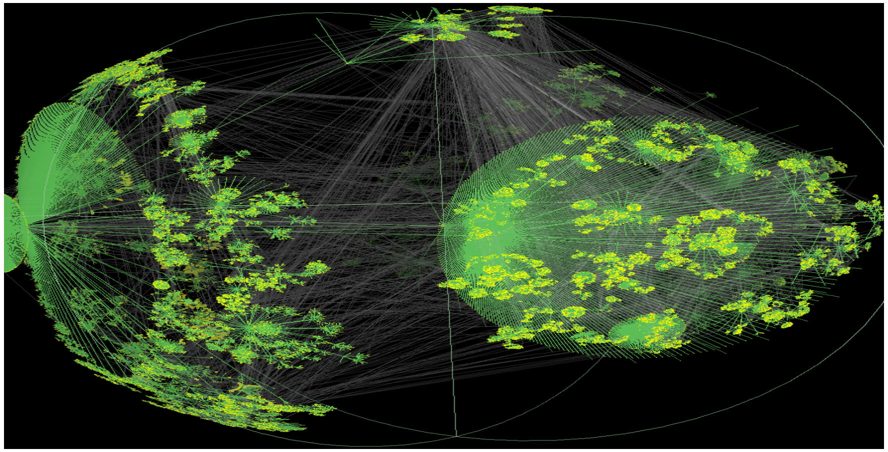
For more on Internet history, please see
http://www.zakon.org/robert/internet/timeline/

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
Jan. 1993	1,313,000
Jan. 1996	9,472,000
Jan. 1999	43,218,000
Jan. 2002	147,344,723
Jan. 2005	317,646,084
Jan. 2007	433,193,199
Jan. 2010	732,740,444
Jan. 2013	963,518,598
Jan. 2016	1,048,766,623
Jan. 2017	1,062,660,523

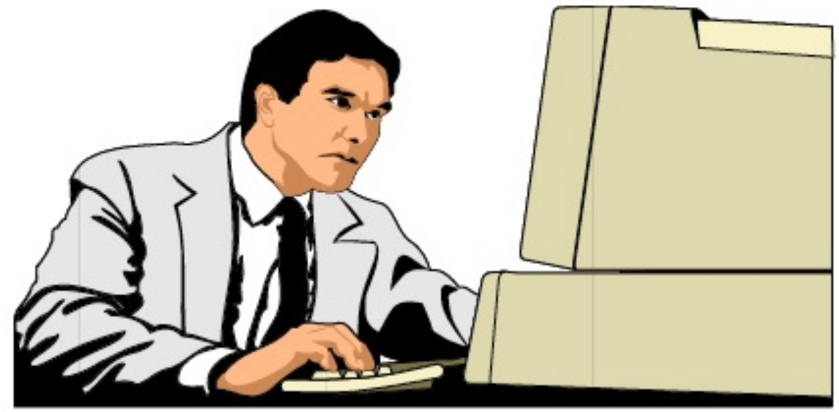




CAIDA router level view

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

Internet 3.0: Always-Connected, Virtualized Life

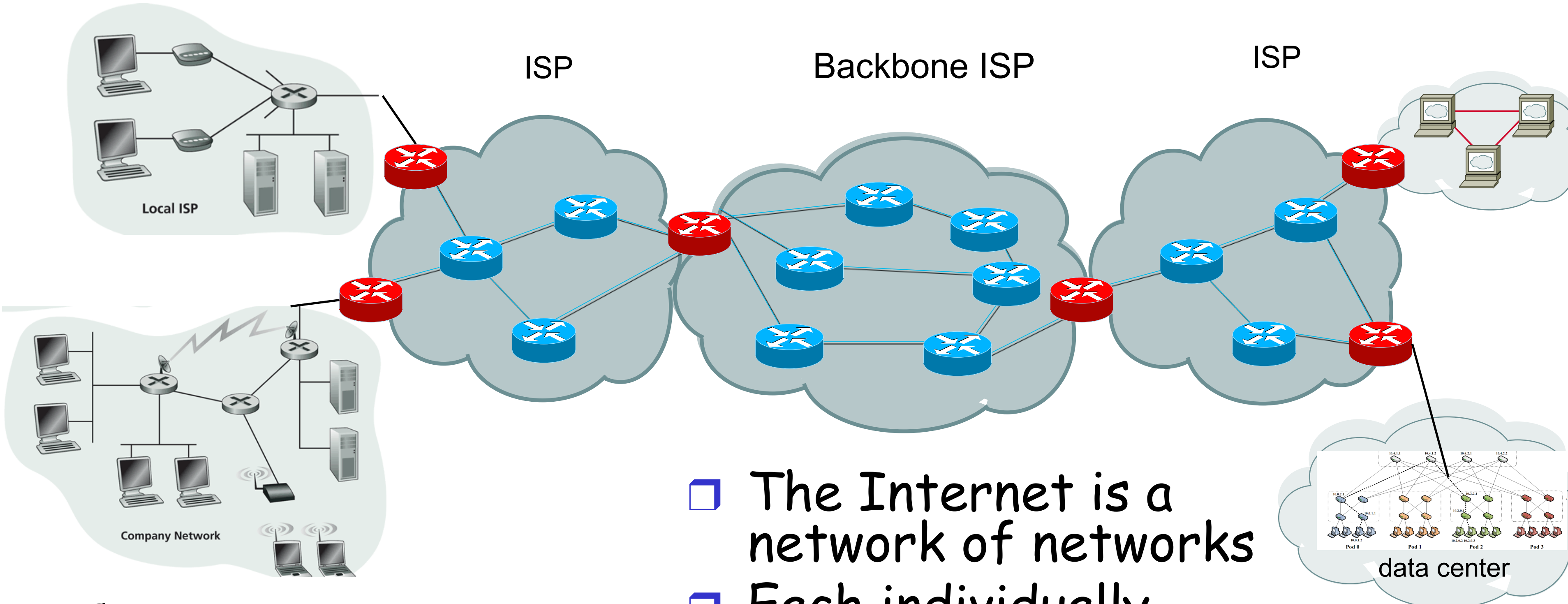
- Office => Virtual workspace
- Shopping => Online shopping
- Education => Remote education
- Entertainment ⇒ Online media/games
- Environment ⇒ Internet of things

Outline

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

Internet Physical Infrastructure

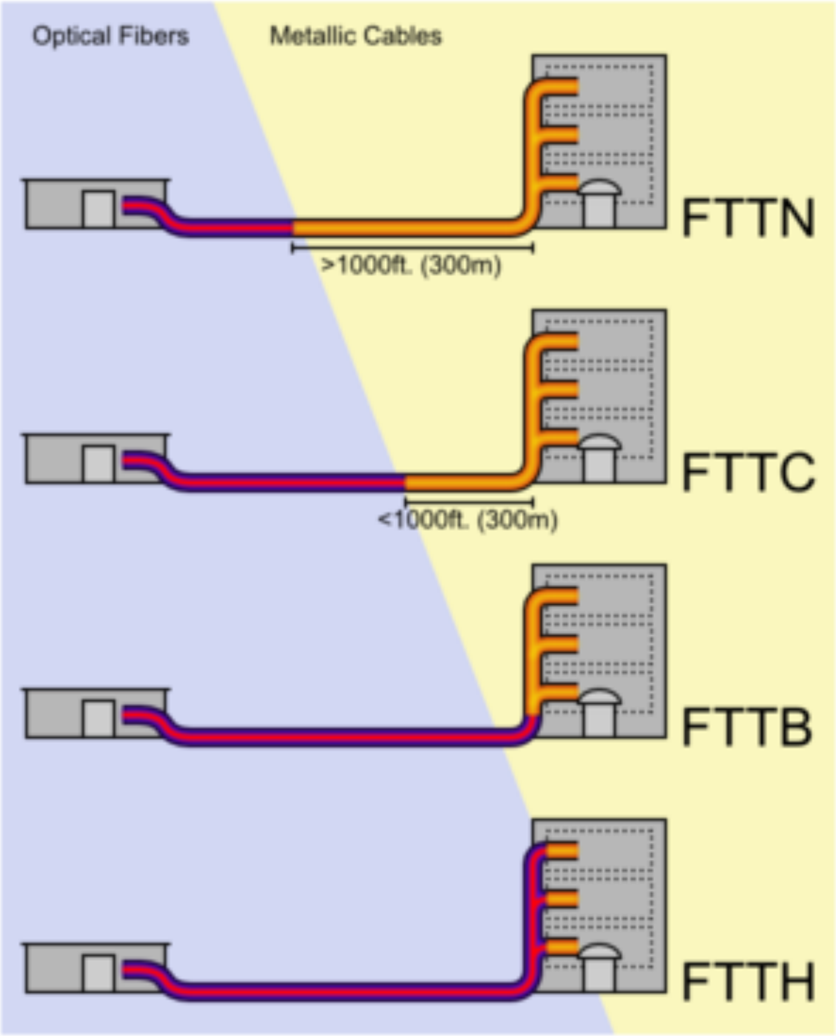
Residential access
- Cable, Fiber, DSL, Wireless



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

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

Access: Fiber to the x

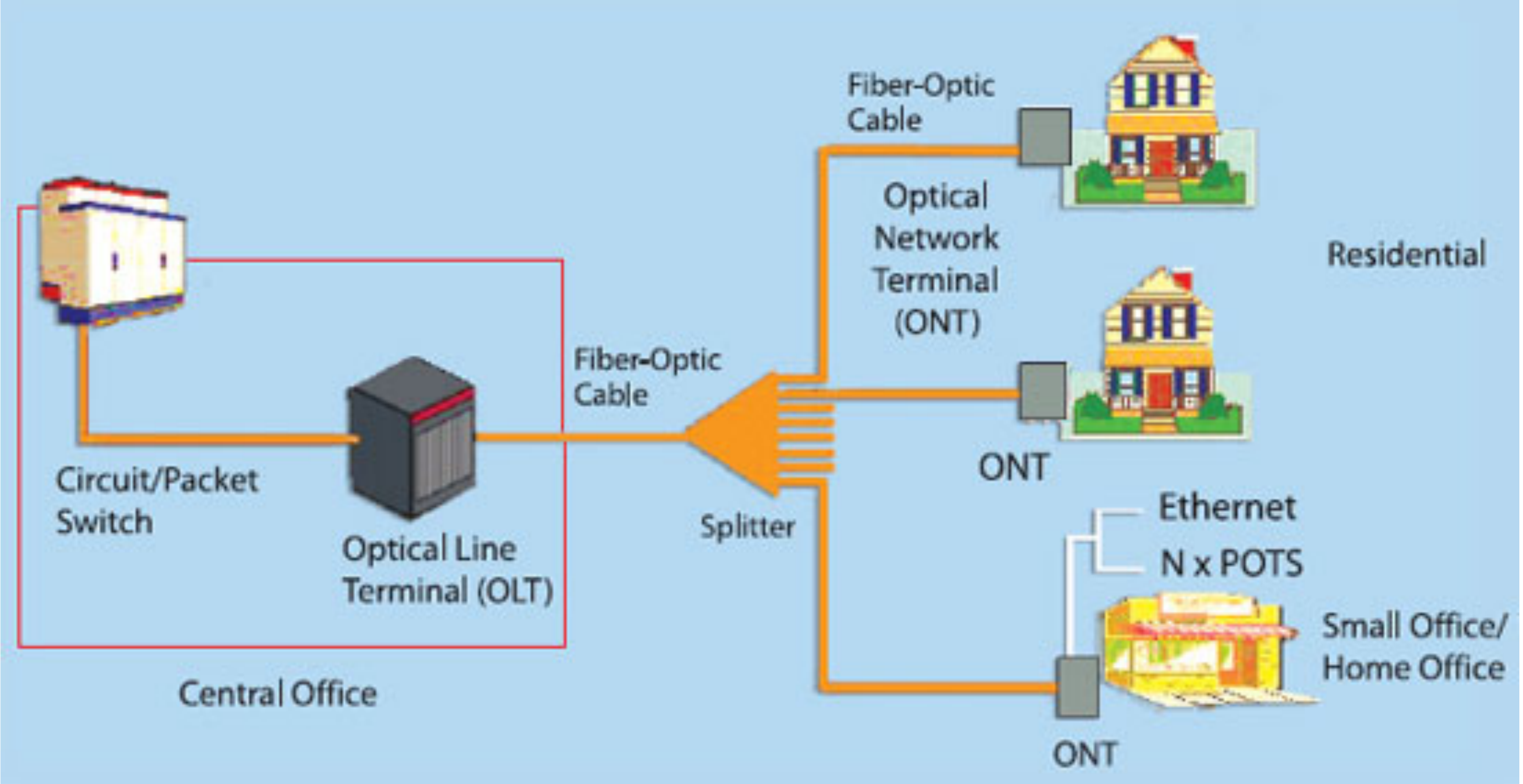


http://en.wikipedia.org/wiki/Fiber_to_the_x

Access: Fiber to the Premises (FTTP)

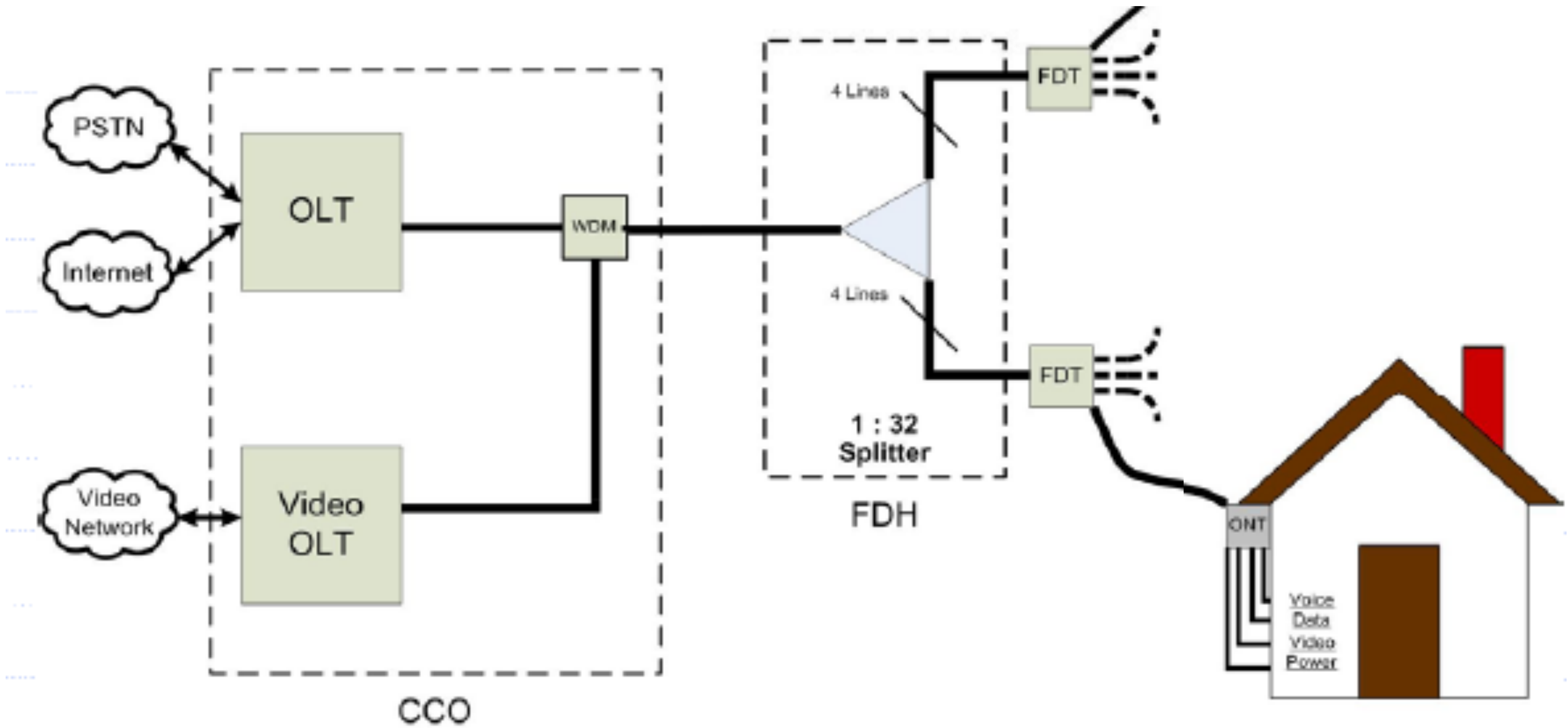
- Deployed by Verizon, AT&T, Google
- One of the largest comm. construction projects

FTTP Architecture

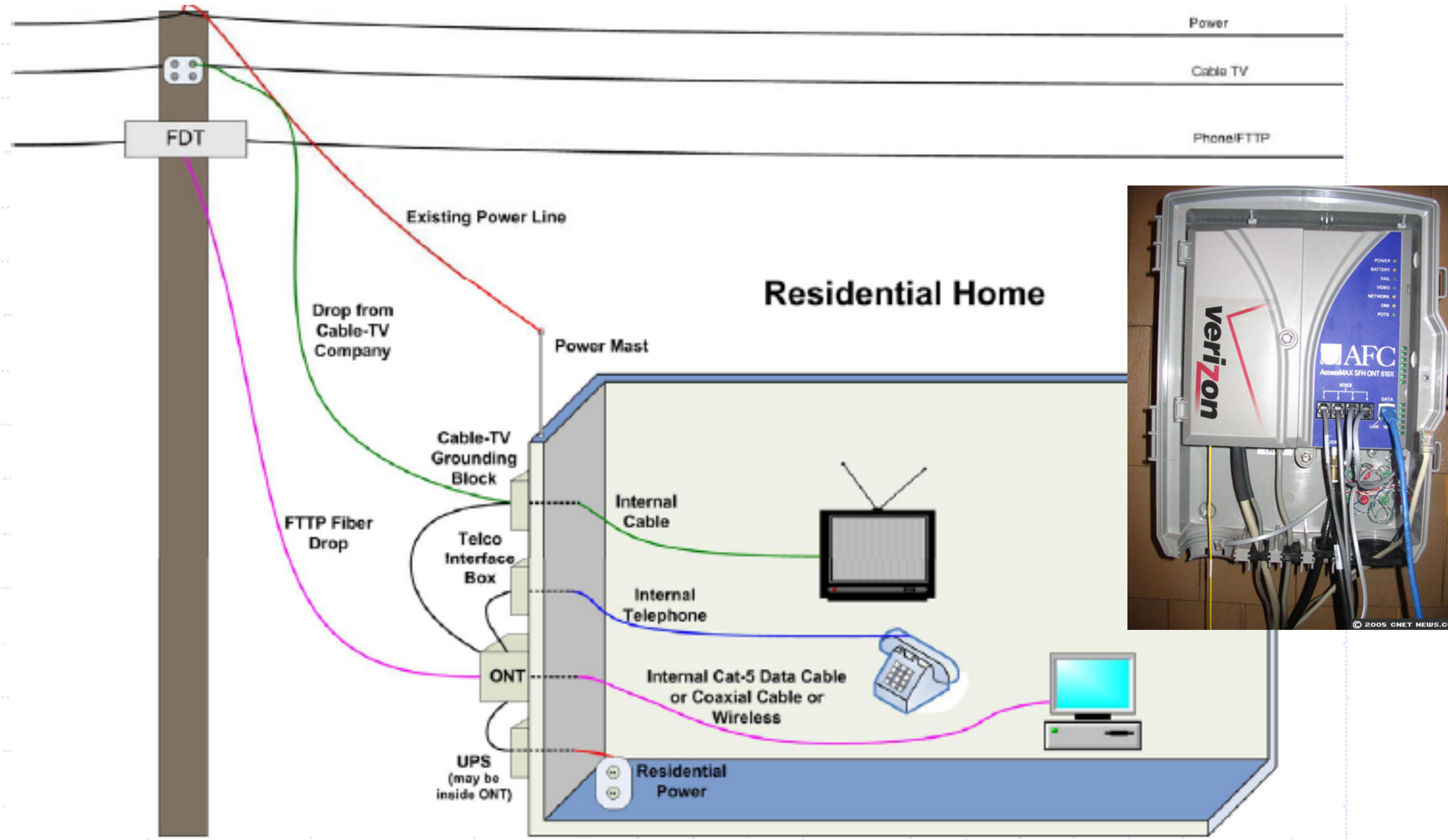


FTTP Architecture

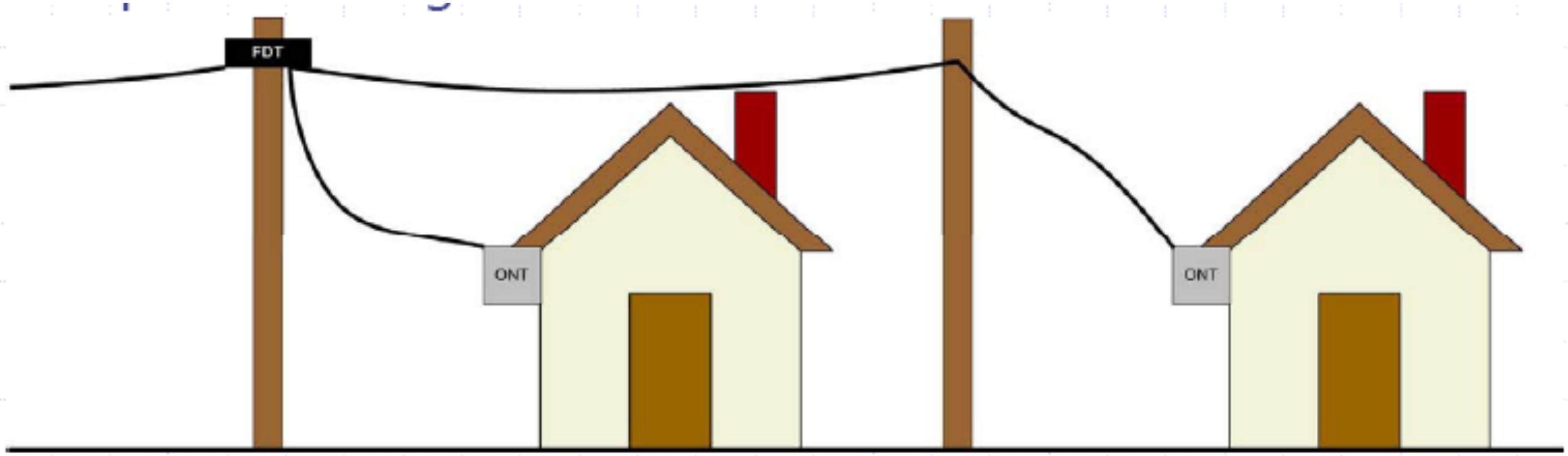
- Optical Network Terminal (ONT) box outside dwelling or business
- Fiber Distribution Terminal (FDT) in poles or pedestals
- Fiber Distribution Hub (FDH) at street cabinet
- Optical Line Terminal (OLT) at central office



FTTP Architecture: To Ho



FTTP Architecture: Fiber Distribution Terminal (FDT)



FTTP Architecture: Central to Fiber Distribution Hub (FDH)

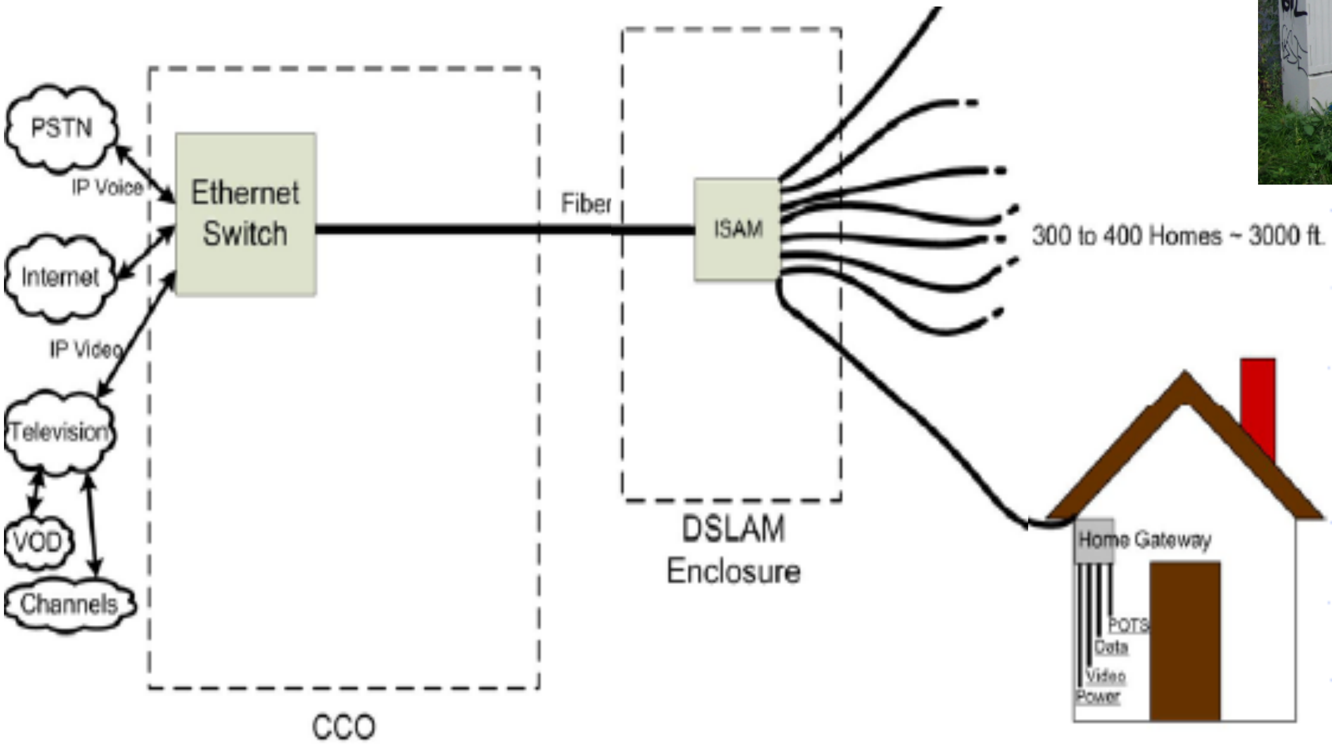
- Backbone fiber ring on primary arterial streets (brown)
- Local distribution fiber plant (red) meets backbone at cabinet

FDH

Access: DSL

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

DSLAM



Access: Wireless

https://x.company/loon/

Access: Wireless

theguardian

home › tech US politics world opinion sports soccer arts lifestyle fa ≡ all

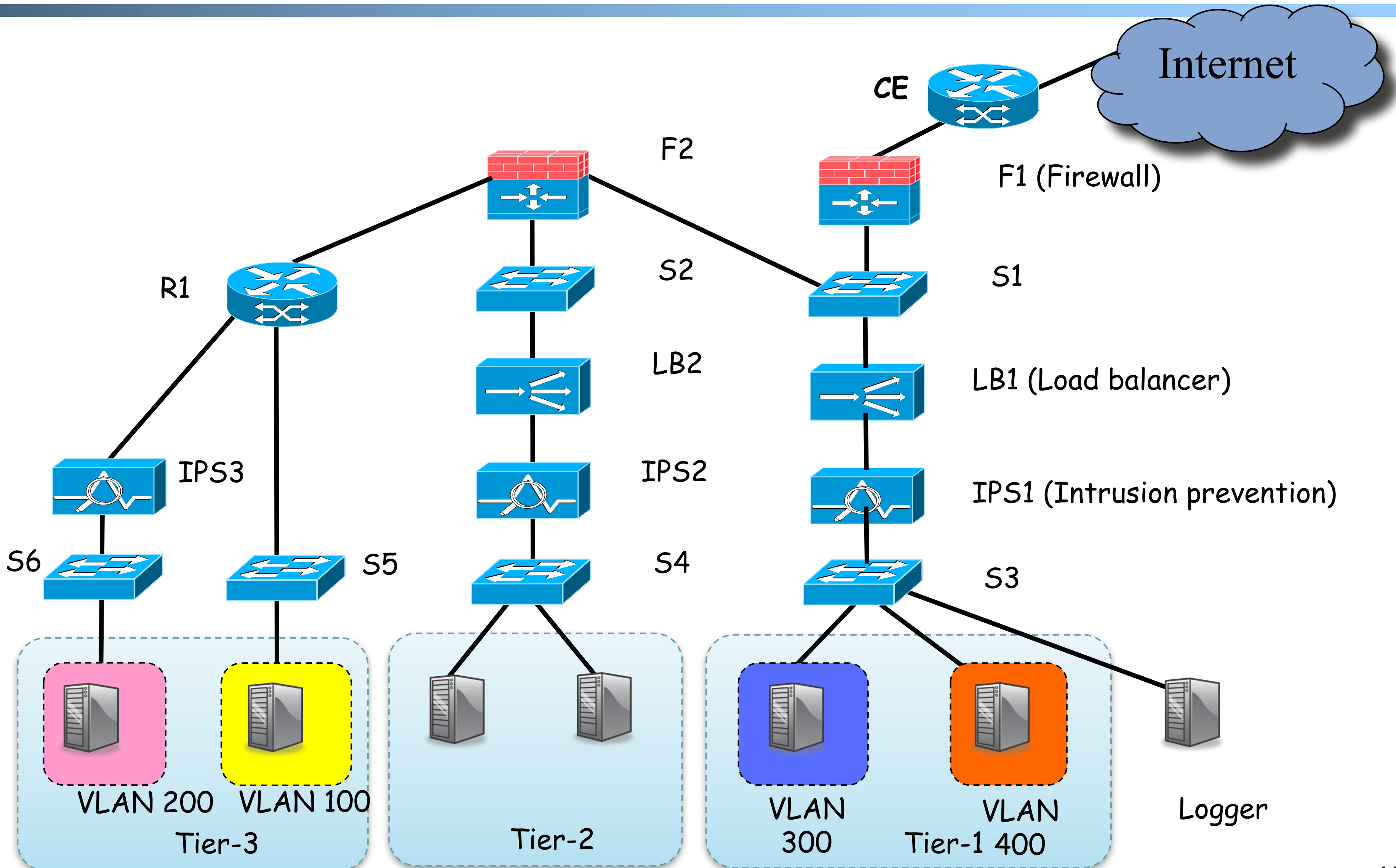
Elon Musk

Elon Musk wants to cover the world with internet from space

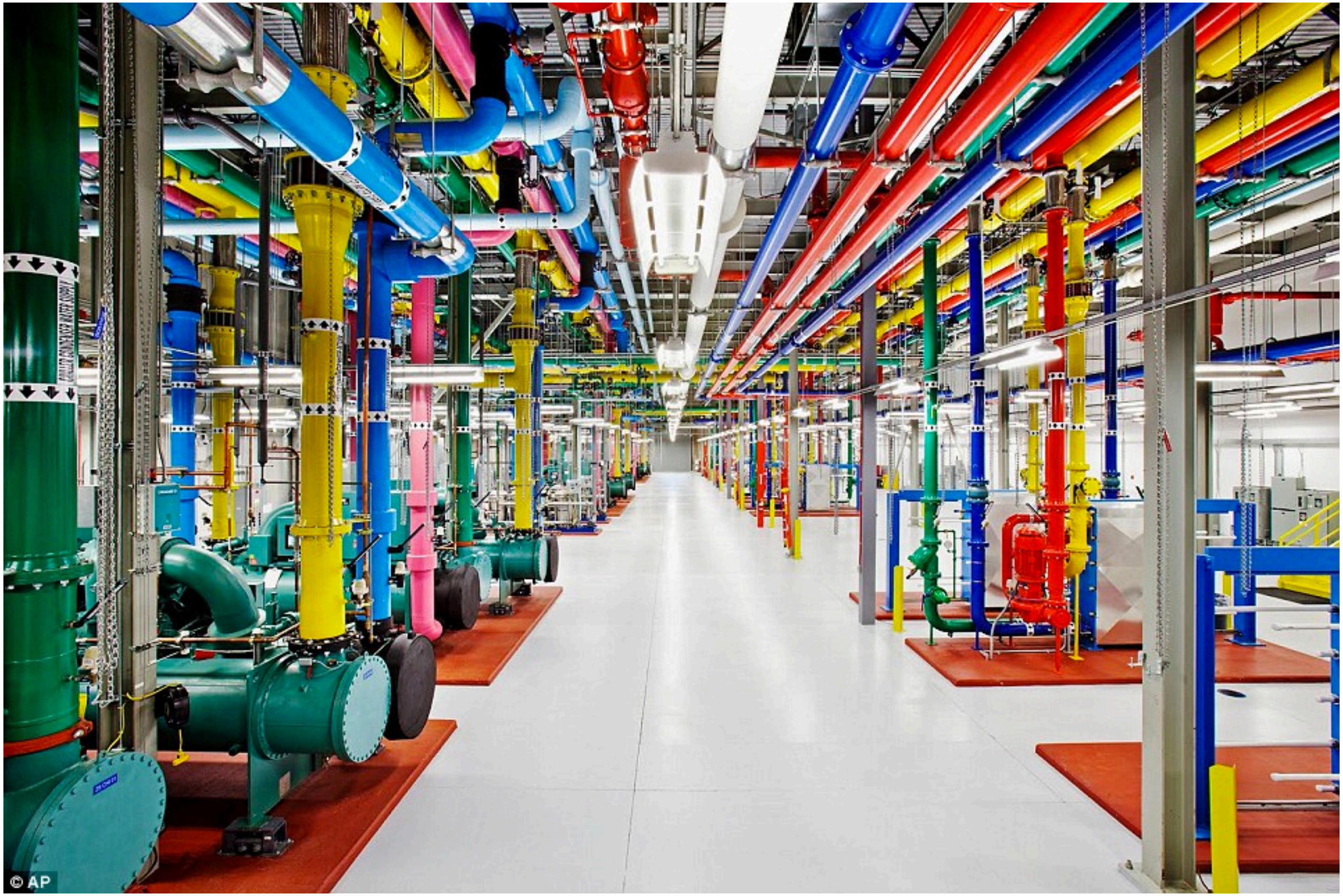
SpaceX requests permission from US government to operate network of 4,425 satellites to provide high-speed, global internet coverage

https://www.theguardian.com/technology/2016/nov/17/elon-musk-satellites-internet-spacex

Campus Network

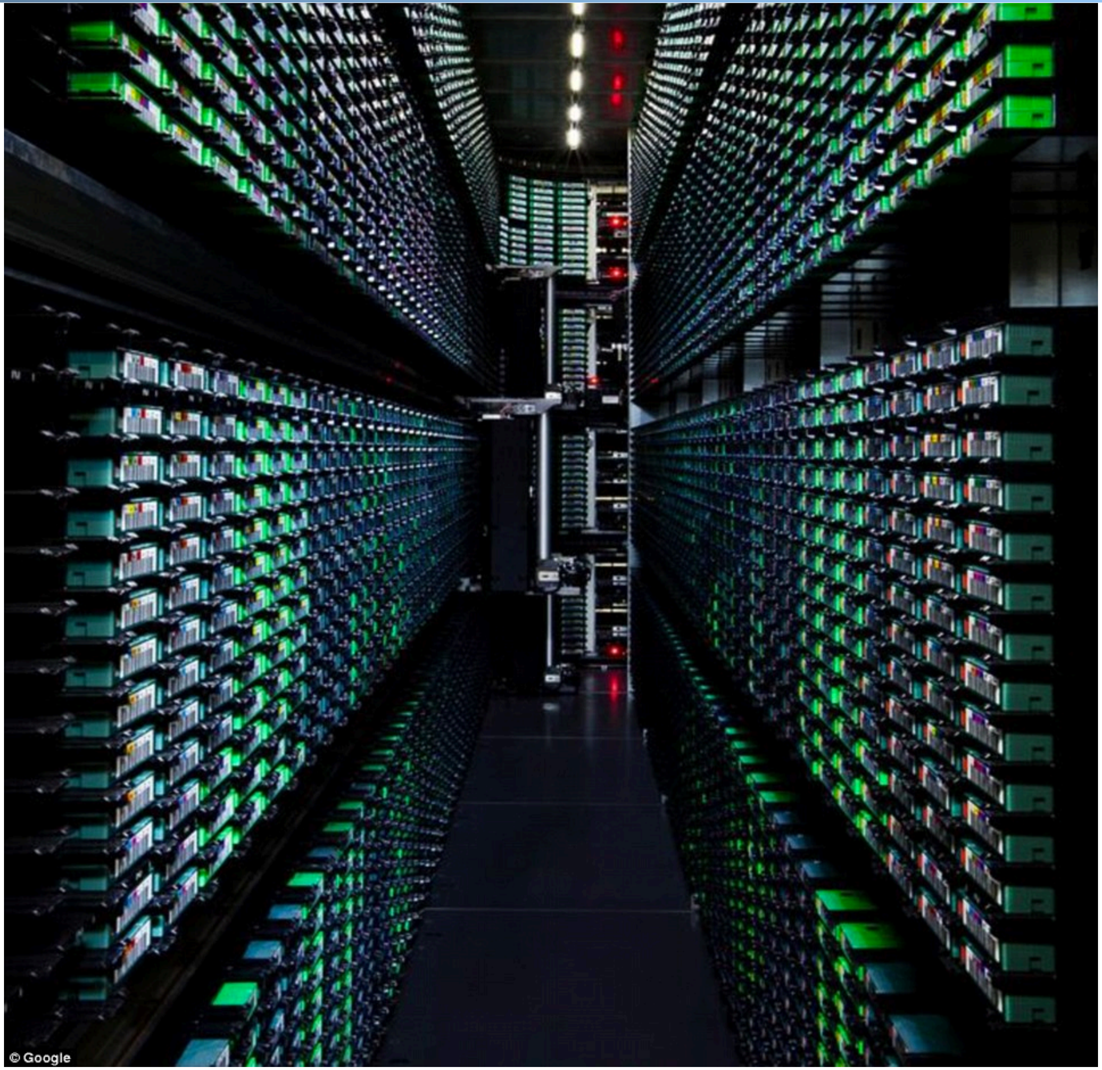


Data Center Networks



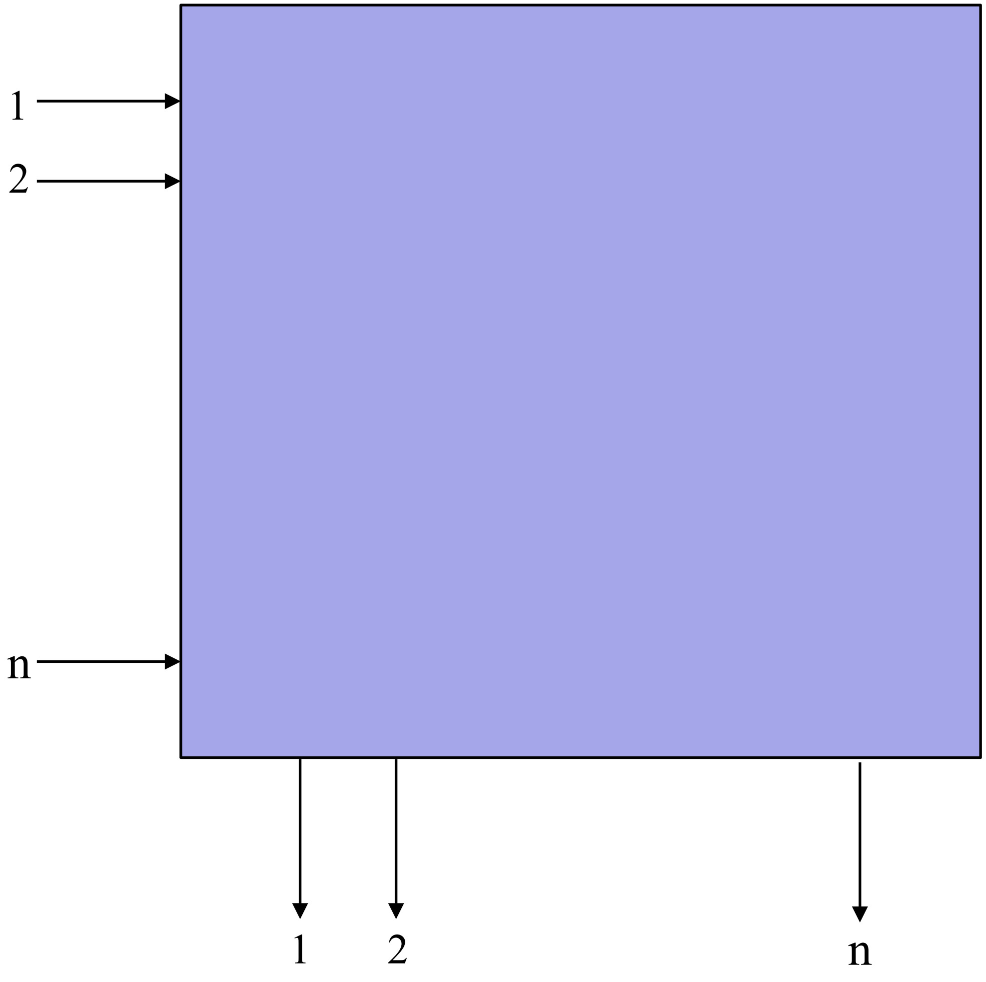
http://www.dailymail.co.uk/sciencetech/article-3369491/Google-s-plan-world-Search-engine-build-half-billion-dollar-data-center-US.html

Data Center Networks

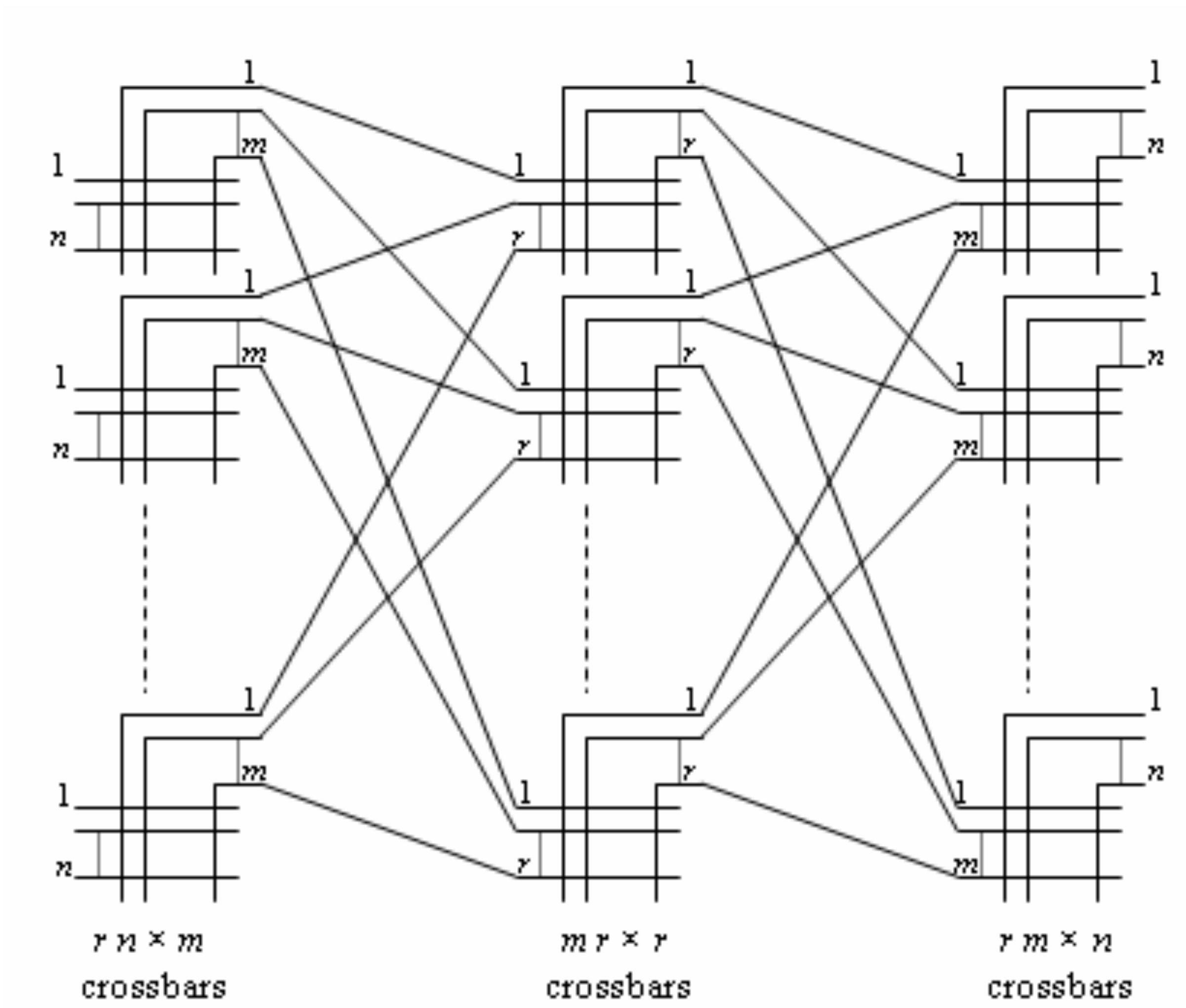


http://www.dailymail.co.uk/sciencetech/article-3369491/Google-s-plan-world-Search-engine-build-half-billion-dollar-data-center-US.html

Foundation of Data Center Networks



Foundation of Data Center Networks: Clos Networks



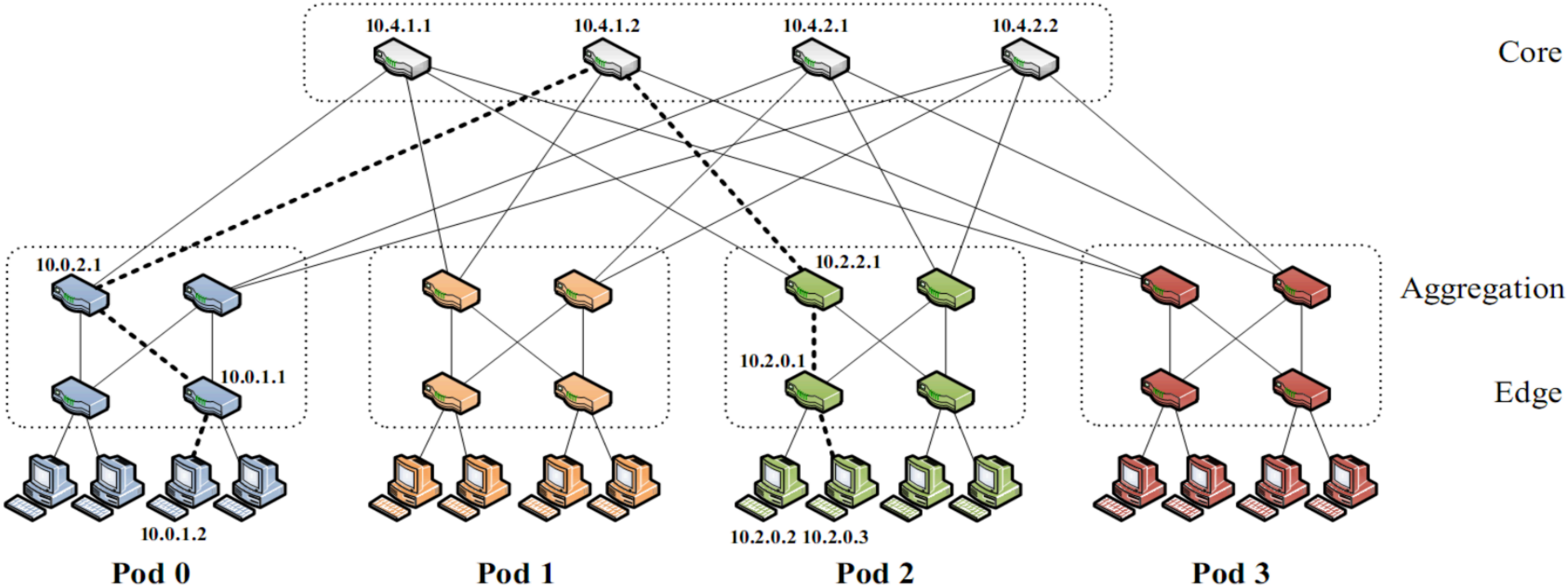
Q: How big is m so that each new call can be established w/o moving current calls?

433/533 Labor day problem: 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



Q: How large a network can k-ary support using k-port switches?

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

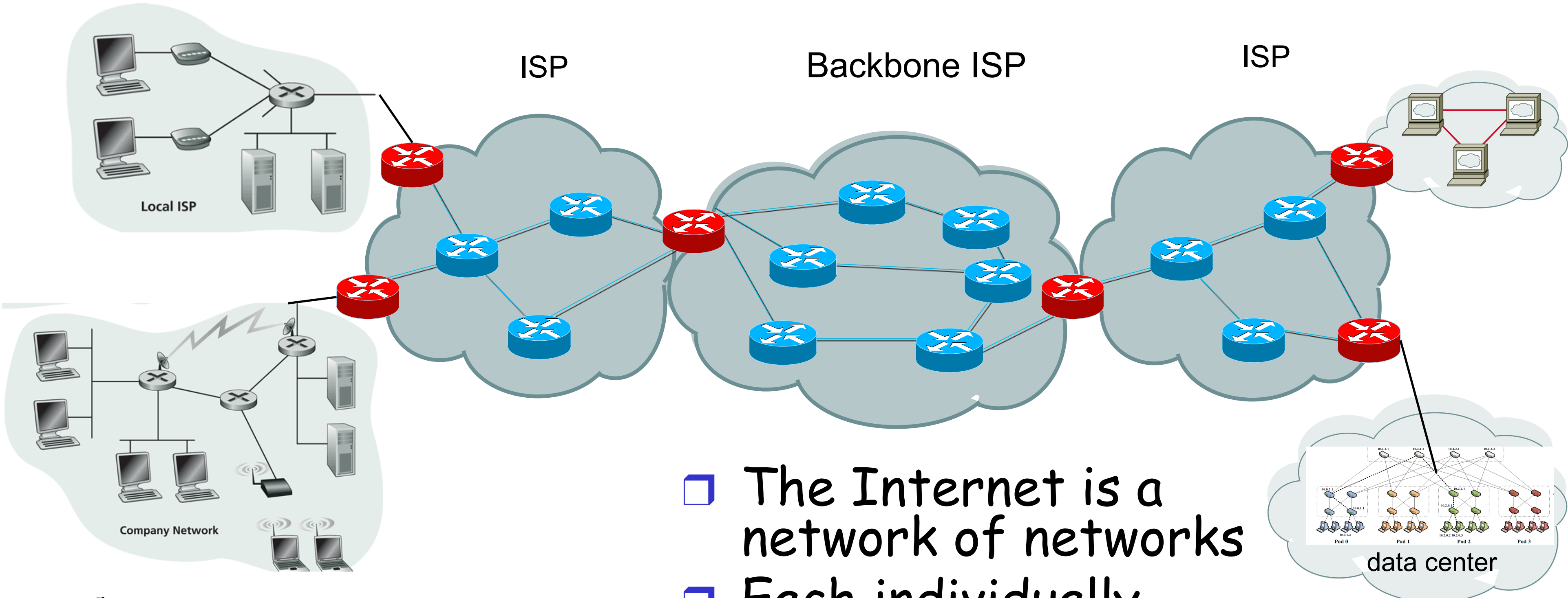
Datacenter Generation	First Deployed	Merchant Silicon	ToR Config	Aggregation Block Config	Spine Block Config	Fabric Speed	Host Speed	Bisection BW
Four-Post CRs	2004	vendor	48x1G	-	-	10G	1G	2T
Firehose 1.0	2005	8x10G 4x10G (ToR)	2x10G up 24x1G down	2x32x10G (B)	32x10G (NB)	10G	1G	10T
Firehose 1.1	2006	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, e.g.,
- Cable, Fiber, DSL, Wireless



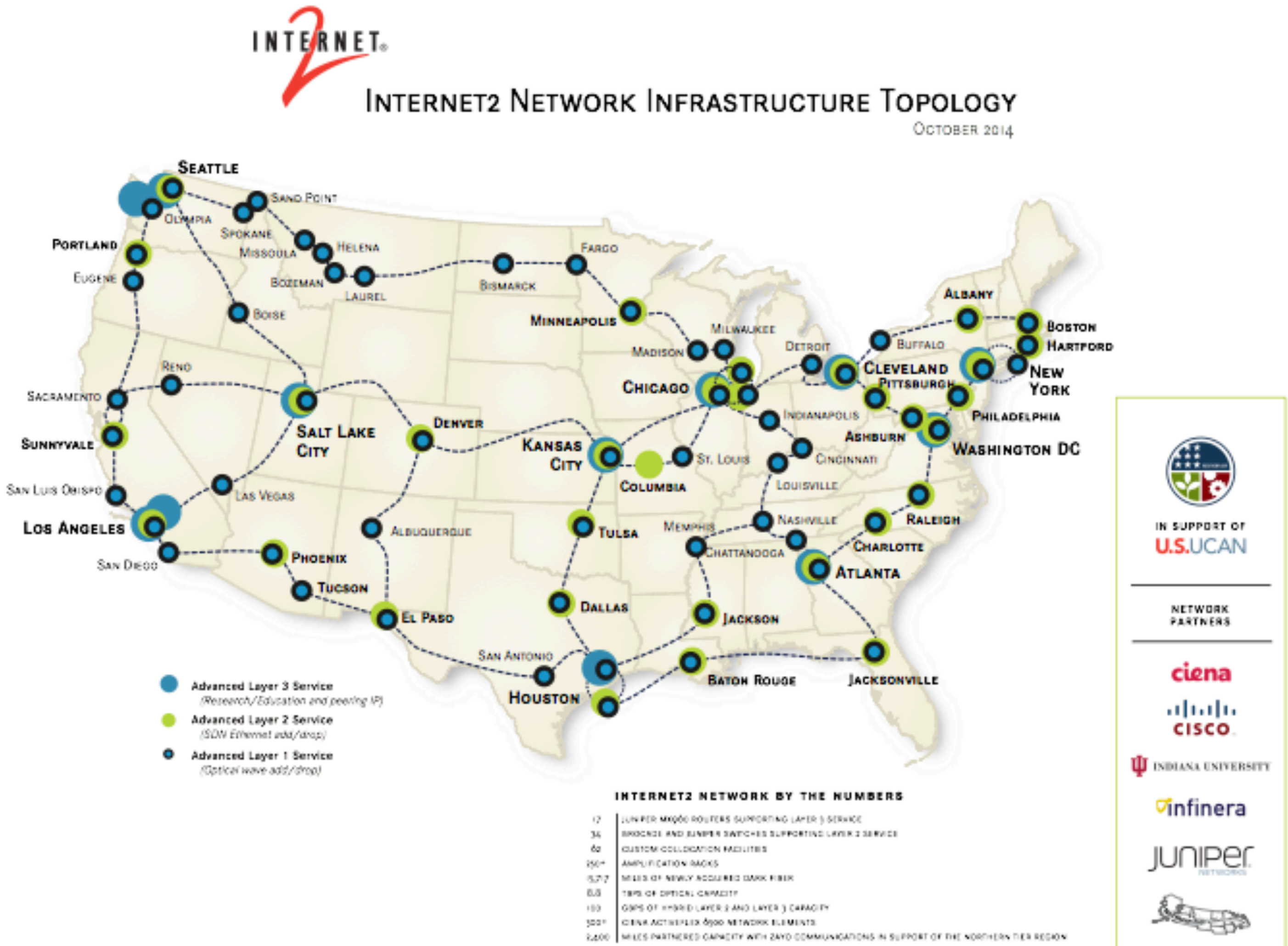
Campus access, e.g.,
- Ethernet, Wireless

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

Yale Internet Connection

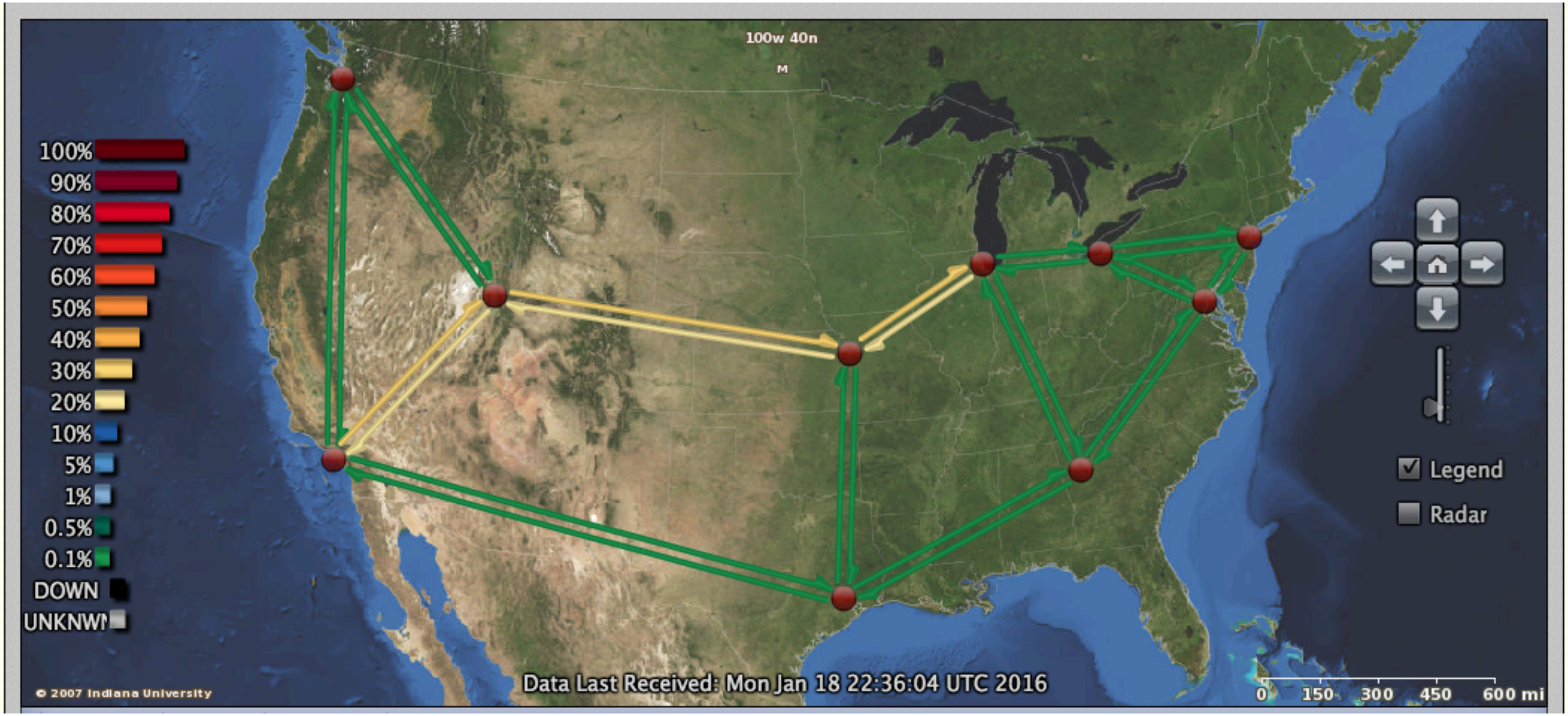
```
cicada:~% traceroute www.tsinghua.edu.cn
 1  college.net.yale.internal (172.28.201.65)  1.440 ms  1.227 ms  1.453 ms
 2  10.1.1.13 (10.1.1.13)  1.359 ms  1.153 ms  1.173 ms
 3  level3-10g-asr.net.yale.internal (10.1.4.40)  2.786 ms  6.110 ms  2.547 ms
 4  cen-10g-yale.net.yale.internal (10.1.3.102)  2.646 ms  3.242 ms  2.576 ms
 5  * * *
 6  enrt064hhh-9k-te0-3-0-5.net.cen.ct.gov (67.218.83.254)  5.169 ms  3.797 ms  6.891 ms
 7  198.71.46.215 (198.71.46.215)  3.615 ms  3.742 ms  3.931 ms
 8  et-10-0-0.1180.rtsw.newy32aoa.net.internet2.edu (198.71.46.214)  6.661 ms  6.532 ms  6.310 ms
 9  et-4-0-0.4079.sdn-sw.phil.net.internet2.edu (162.252.70.103)  8.658 ms  8.714 ms  8.666 ms
10  et-1-1-0.4079.rtsw.wash.net.internet2.edu (162.252.70.119)  11.787 ms  30.111 ms  11.900 ms
11  et-8-1-0.4079.sdn-sw.ashb.net.internet2.edu (162.252.70.62)  12.428 ms  16.654 ms  15.862 ms
12  et-7-1-0.4079.rtsw.chic.net.internet2.edu (162.252.70.61)  28.898 ms  28.999 ms  28.908 ms
13  et-3-1-0.4070.rtsw.kans.net.internet2.edu (198.71.47.207)  40.084 ms  39.958 ms  39.695 ms
14  et-8-0-0.4079.sdn-sw.denv.net.internet2.edu (162.252.70.10)  50.195 ms  50.562 ms  50.258 
ms
15  et-4-1-0.4079.rtsw.salt.net.internet2.edu (162.252.70.9)  59.707 ms  60.261 ms  59.762 ms
16  et-7-0-0.4079.sdn-sw.lasv.net.internet2.edu (162.252.70.30)  67.555 ms  67.539 ms  67.312 
ms
17  et-4-1-0.4079.rtsw.losa.net.internet2.edu (162.252.70.29)  72.419 ms  72.428 ms  72.376 ms
…
```

Internet2



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

Internet2



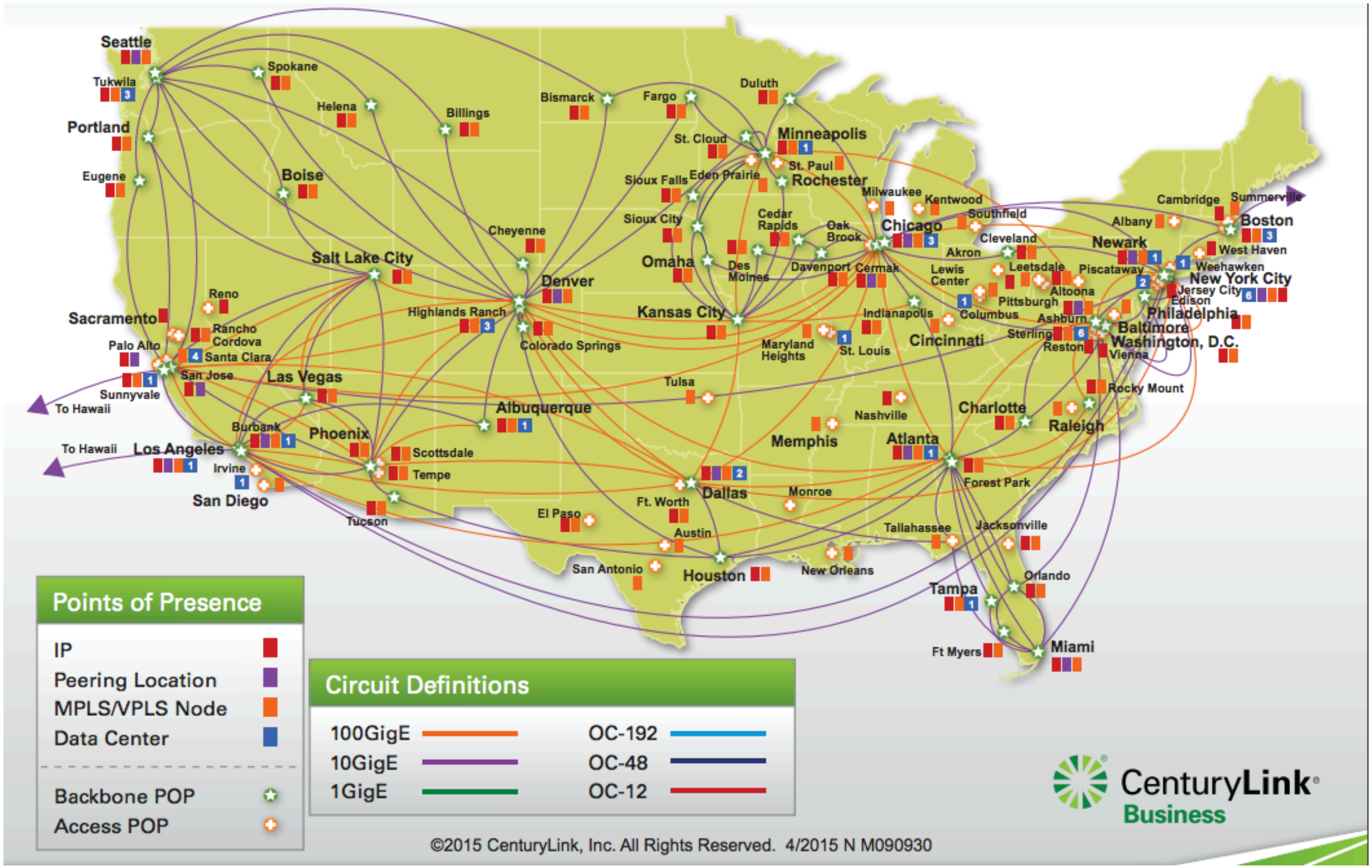
http://atlas.grnoc.iu.edu/atlas.cgi?map_name=Internet2%20IP%20Layer

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/)

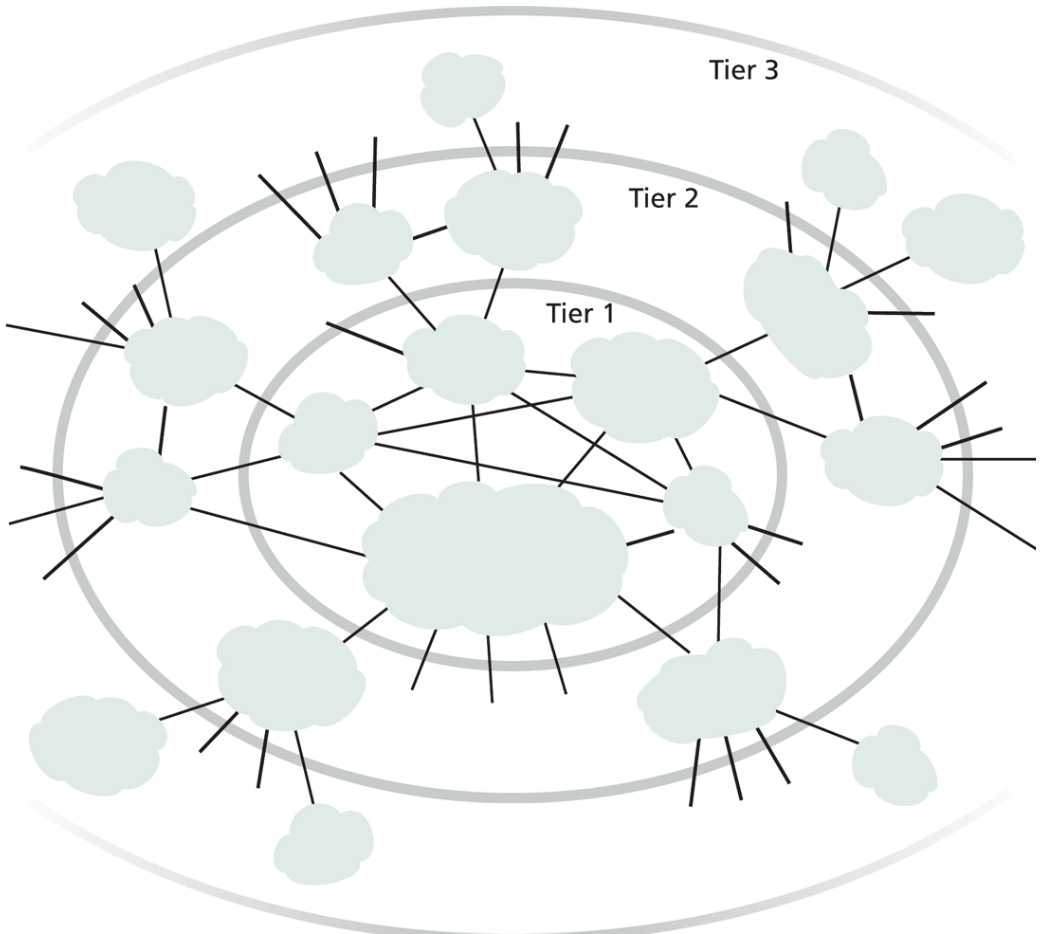
http://www.centurylink.com/business/resource-center/network-maps/

Level3 Network Map

http://www.level3.com/-/media/files/maps/en-network-services-level-3-network-map.pdf

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

- **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

1 Exabyte
1,000 Petabytes or
250 million DVDs

- **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
1,000 Exabytes or
250 billion DVDs

- **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 ‡

1 Yottabyte
1,000 Zettabytes or
250 trillion DVDs

- **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.

RANK	SITE	MONTHLY PEOPLE	DIRECTLY MEASURED
1	google.com	190,409,216	
2	amazon.com	177,870,048	
3	youtube.com	173,836,752	
4	facebook.com	150,061,936	
5	ebay.com	149,668,192	
6	wikipedia.org	148,995,264	
7	twitter.com	134,187,424	
8	yahoo.com	97,040,432	
9	reddit.com	80,005,704	
10	yelp.com	75,762,200	✓
11	buzzfeed.com	59,626,244	✓
12	linkedin.com	53,046,072	
13	adobe.com	52,079,480	
14	walmart.com	47,661,268	
15	bing.com	47,000,024	
16	live.com	45,796,316	
17	netflix.com	45,682,088	

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

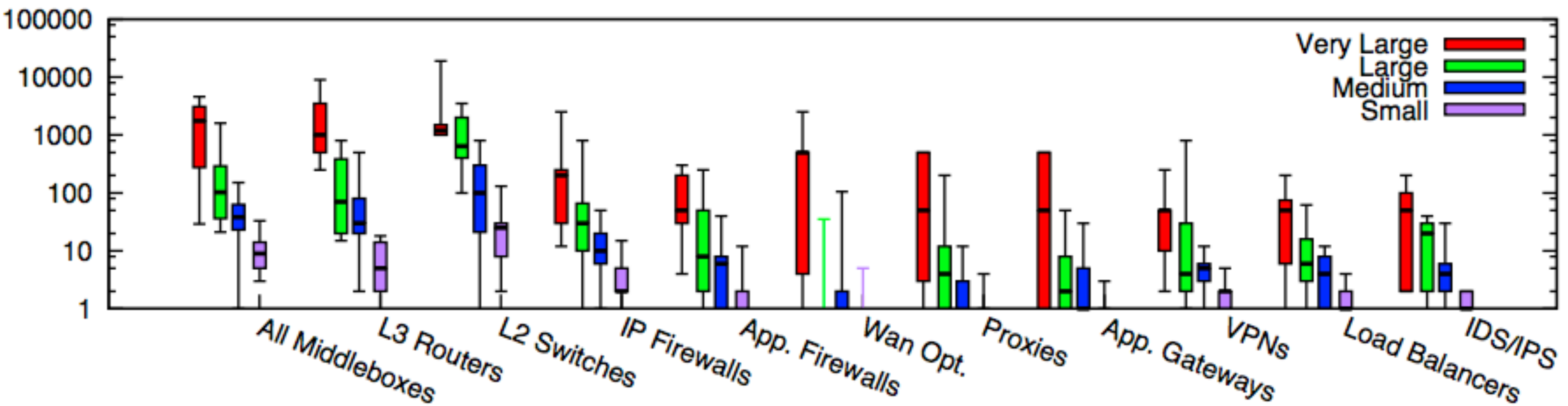
General Complexity

- 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.

Core: Simple Forwarding to Network Functions

- Modern networks contain diverse types of equipment beyond simple routing/forwarding

Enterprise networks



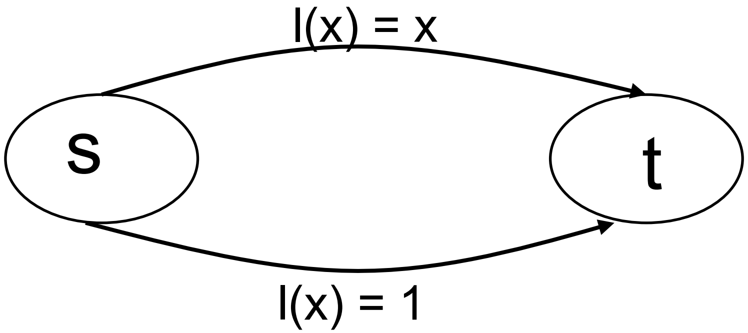
Small: <=1k hosts; Medium: 1k-10k; Large: 10k-100k; Very Large: >=100k

Source: [Sherry, et. al SIGCOMM'12]

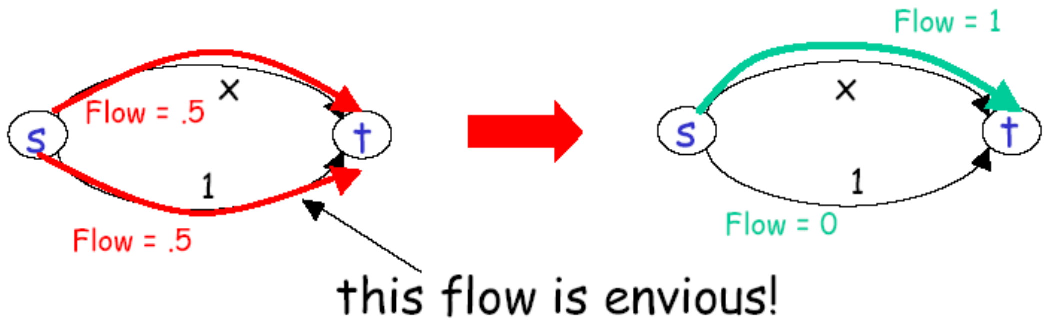
Centralized vs Decentralized (Price of Anarchy)

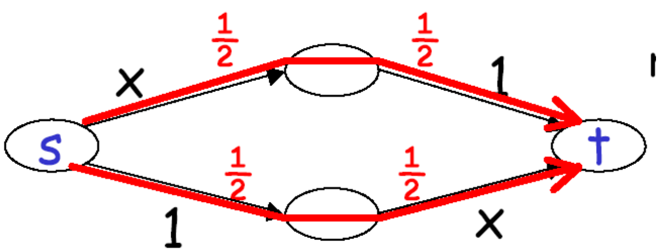
- Autonomous ("Selfish") App: Assume each link has a latency function $l_e(x)$: latency of link e when x amount of traffic goes through e:

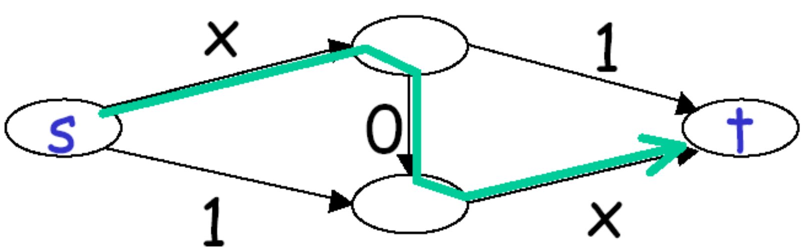
total traffic



Autonomous ("Selfish") App

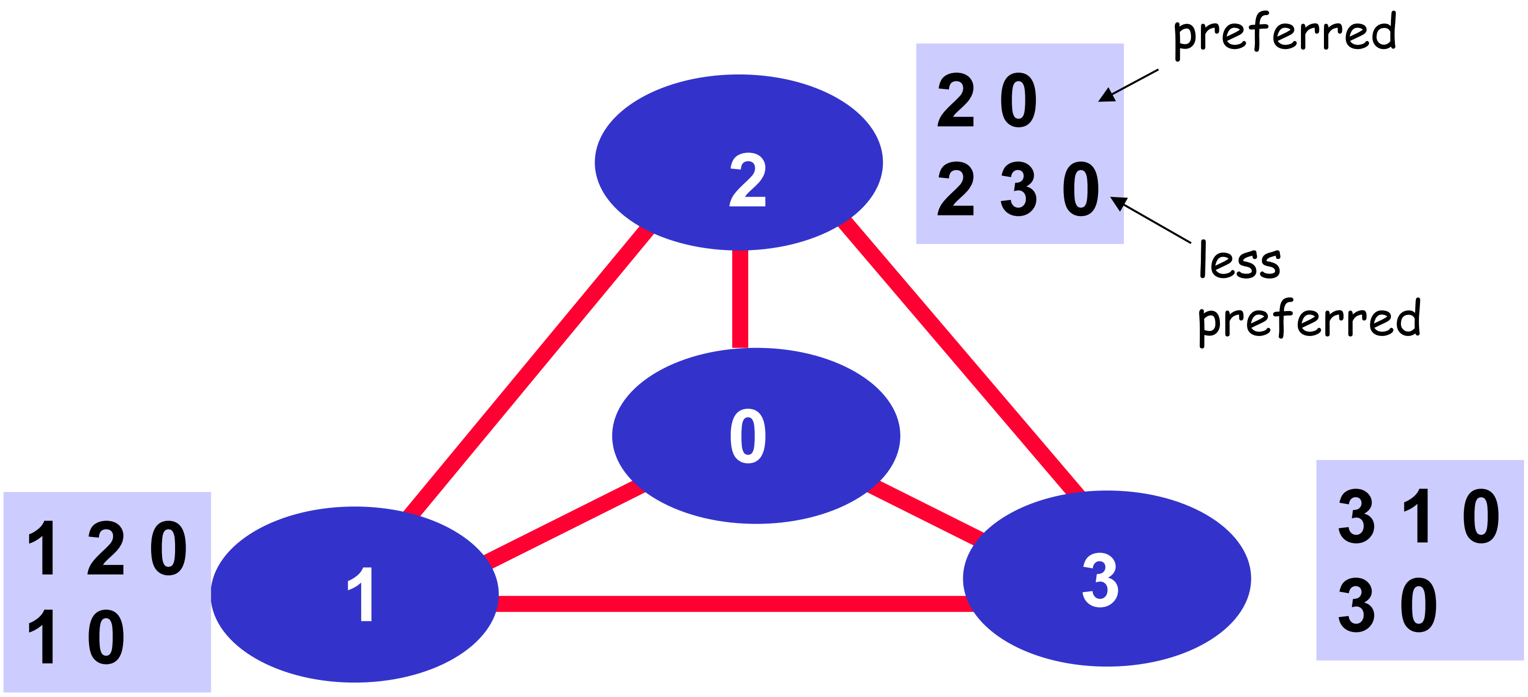




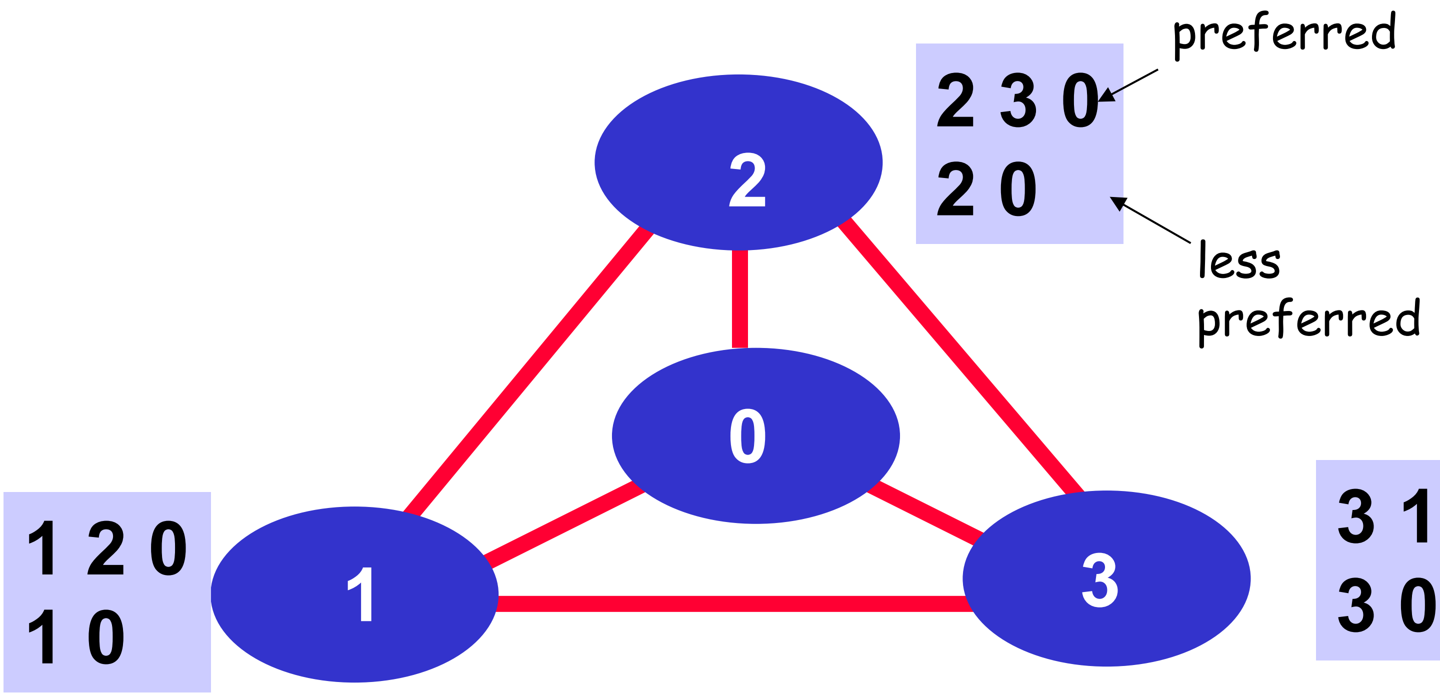


Braess's paradox

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, P2P, Blockchain, Content distribution

- Transport
  - transport services
  - reliability; distributed resource allocation; primal-dual
  - transport protocols: TCP/UDP

What Will We Cover?

- Network and link layers
  - distributed, asynchronous, autonomous routing algorithms; scalable router design; IP/IPv6; mobile IP; cellular networks
  - multiple access; queueing analysis; capacity analysis
  - 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

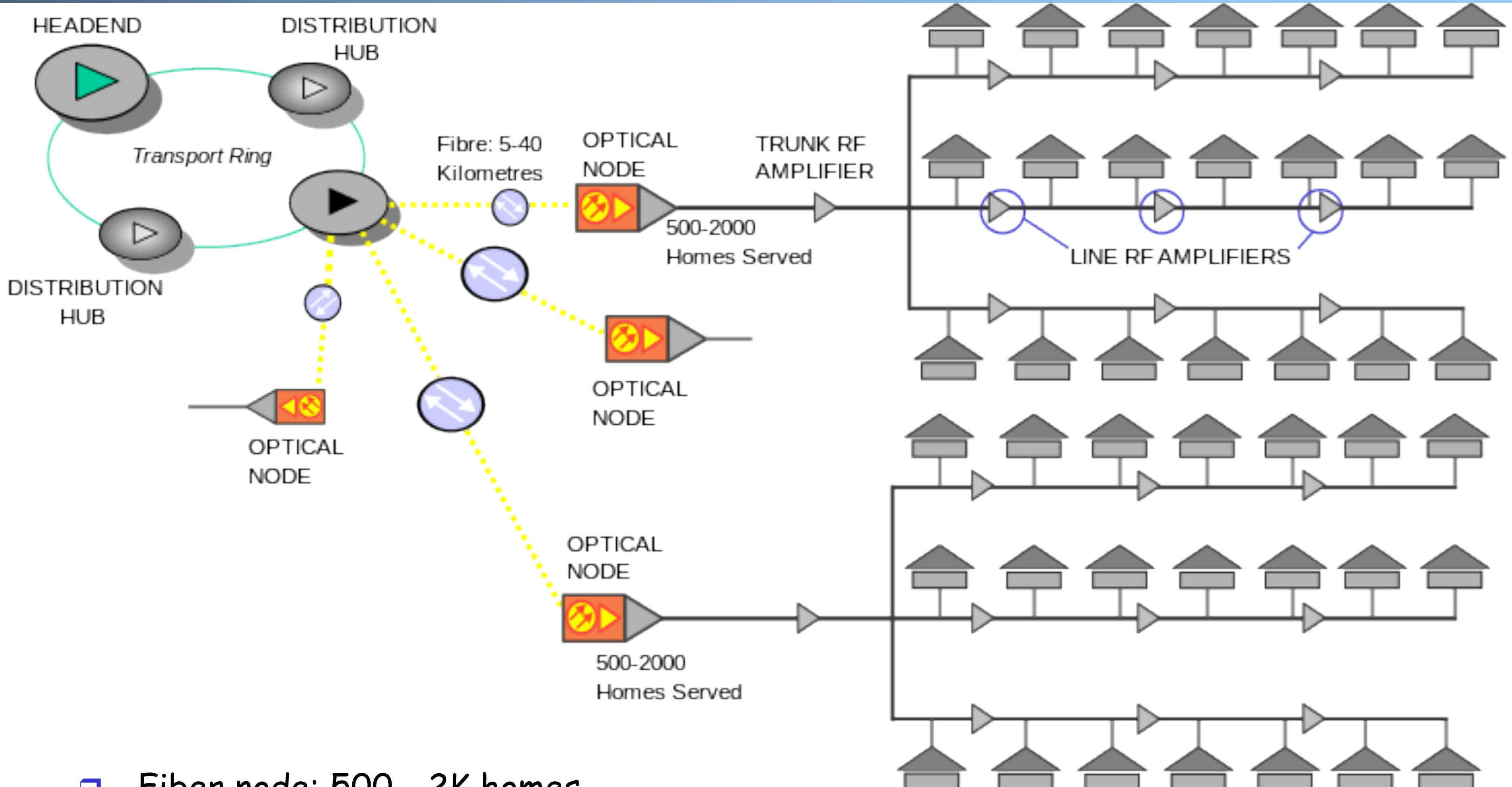
Preview

- 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

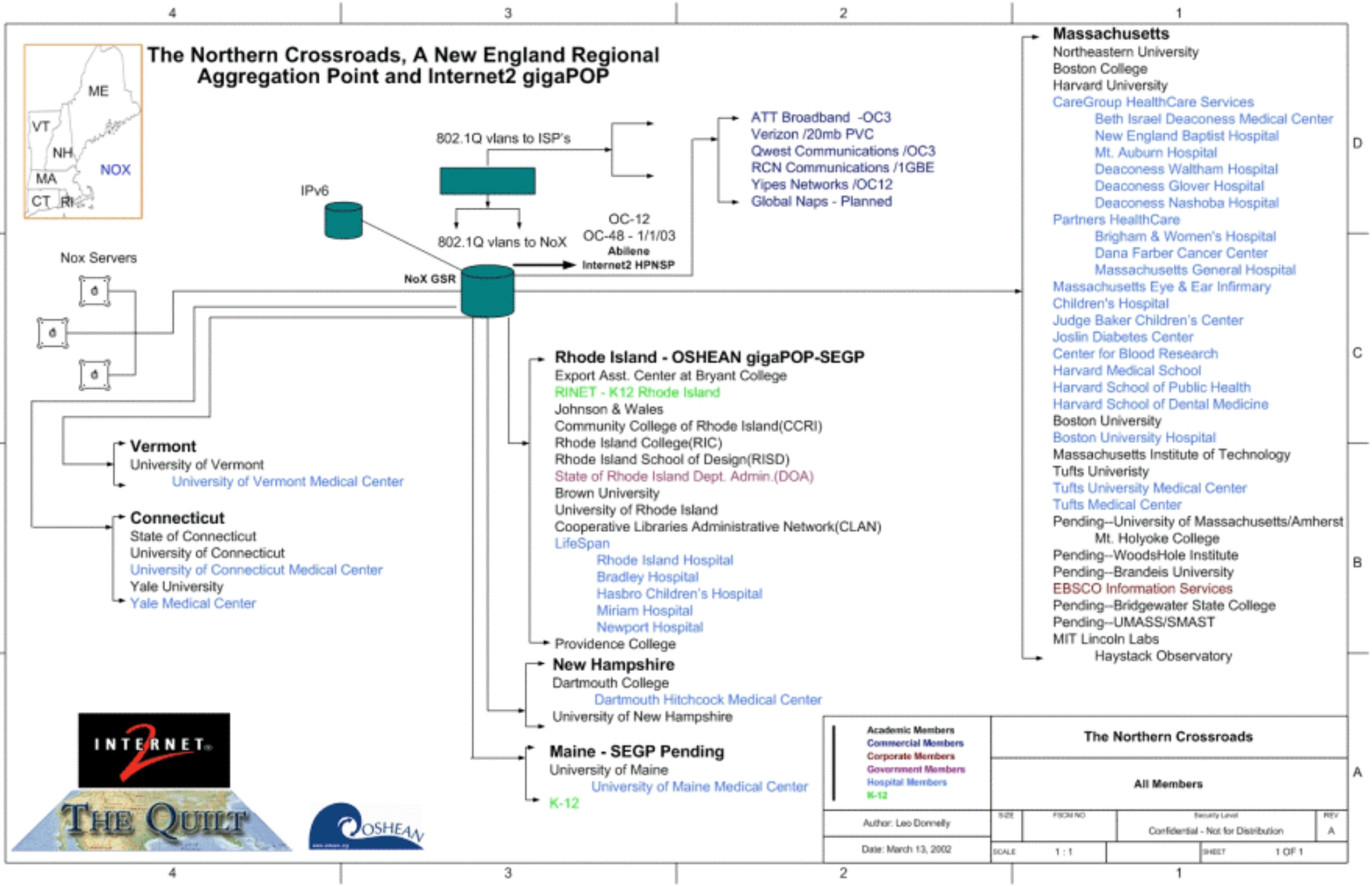
Access: Cable

Also called Hybrid Fiber-coaxial Cable (HFC)

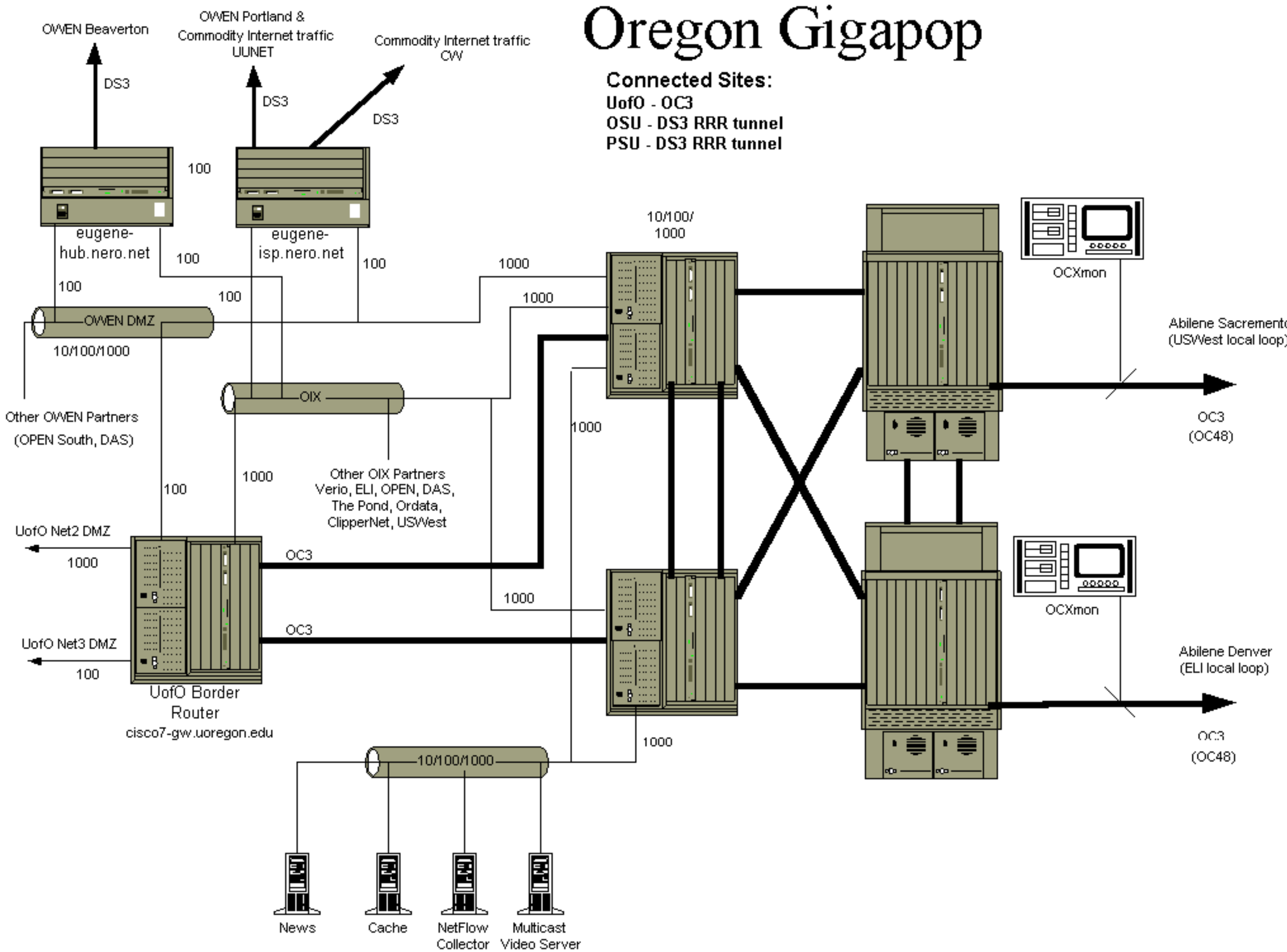


- Fiber node: 500 - 2K homes
- Distribution hub: 20K - 40 K homes
- Regional headend: 200 K - 400 K homes

Northern CrossRoads (NoX) Aggregation Point (AP)



http://www.uis.harvard.edu/emerging_technologies/Northern_Crossroads_Map.gif



http://www.oregon-gigapop.net/images/OregonGigapop2.gif