A Taxonomy of Communication Networks

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https://sngroup.org.cn/courses/cnns-xmuf25/index.shtml

09/04/2025

This deck of slides are heavily based on CPSC 433/533 at Yale University, by courtesy of Dr. Y. Richard Yang.

Outline

- *Admin. and recap*
- A brief introduction to the Internet:
  - present
- Challenges of Internet networks and apps
- A taxonomy of communication networks

Admin.

- If you haven't filled out the survey, please go to the class website to do so

Recap

- 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 or receipt of a message or other events.
- Key Internet milestones and their implications:
  - ARPANET is sponsored by ARPA →

    design should survive failures
  - The initial IMPs (routers) were made by a small company → keep the network simple
  - Many networks →

    internetworking: need a network to connect networks
  - Commercialization →

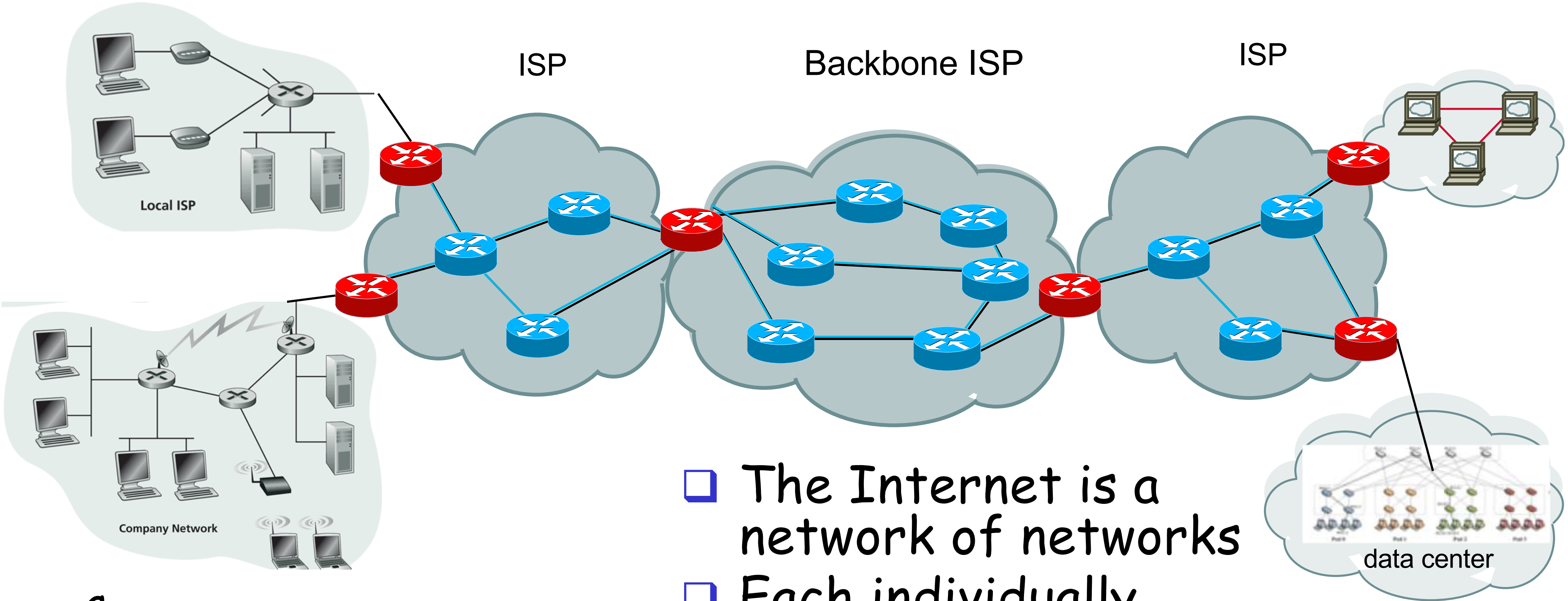
    architecture supporting decentralized, autonomous systems

Outline

- Admin. and recaps
- *A brief introduction to the Internet*
  - past
  - *present*

Internet Physical Infrastructure

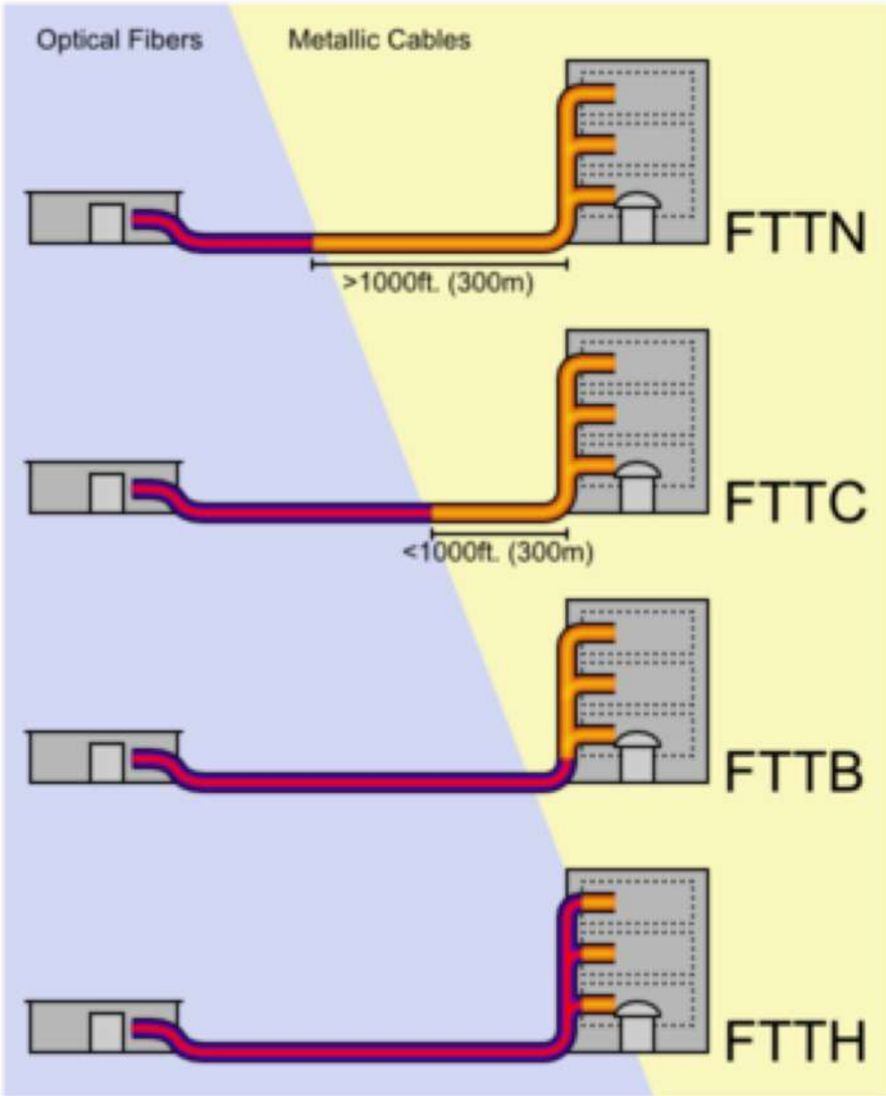
Residential access
- Cable, Fiber, DSL, Wireless



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

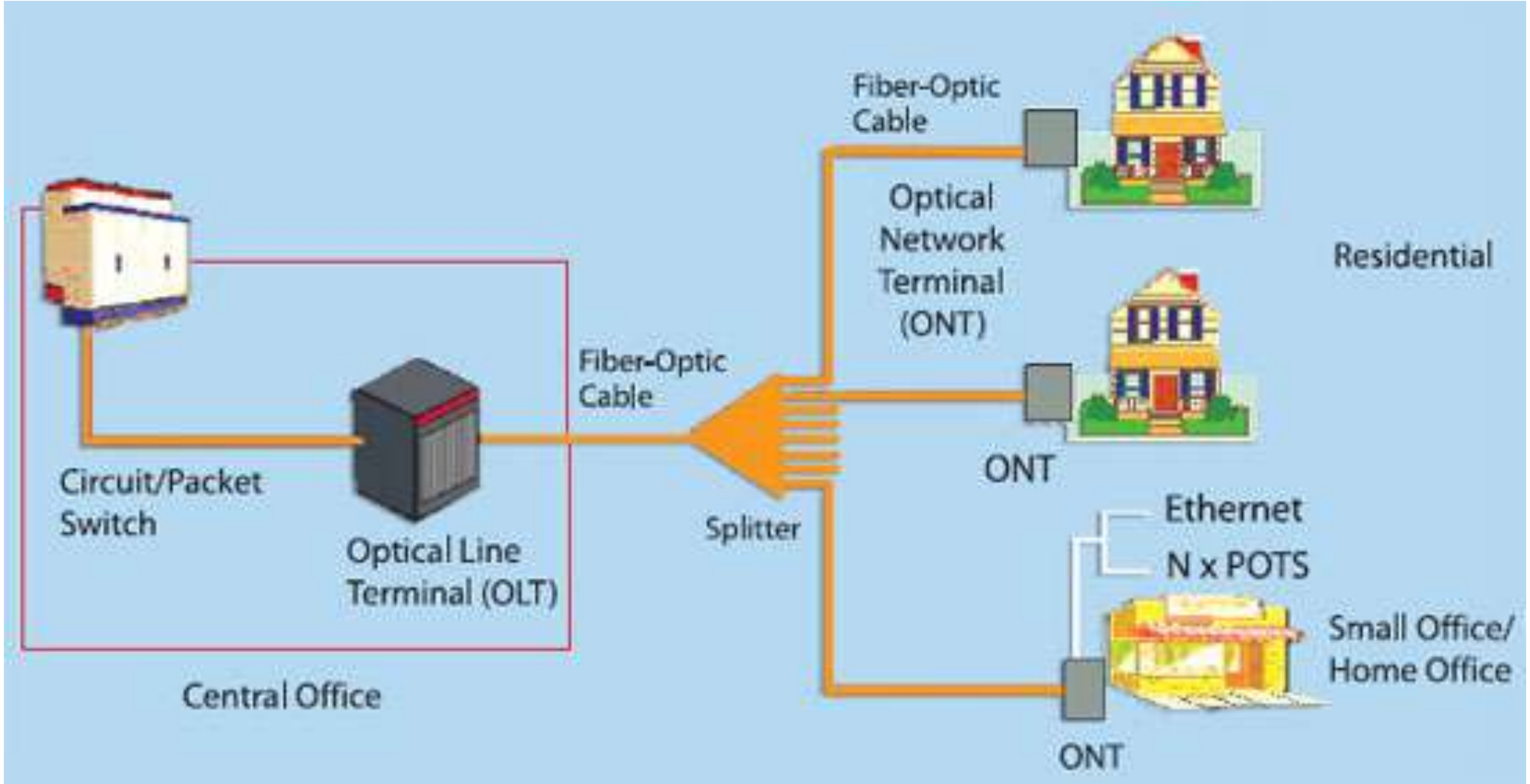


http://en.wikipedia.org/wiki/Fiber_to_the_x

Access: Fiber to the Premises (FTTP)

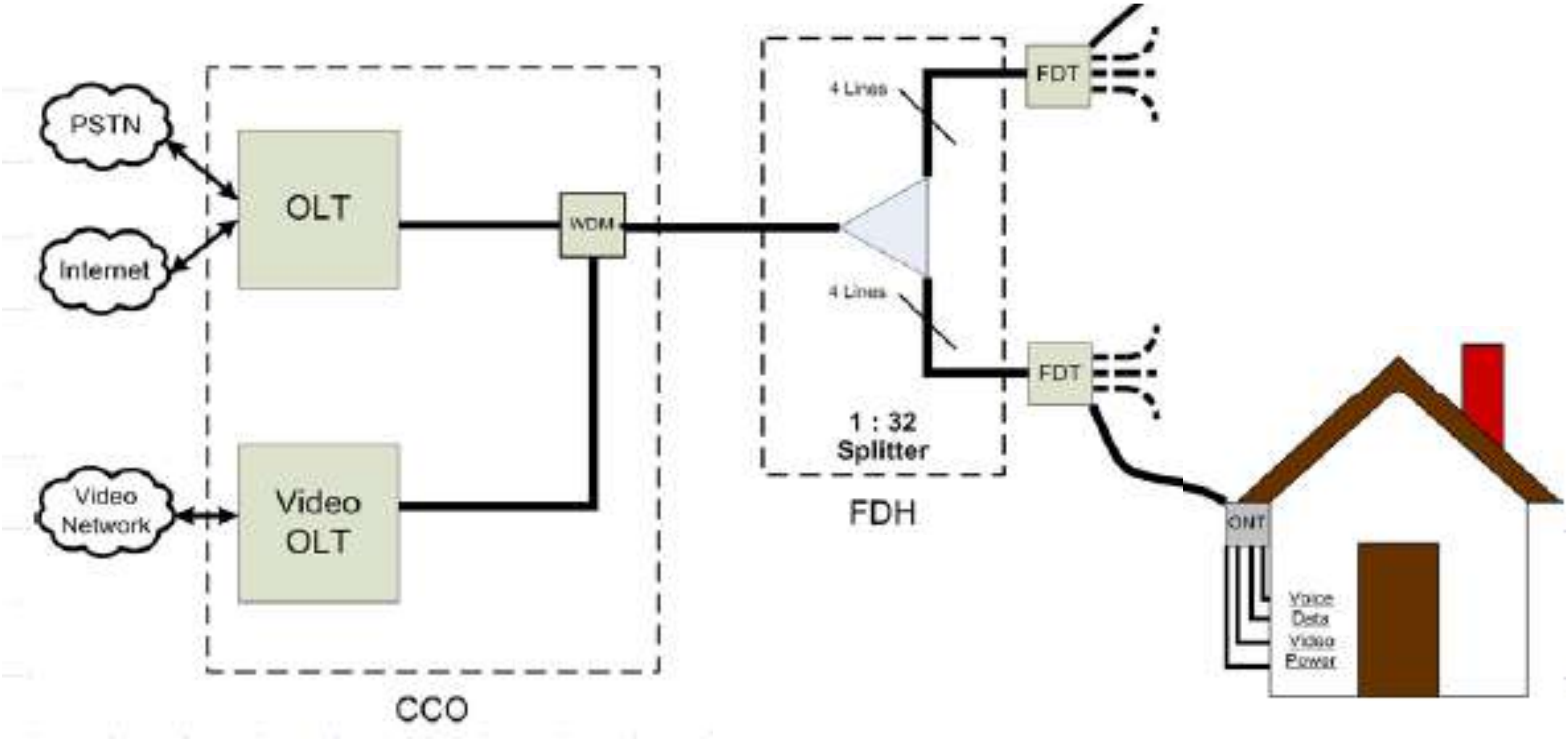
- Deployed by Verizon, AT&T, Google,
- One of the largest comm. construction projects

FTTP Architecture

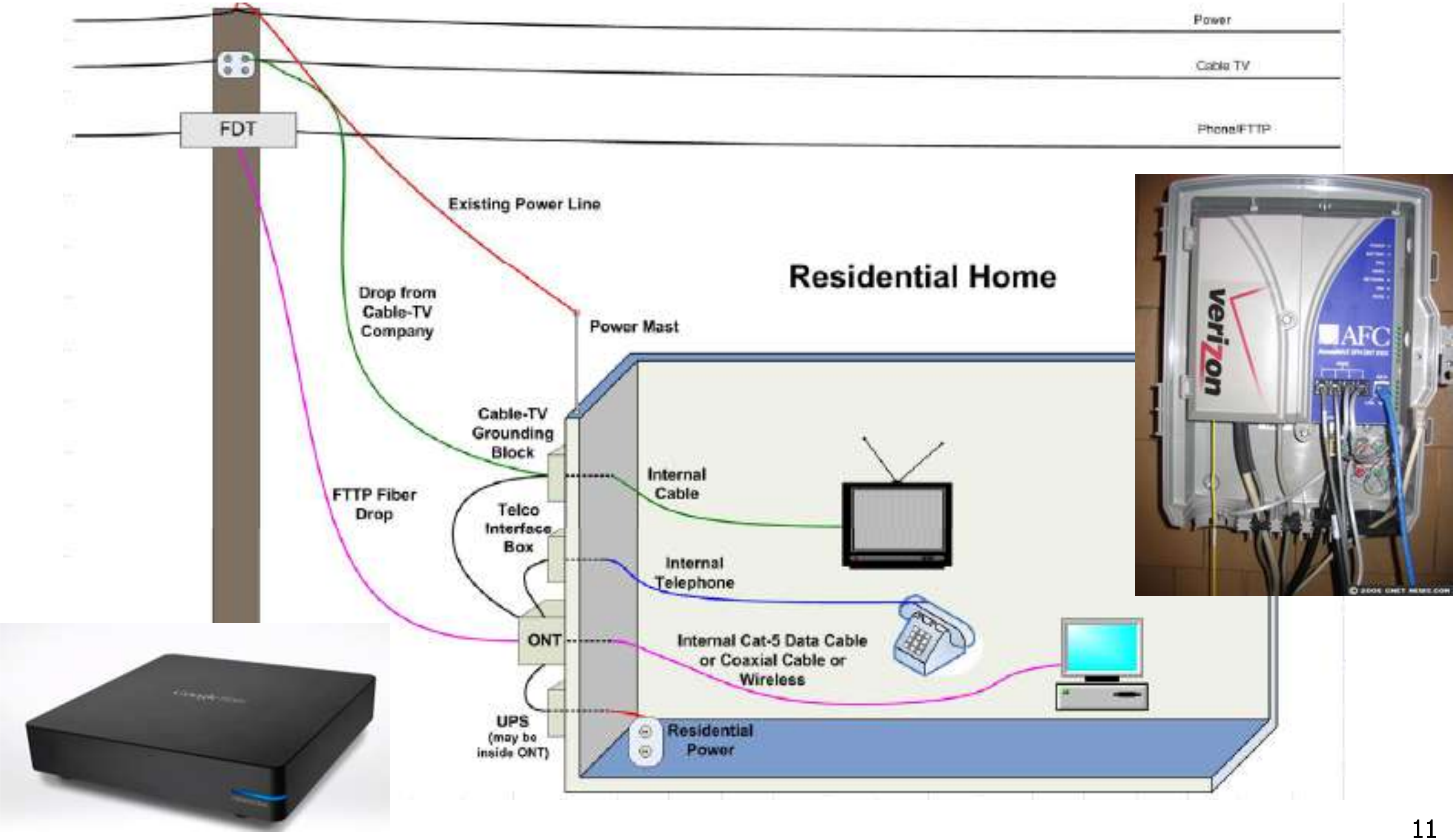


FTTP Architecture

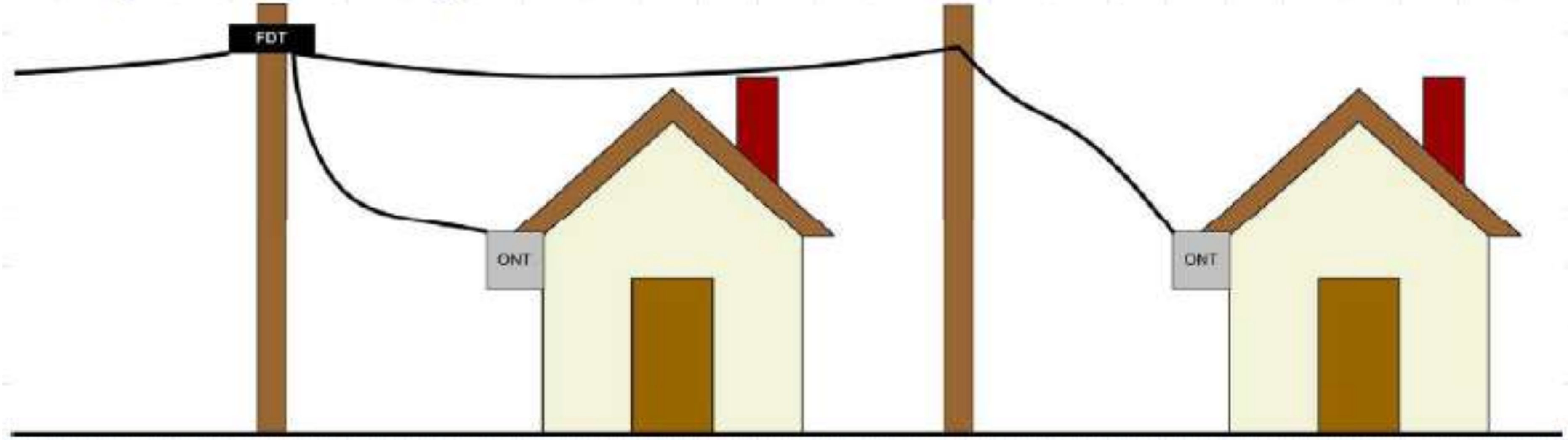
- Optical Network Terminal (ONT) box outside dwelling or business
- Fiber Distribution Terminal (FDT) in poles or pedestals
- Fiber Distribution Hub (FDH) at street cabinet
- Optical Line Terminal (OLT) at central office



FTTP Architecture: To Home



FTTP Architecture:
Fiber Distribution Terminal (FDT)



FTTP Architecture: Central to Fiber Distribution Hub (FDH)

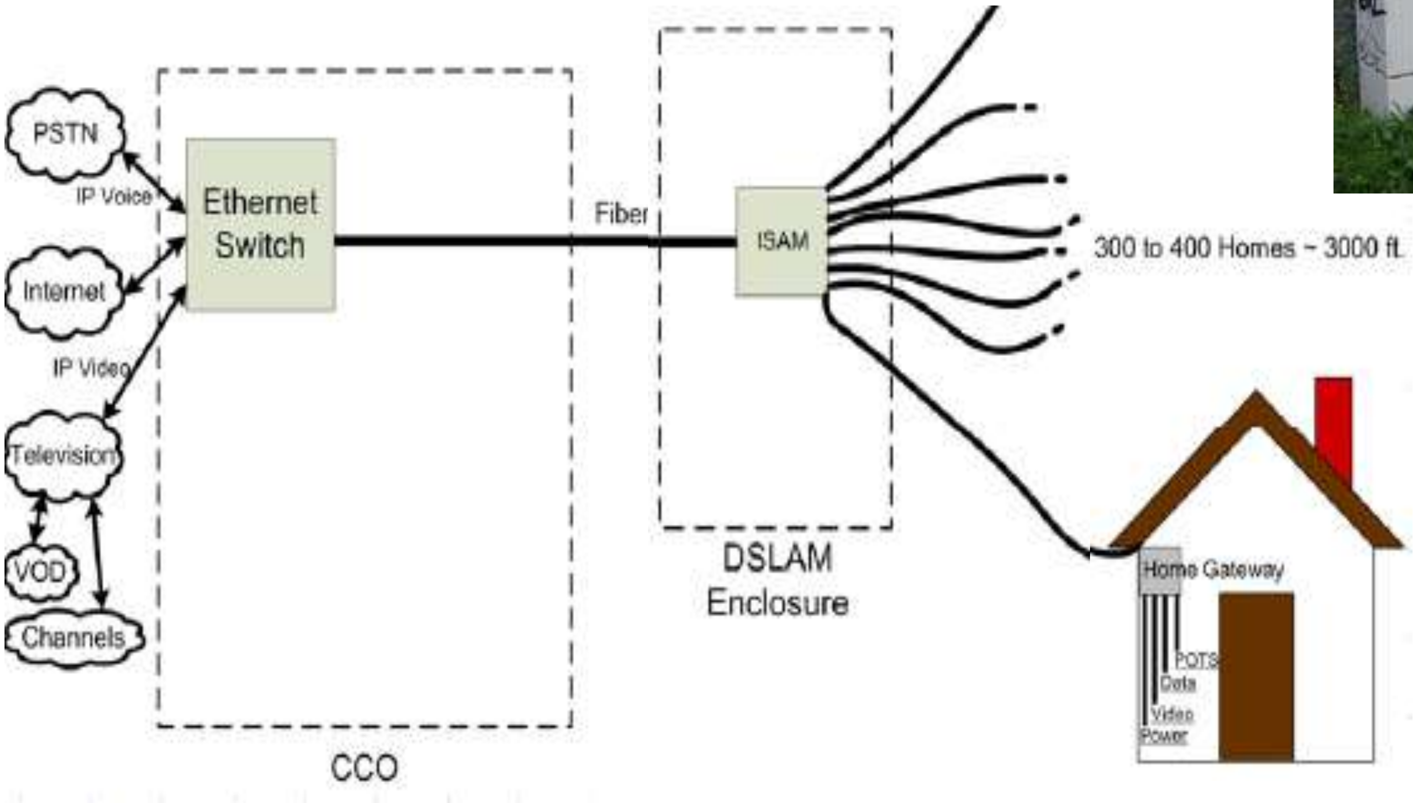
- Backbone fiber ring on primary arterial streets (brown)
- Local distribution fiber plant (red) meets backbone at cabinet

FDH

Access: DSL

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

DSLAM



Access: Wireless

https://x.company/loon/

Access: Wireless

Starlink explained: Everything you should know about Elon Musk's satellite internet venture

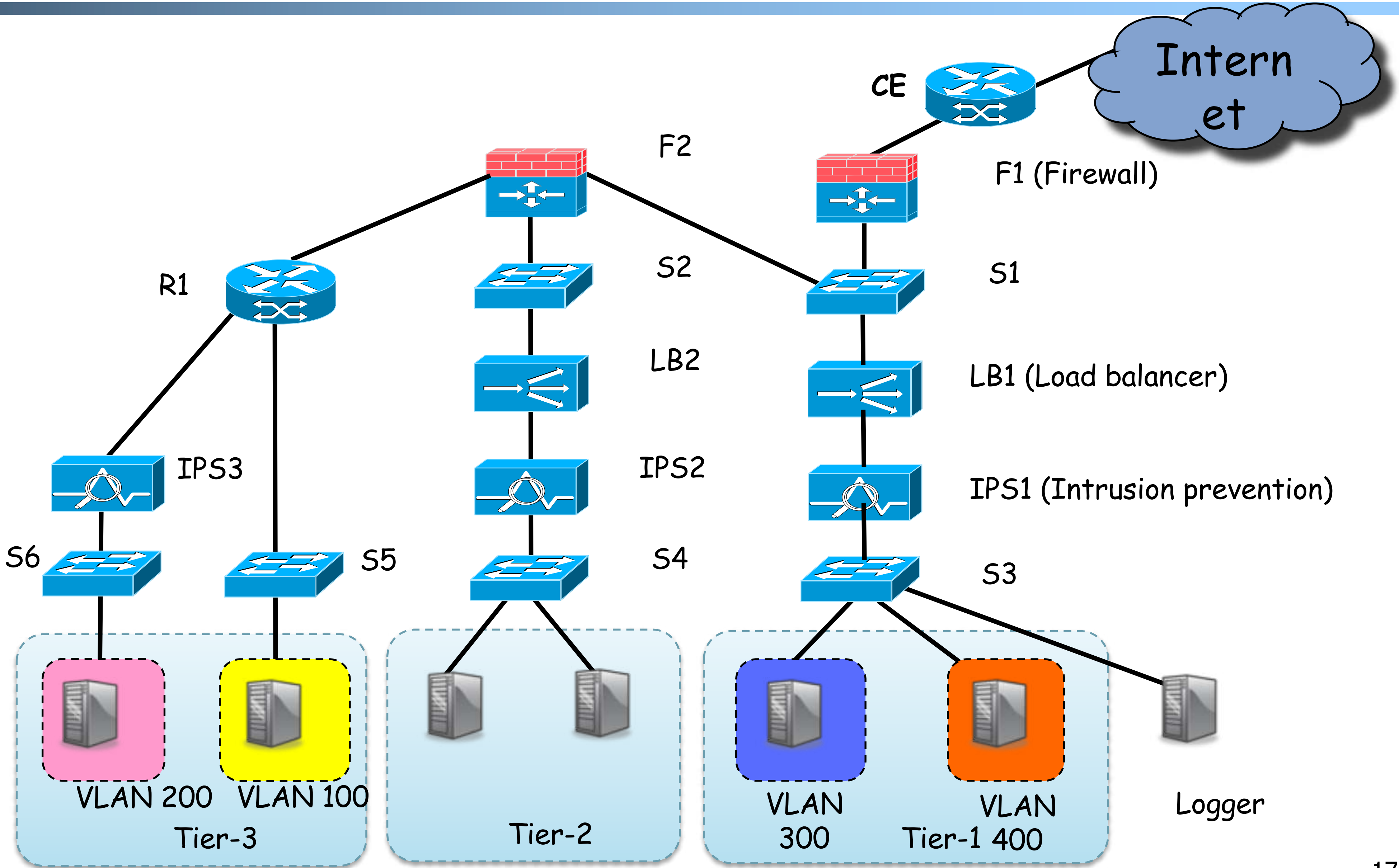
The billionaire SpaceX CEO is launching satellites into orbit and promising to deliver high-speed broadband internet to as many users as possible.

Ry Crist Aug. 24, 2021 5:15 p.m. PT

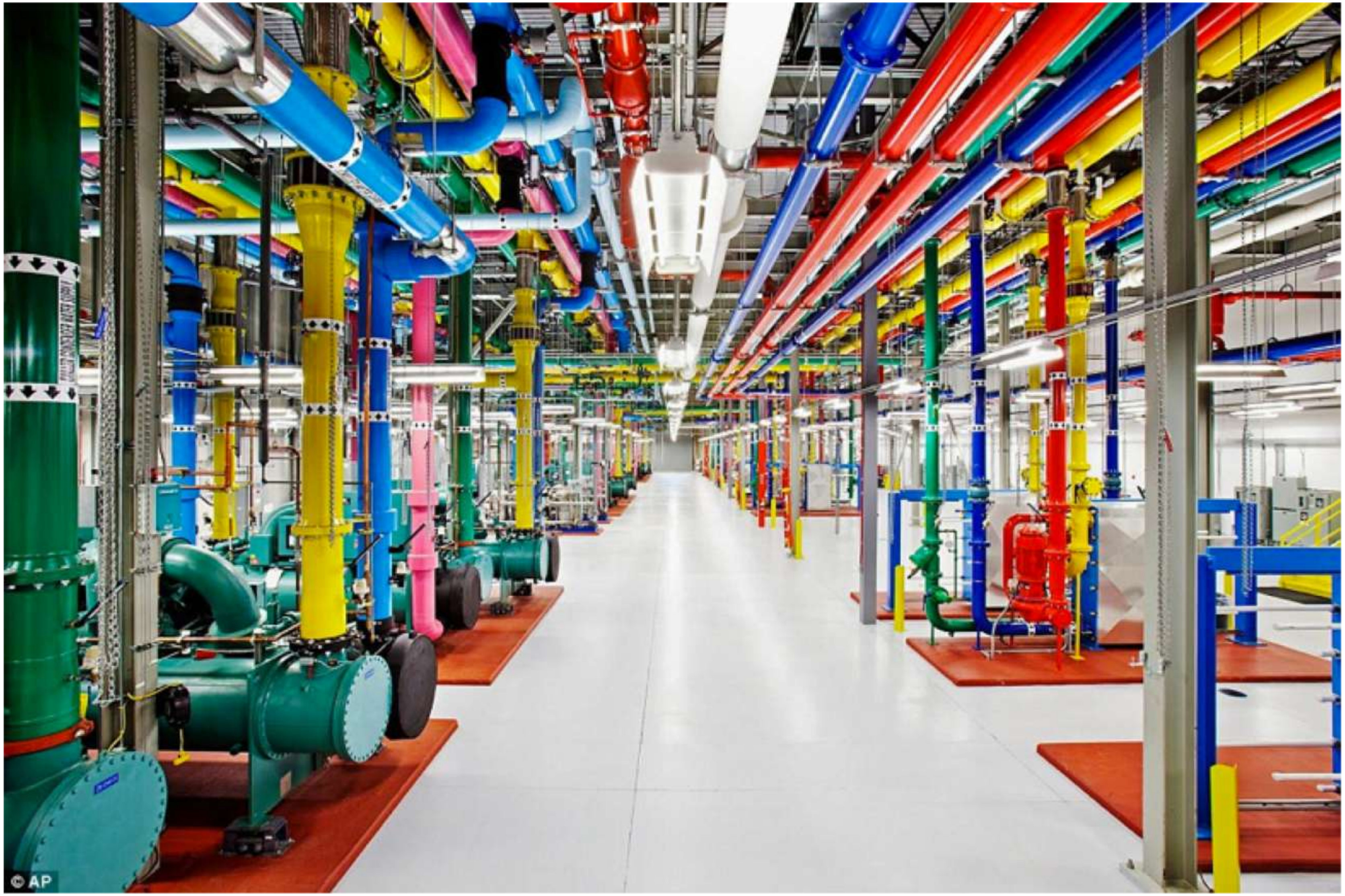
▶ LISTEN - 13:07

https://www.cnet.com/home/internet/starlink-satellite-internet-explained/

Campus Network

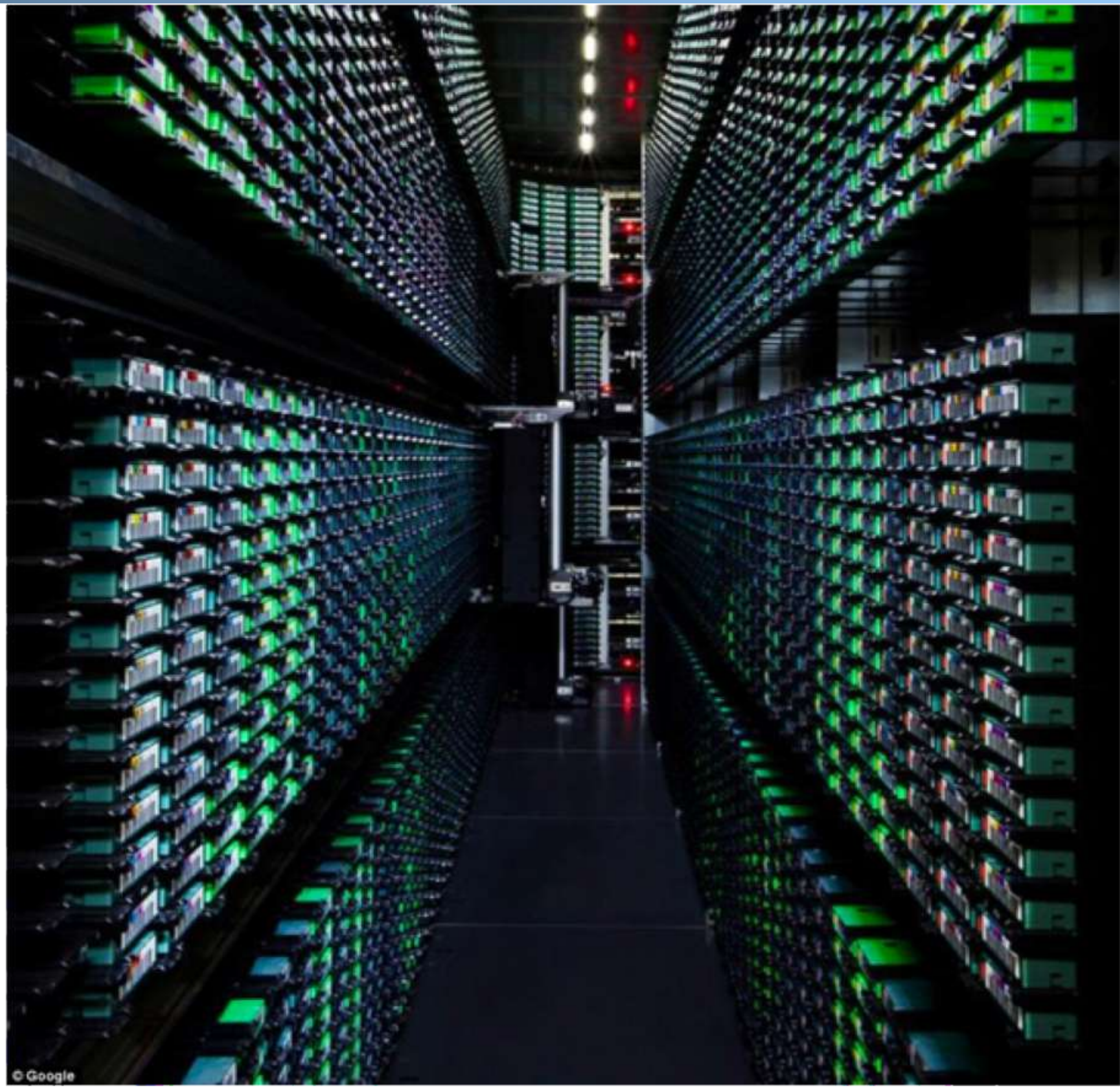


Data Center Networks



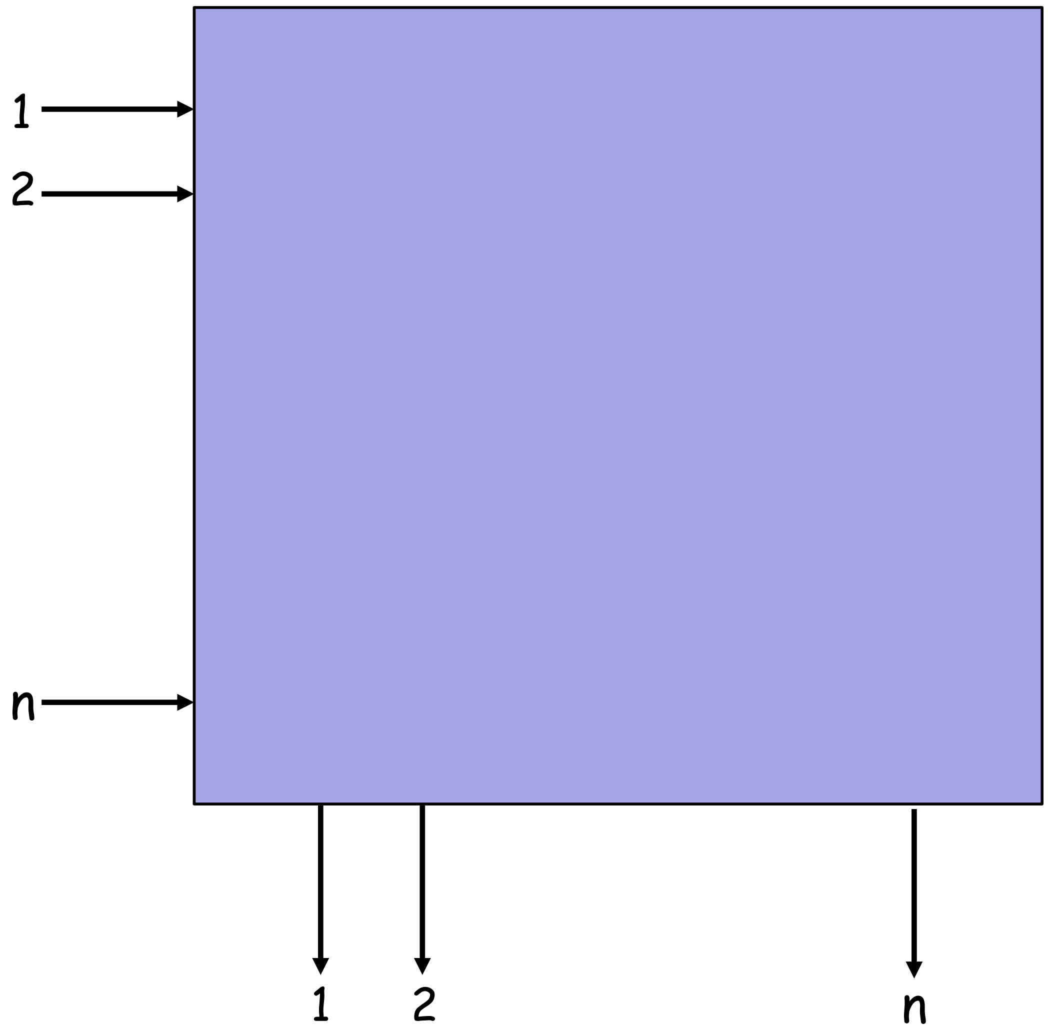
http://www.dailymail.co.uk/sciencetech/article-3369491/Google-s-plan-world-Search-engine-build-half-billion-dollar-data-center-US.html

Data Center Networks

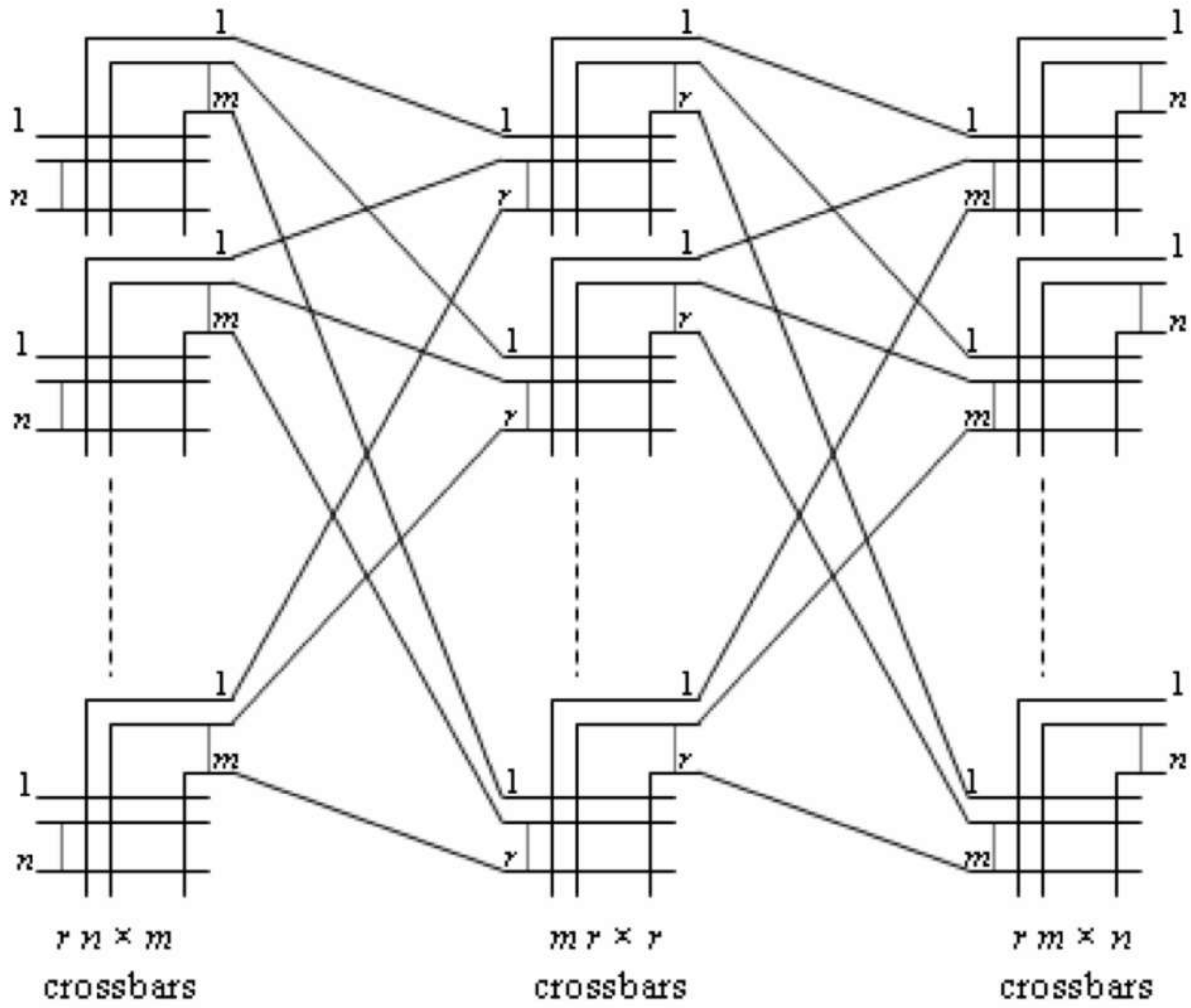


http://www.dailymail.co.uk/sciencetech/article-3369491/Google-s-plan-world-Search-engine-build-half-billion-dollar-data-center-US.html

Foundation of Data Center Networks



Foundation of Data Center Networks: Clos Networks



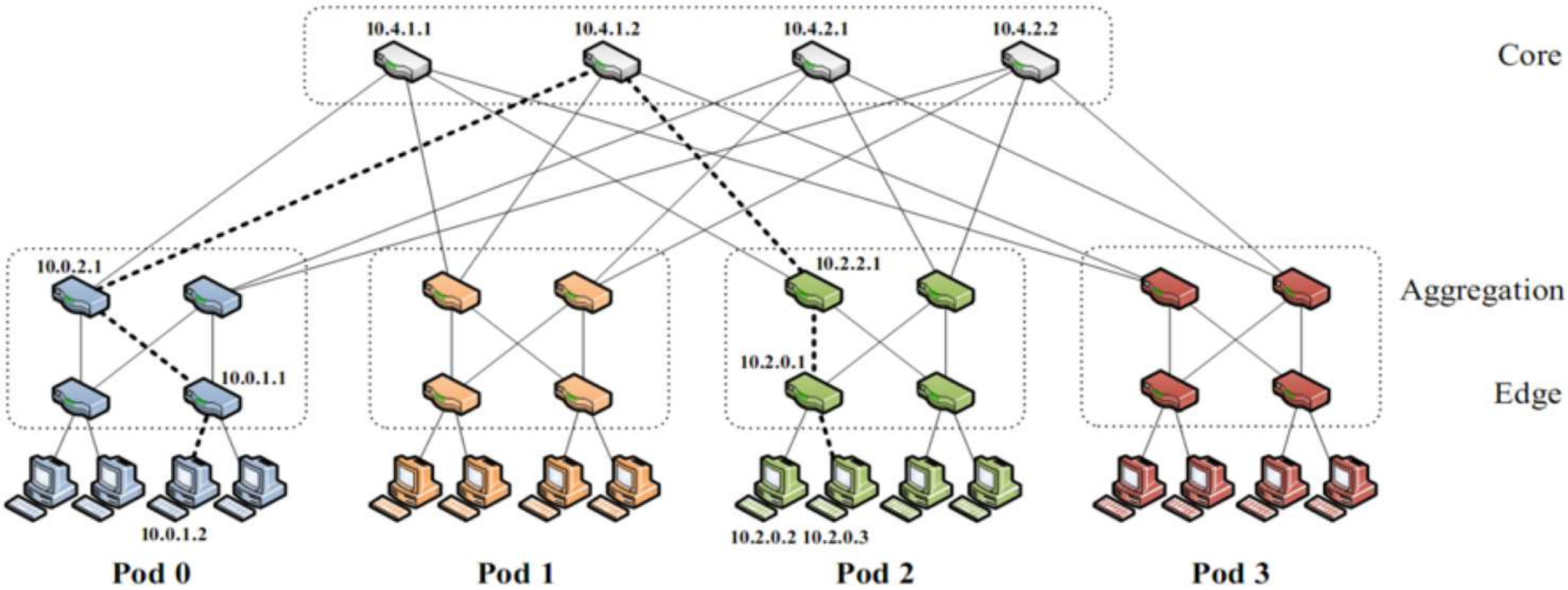
Q: How big is m so that each new call can be established w/o moving current calls?

Challenge to the class:
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

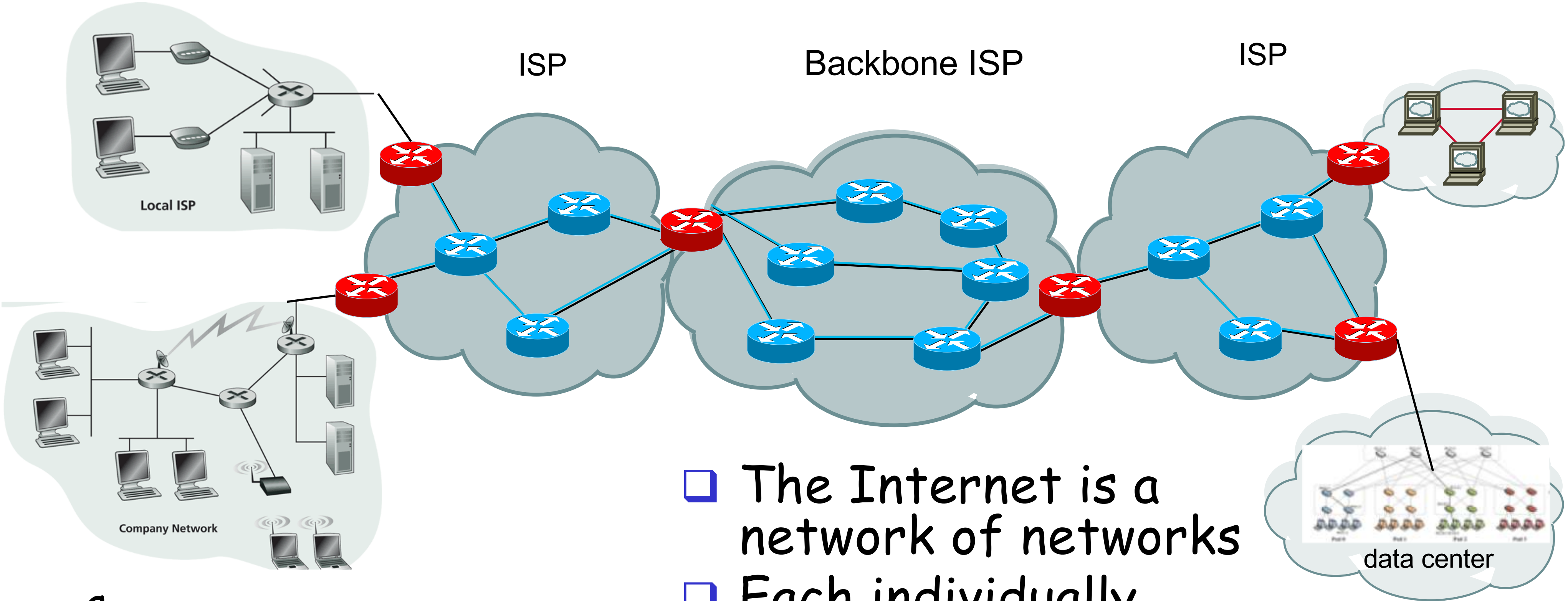
Datacenter Generation	First Deployed	Merchant Silicon	ToR Config	Aggregation Block Config	Spine Block Config	Fabric Speed	Host Speed	Bisection BW
Four-Post CRs	2004	vendor	48x1G	-	-	10G	1G	2T
Firehose 1.0	2005	8x10G 4x10G (ToR)	2x10G up 24x1G down	2x32x10G (B)	32x10G (NB)	10G	1G	10T
Firehose 1.1	2006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

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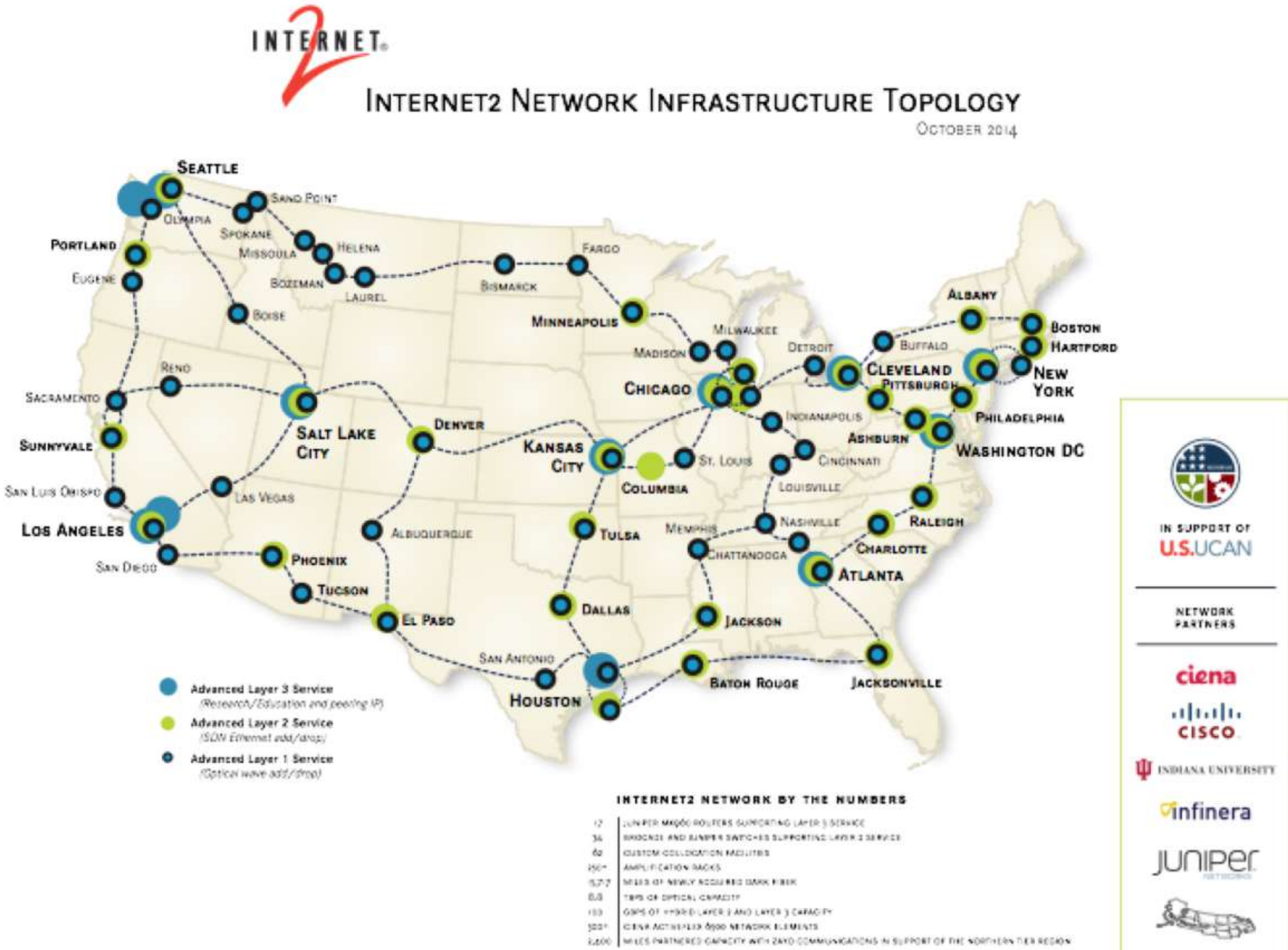
Yale Internet Connection

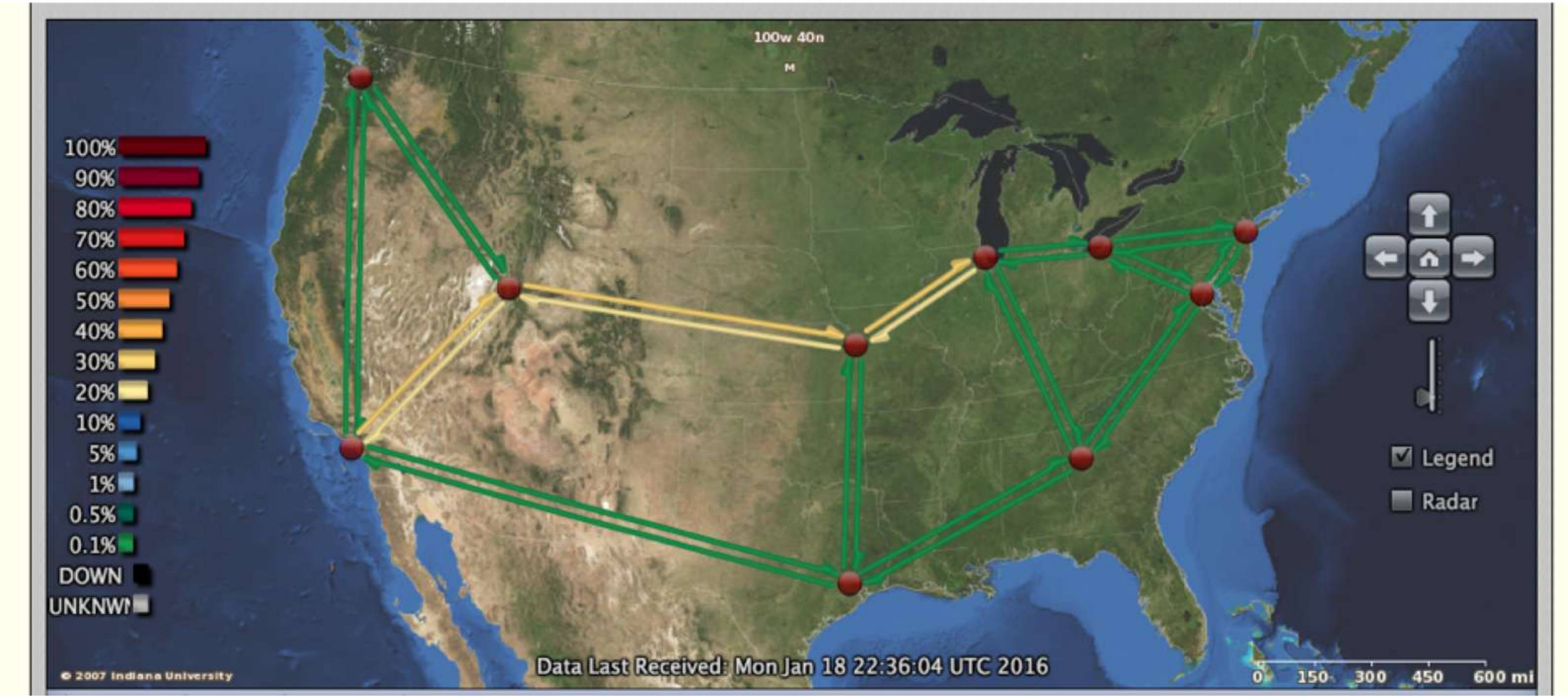
traceroute www.tsinghua.edu.cn
1 college.net.yale.internal (172.28.201.65) 1.440 ms 1.227 ms 1.453 ms
2 10.1.1.13 (10.1.1.13) 1.359 ms 1.153 ms 1.173 ms
3 level3-10g-asr.net.yale.internal (10.1.4.40) 2.786 ms 6.110 ms 2.547 ms
4 cen-10g-yale.net.yale.internal (10.1.3.102) 2.646 ms 3.242 ms 2.576 ms
5 * * *
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



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

Internet2



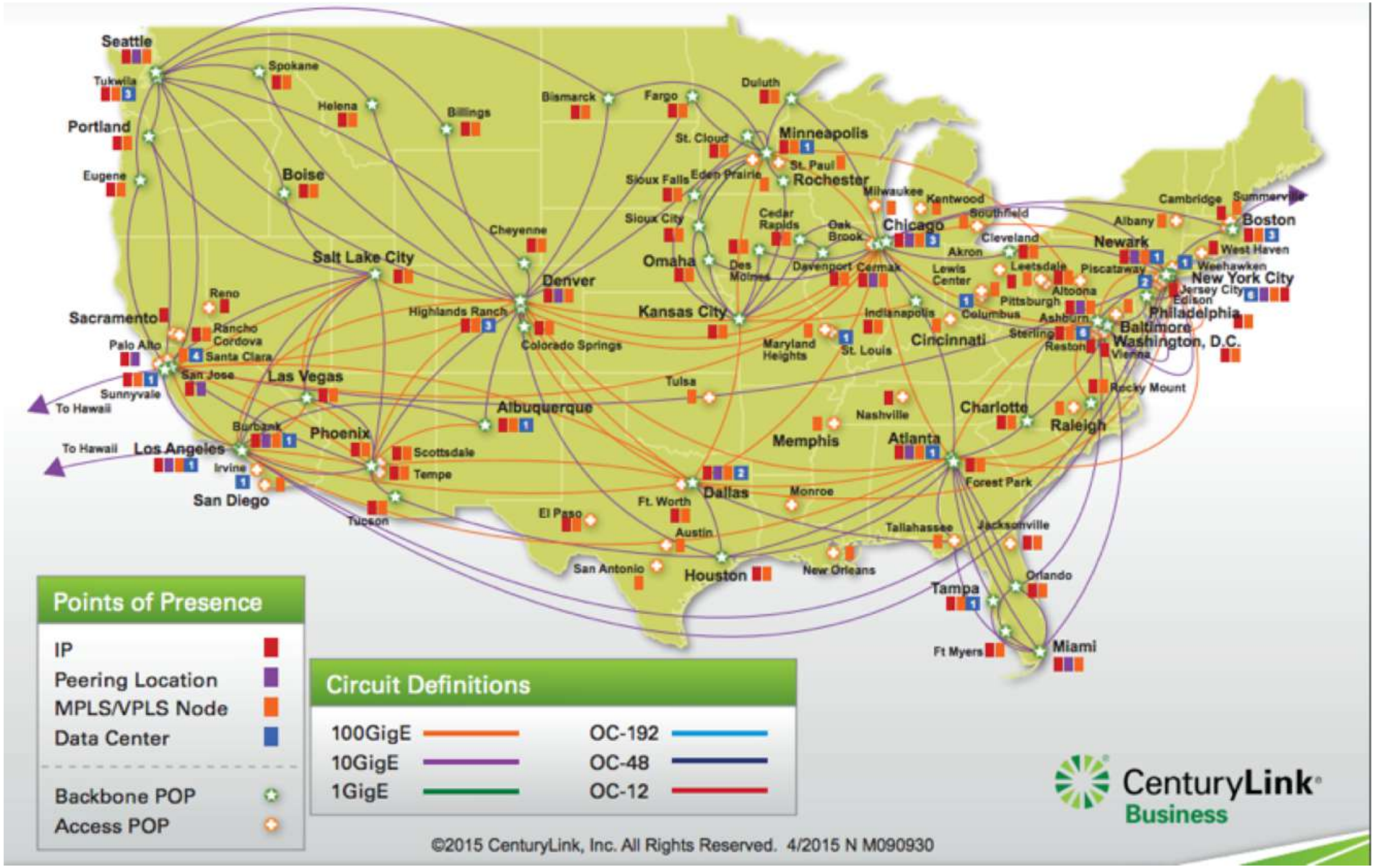
http://atlas.grnoc.iu.edu/atlas.cgi?map_name=Internet2%20IP%20Layer

XMU Internet Connection

Try traceroute from XMU to

- www.microsoft.com
- www.baidu.com
- www.sina.com.cn
- www.taobao.com

Qwest (CentryLink) Network Maps



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

Qwest Backbone Map

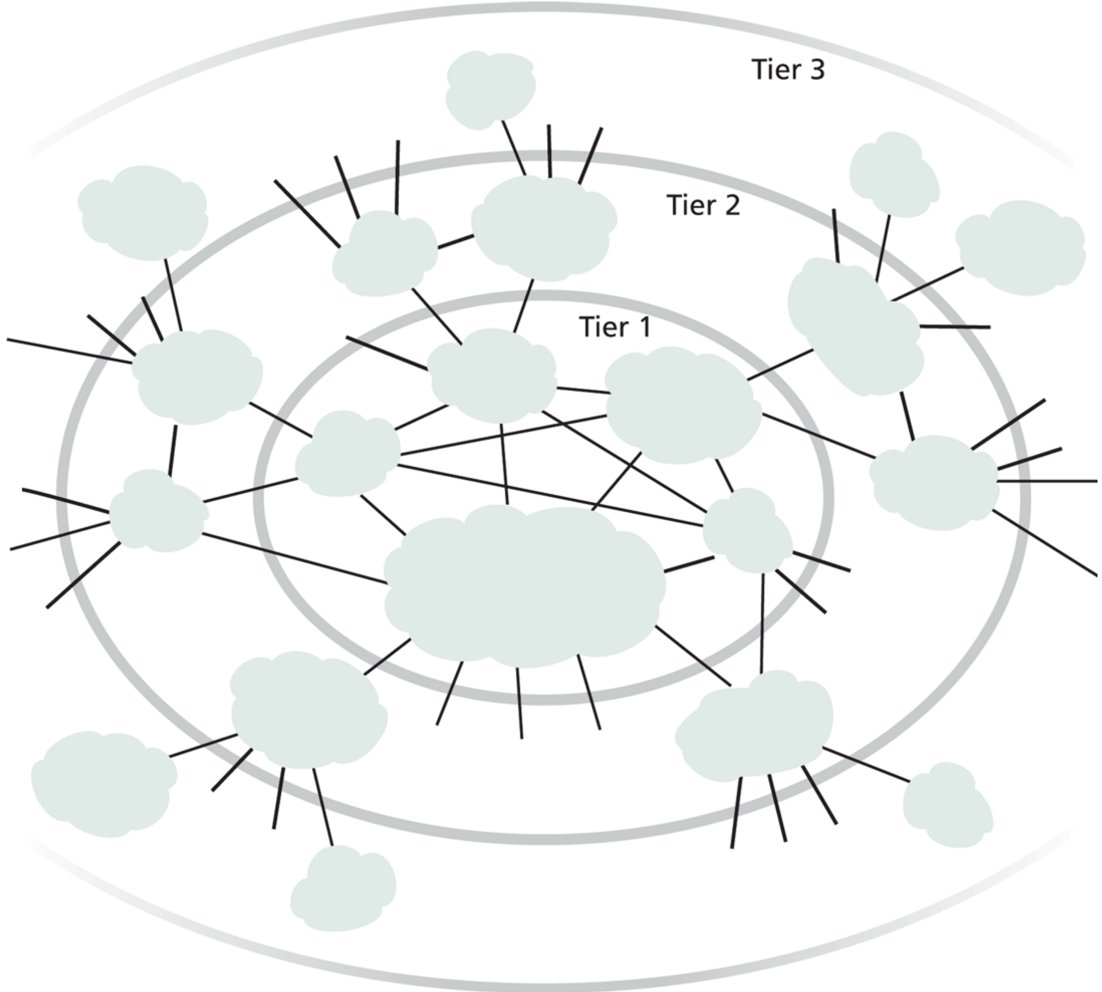
http://www.centurylink.com/business/resource-center/network-maps/

Level3 (now part of LUMEN) Network Map

https://www.lumen.com/en-us/resources/network-maps.html

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

- Admin. and recaps
- *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

- Admin. and recaps
- A brief introduction to the Internet: past and present
- *Challenges of Internet networks and apps*

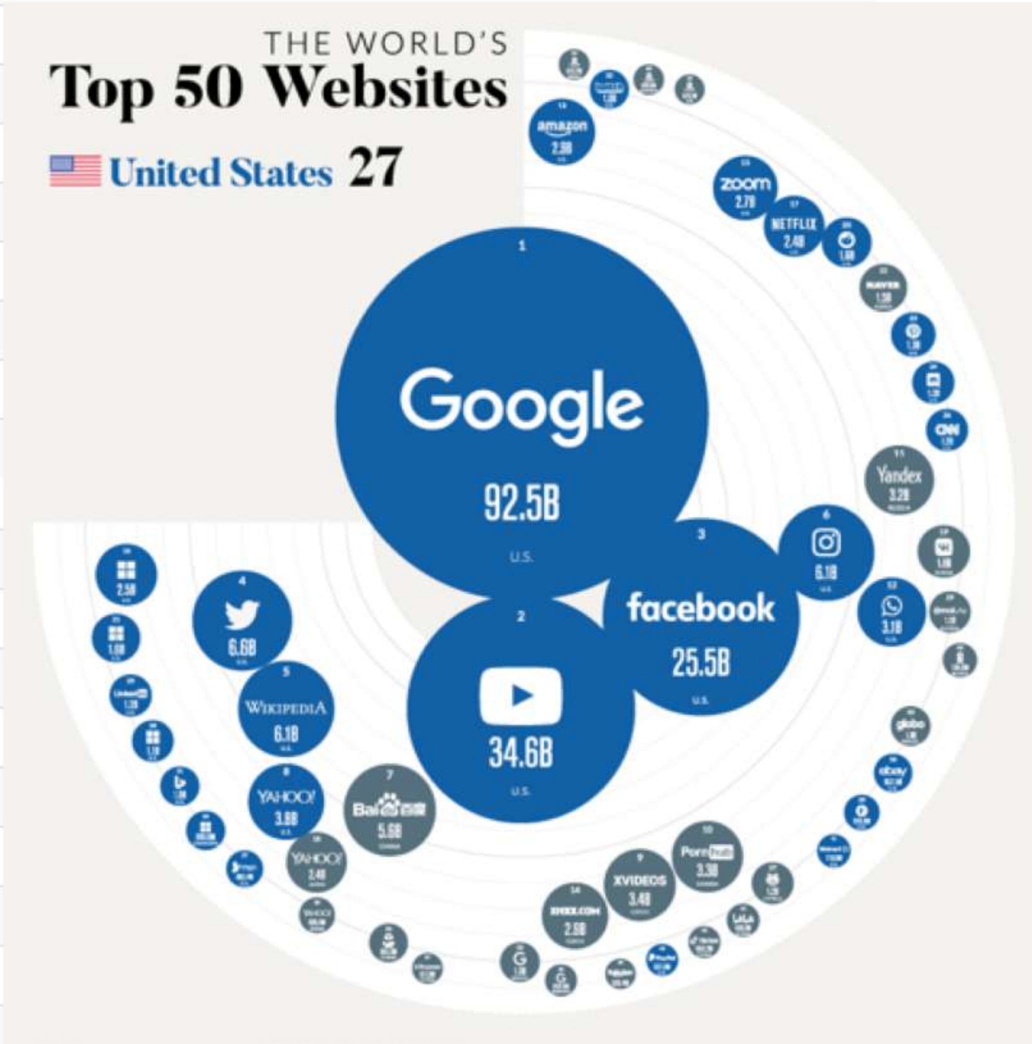
Scale

"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 the World

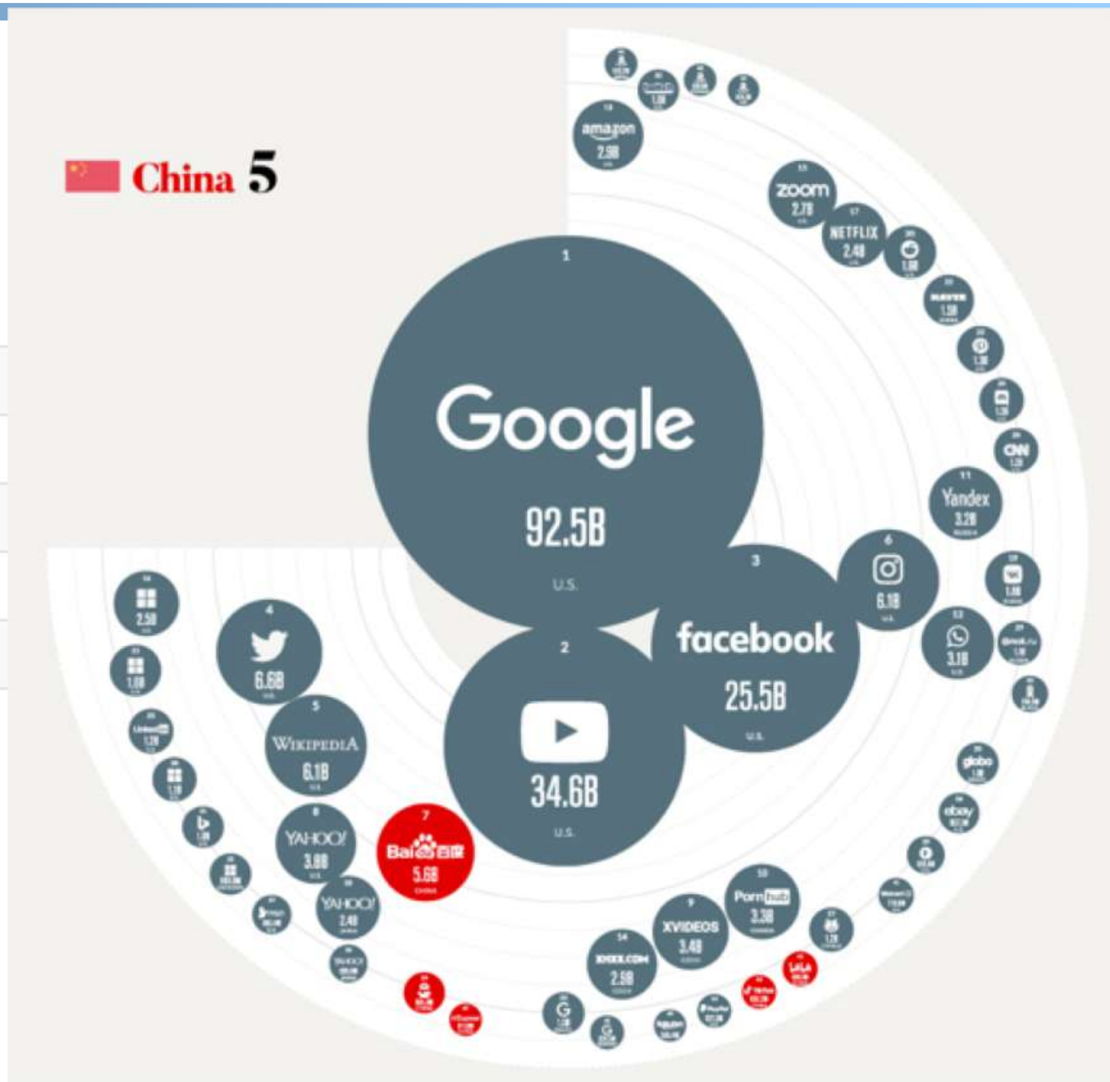
1	Google.com	92.5B
2	Youtube.com	34.6B
3	Facebook.com	25.5B
4	Twitter.com	6.6B
5	Wikipedia.org	6.1B
6	Instagram.com	6.1B
8	Yahoo.com	3.8B
12	Whatsapp.com	3.1B
13	Amazon.com	2.9B
15	Zoom.us	2.7B
16	Live.com	2.5B
17	Netflix.com	2.4B
20	Reddit.com	1.6B
21	Office.com	1.6B
23	Pinterest.com	1.3B
24	Discord.com	1.2B
25	Linkedin.com	1.2B
26	Cnn.com	1.2B



https://www.visualcapitalist.com/wp-content/uploads/2021/01/Country-With-the-Most-Websites.html

Largest Internet Sites in the World

7	Baidu.com	5.6B
34	QQ.com	981.3M
42	Bilibili.com	686.0M
43	Tiktok.com	663.2M
47	Aliexpress.com	611.0M



https://www.visualcapitalist.com/the-50-most-visited-websites-in-the-world/

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.

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.

Recall: Internet Physical Infrastructure

Residential access, e.g.,
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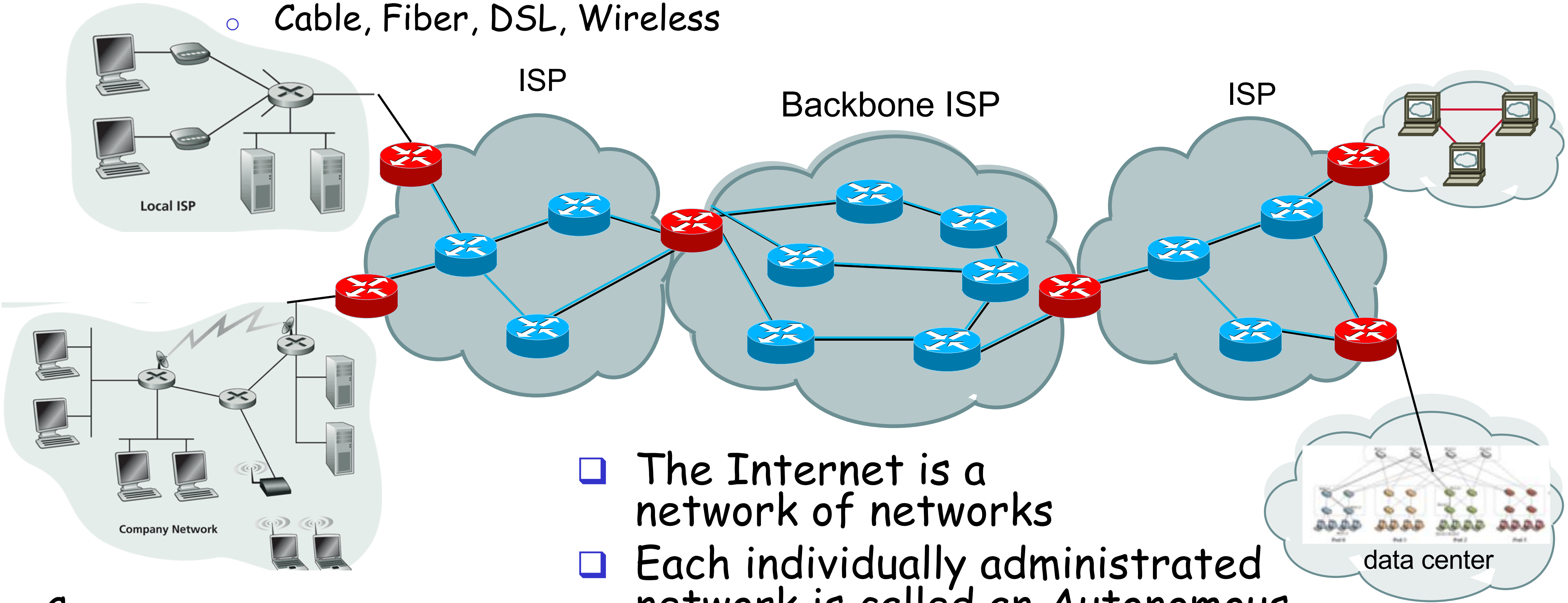

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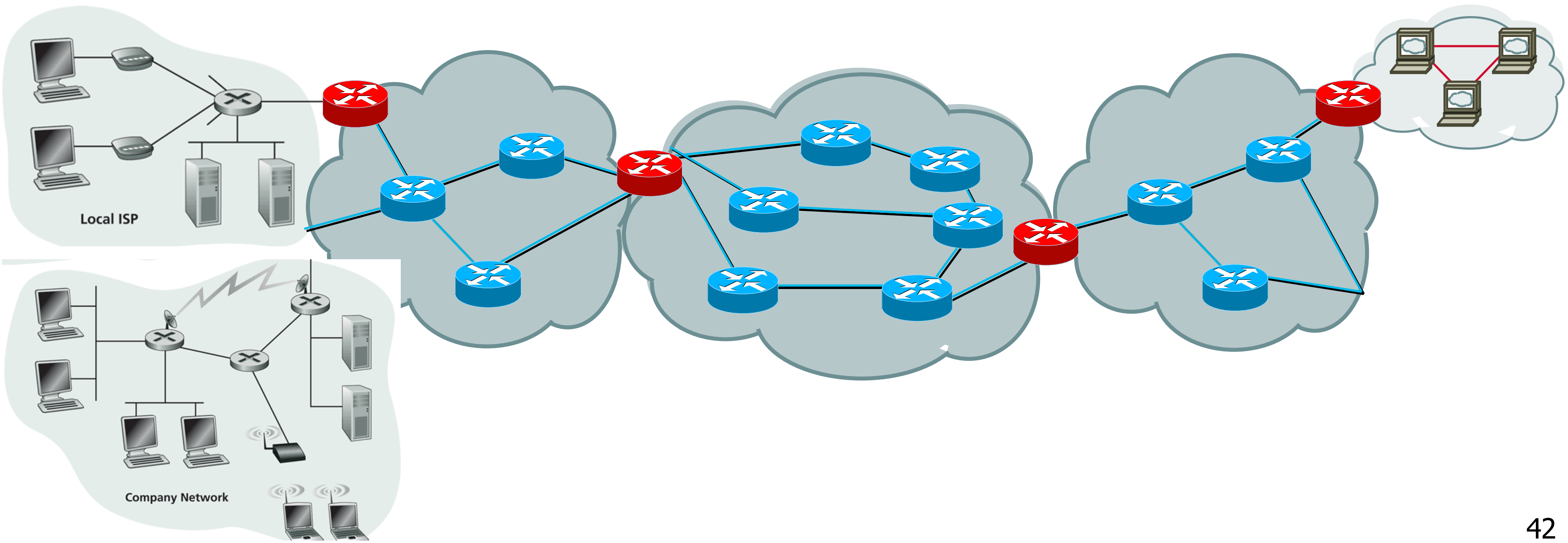
- Each individually administrated network is called an Autonomous System (AS)

  ~ 58000 ASes; Avg 5.7 hops; (http://bgp.potaroo.net/as2.0/bgp-active.html)

Roadmap

- So far we have looked at only the topology and physical connectivity of the Internet: a mesh of computers interconnected via various physical media
- *A basic question:* how are data (the bits) transferred through communication networks?



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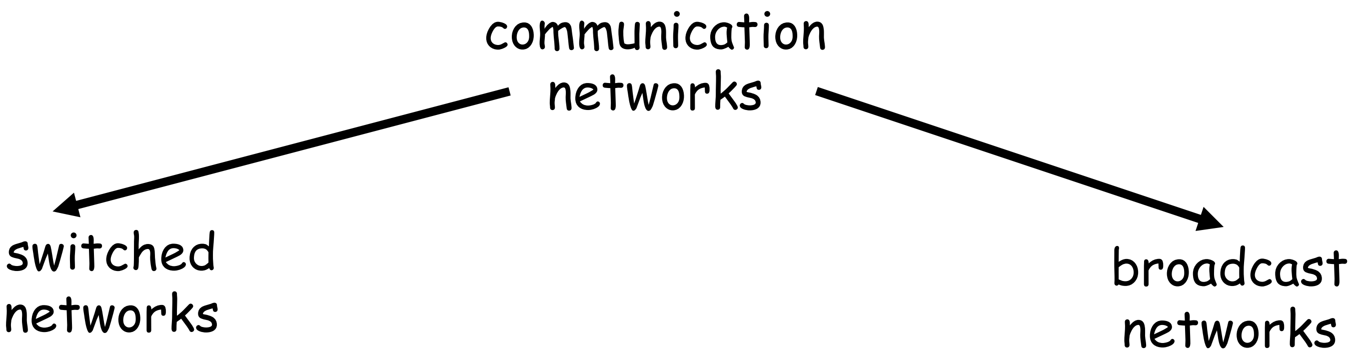
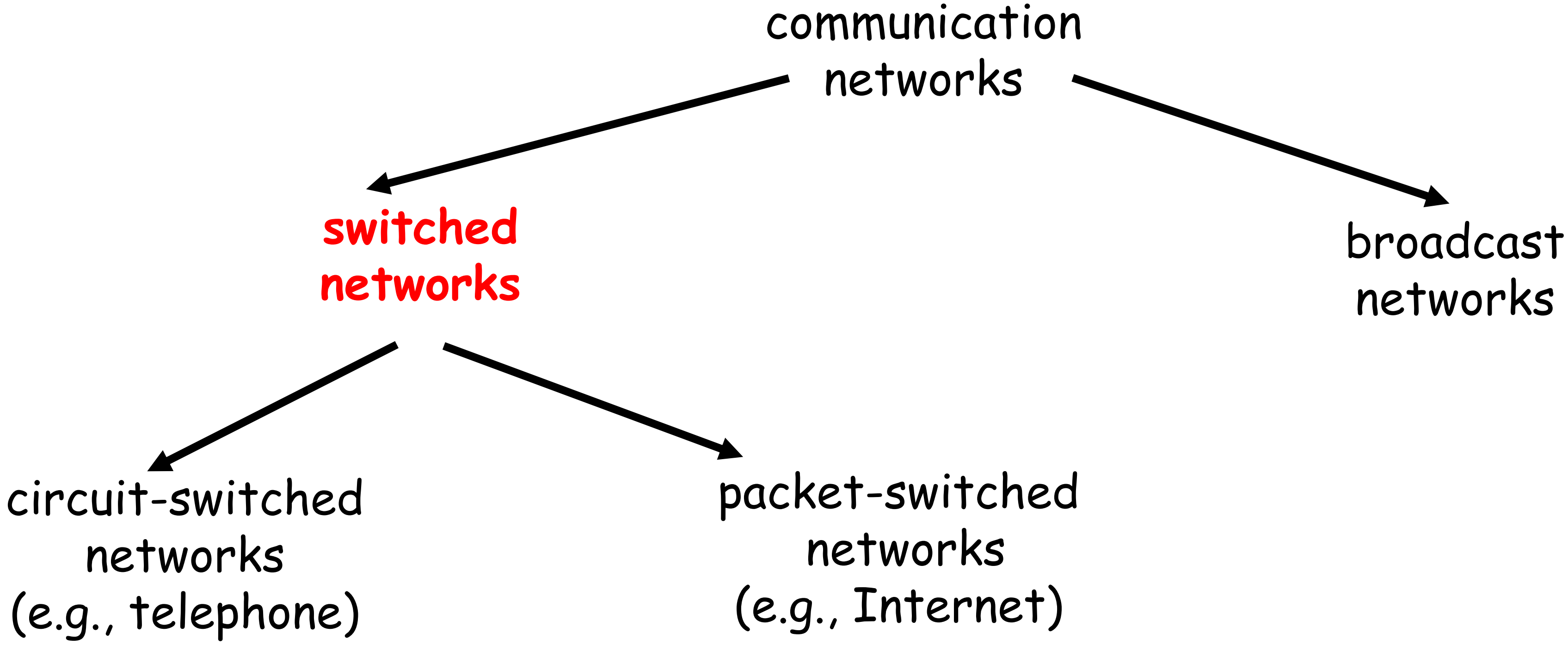
- A brief introduction to the Internet: past and present
- Challenges of Internet networks and apps
- *A taxonomy of communication networks*

Taxonomy of Communication Networks



- **Broadcast networks**
  - nodes share a common channel; information transmitted by a node is received by all other nodes in the network
  - examples: TV, radio
- **Switched networks**
  - information is transmitted to a small sub-set (usually only one) of the nodes

A Taxonomy of Switched Networks



- Circuit switching: dedicated circuit per call/session:
  - e.g., telephone, cellular voice
- Packet switching: data sent thru network in discrete "chunks"
  - e.g., Internet, cellular data

Outline

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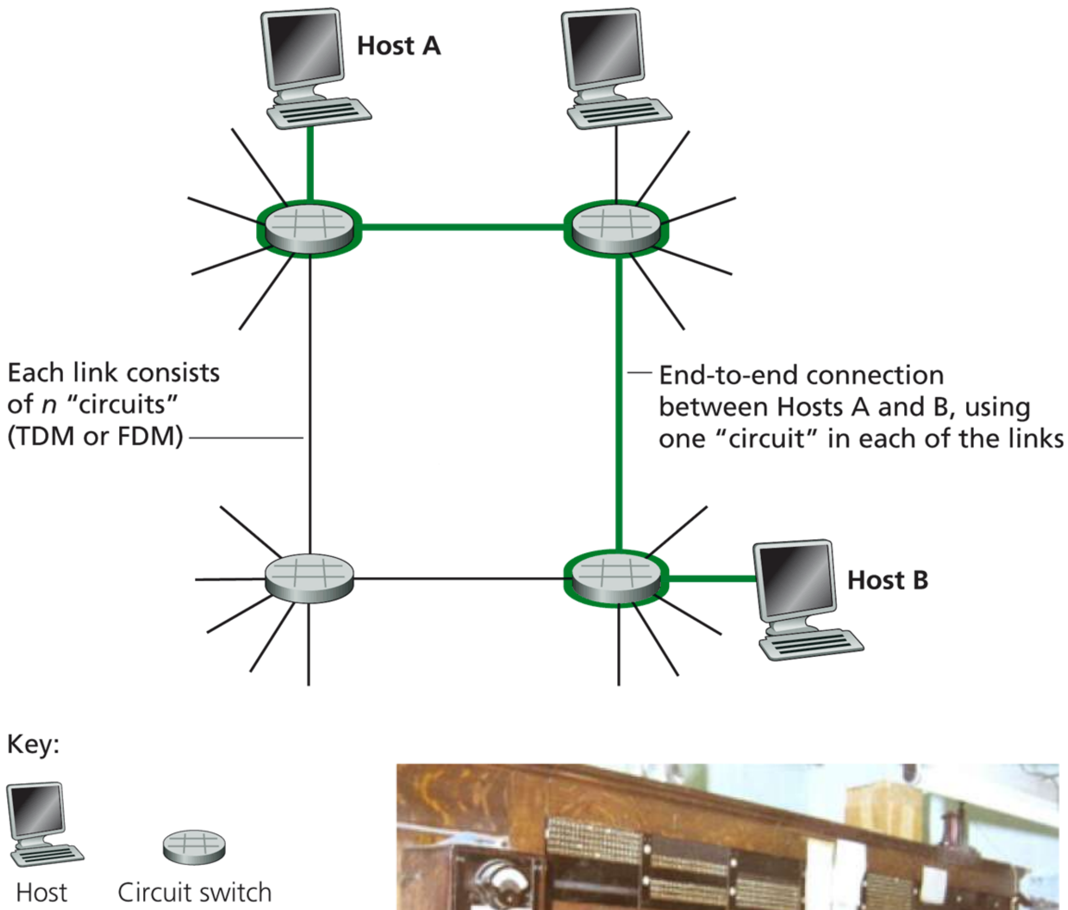
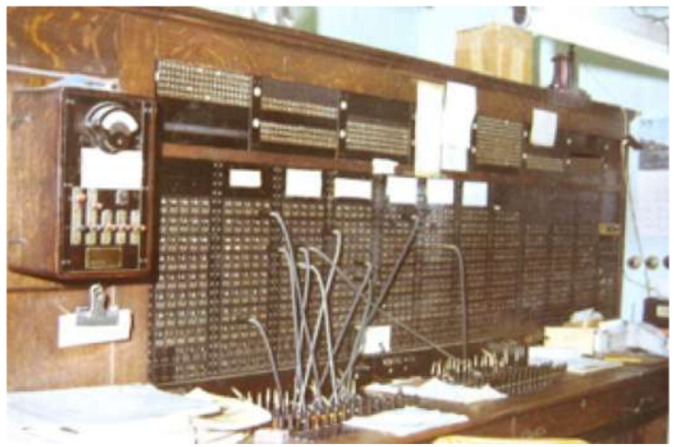
  - *circuit switched networks*

Circuit Switching

- Each link has a number of "circuits"
  - sometime we refer to a "circuit" as a channel or a line
- An end-to-end connection reserves one "circuit" at each link

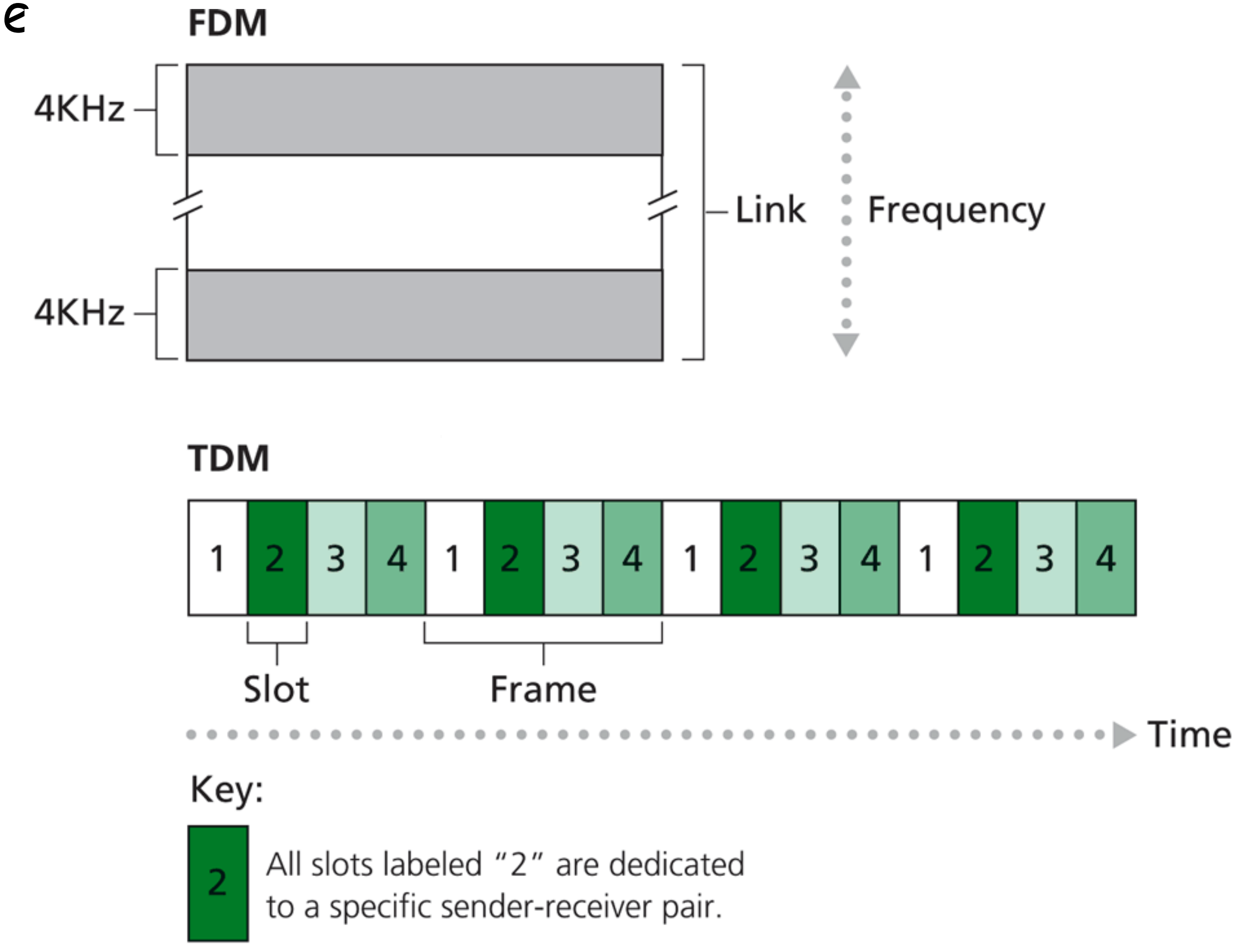


First commercial telephone switchboard was opened in 1878 to serve the 21 telephone customers in New Haven



Circuit Switching: Resources/Circuits (Frequency, Time and others)

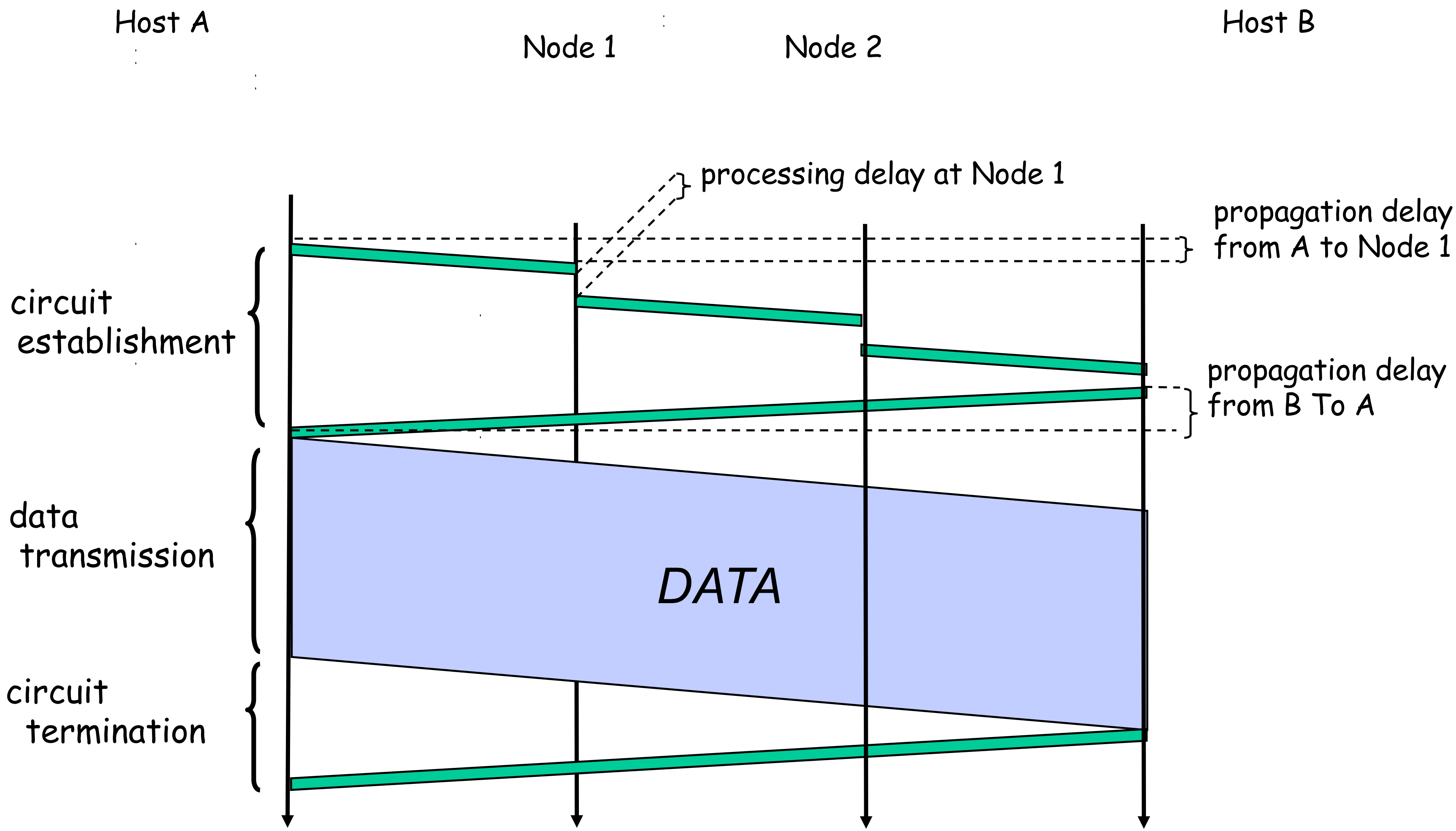
- Divide link resource into "circuits"
  - frequency division multiplexing (FDM)
  - time division multiplexing (TDM)
  - others such as code division multiplexing (CDM), color/lambda division



Circuit Switching: The Process

- Three phases
  - circuit establishment
  - data transfer
  - circuit termination

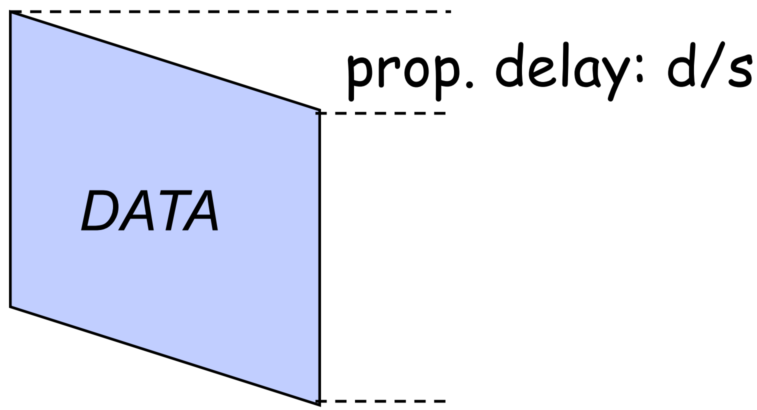
Timing Diagram of Circuit Switching



Delay Calculation in Circuit Switched Networks

- Propagation delay: delay for the first bit to go from a source to a destination

Propagation delay:
- d = length of physical link
- s = propagation speed in medium (~2x10^5 km/sec)

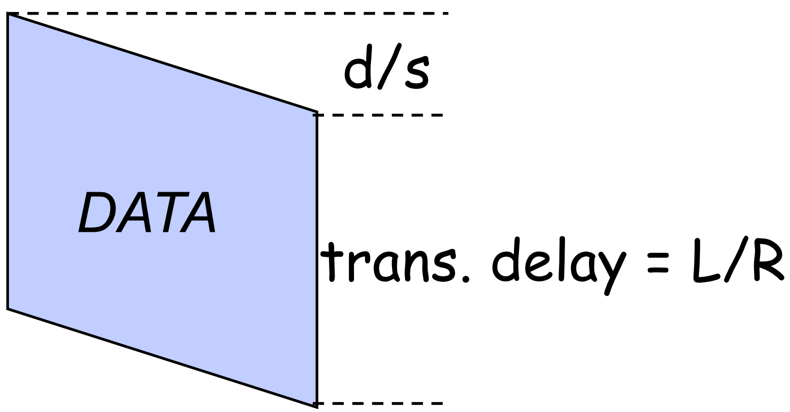


Delay Calculation in Circuit Switched Networks

- Transmission delay: time to pump data onto link at *line* rate

Transmission delay:

- R = reserved bandwidth (bps)
- L = message length (bits)



An Example

- Propagation delay
  - suppose the distance between A and B is 4000 km, then one-way propagation delay is:

$$\frac{4000\,km}{200{,}000\,km/s} = 20ms$$

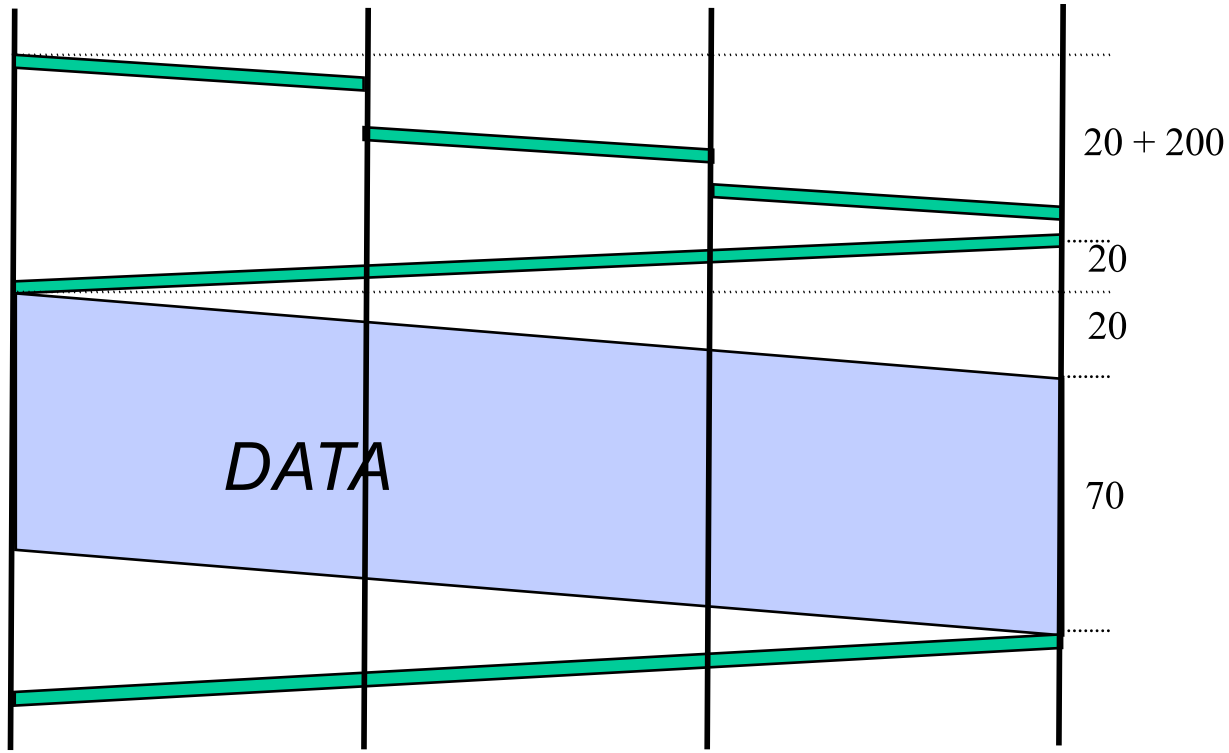
- Transmission delay
  - suppose your iphone reserves a one-slot HSCSD channel
    - each HSCSD frame can transmit about 115 kbps
    - a frame is divided into 8 slots
  - then the transmission delay of using one reserved slot for a message of 1 Kbits:

$$\frac{1kbits}{14kbps} \approx 70ms$$

An Example (cont.)

- Suppose the setup message is very small, and the total setup processing delay is 200 ms
  - Then the delay to transfer a message of 1 Kbits from A to B (from the beginning until host receives last bit) is:

$$20 + 200 + 20 + 20 + 70 = 330ms$$



Outline

- Admin. and recaps
- A brief introduction to the Internet: past and present
- Challenges of Internet networks and apps
- A taxonomy of communication networks
  - circuit switched networks
  - *packet switched networks*

Packet Switching

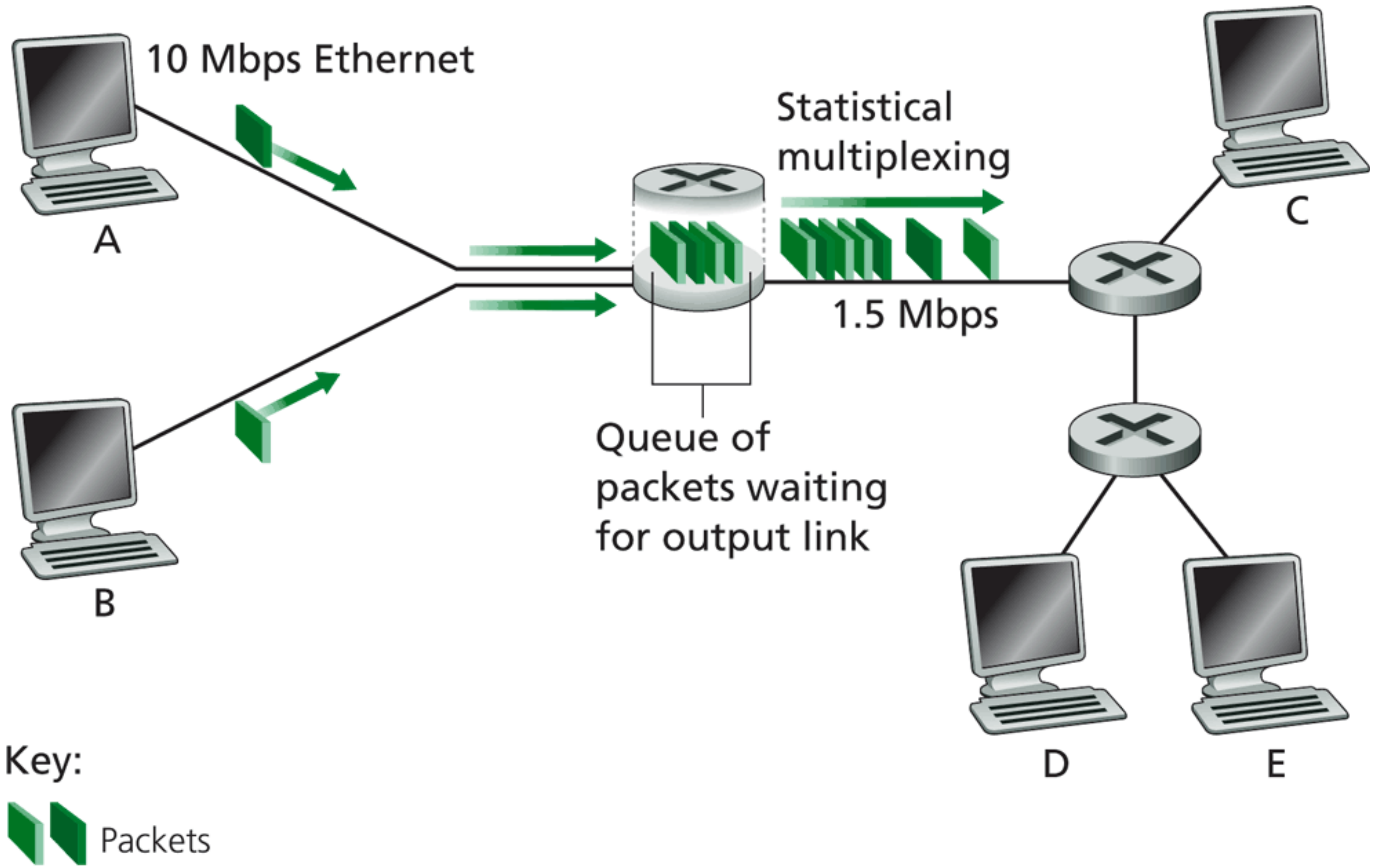
Each end-to-end data **flow** (i.e., a sender-receiver pair) divided into ***packets***

- Packets have the following structure:

  - header and trailer carry control information (e.g., destination address, check sum)
  - where is the control information for circuit switching?

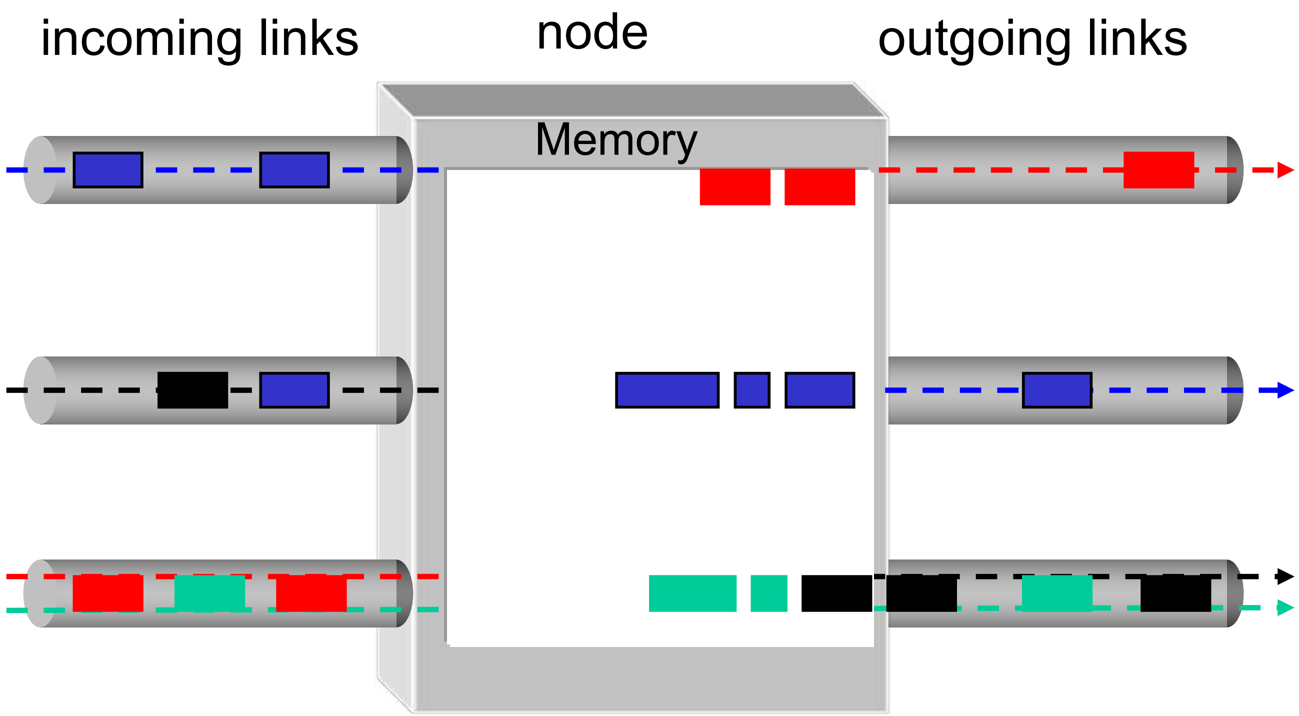
- At each node the entire packet is received, processed (e.g., routing), stored briefly, and then forwarded to the next node; thus packet-switched networks are also called **store-and-forward networks.** On its turn, a packet uses full link bandwidth

Packet Switching



Inside a Packet Switching Router

An output queueing switch



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Packet Switching vs. Circuit Switching

- The early history of the Internet was a heated debate between Packet Switching and Circuit Switching
  - the telephone network was the dominant network

- Need to compare packet switching with circuit switching

Circuit Switching vs. Packet Switching

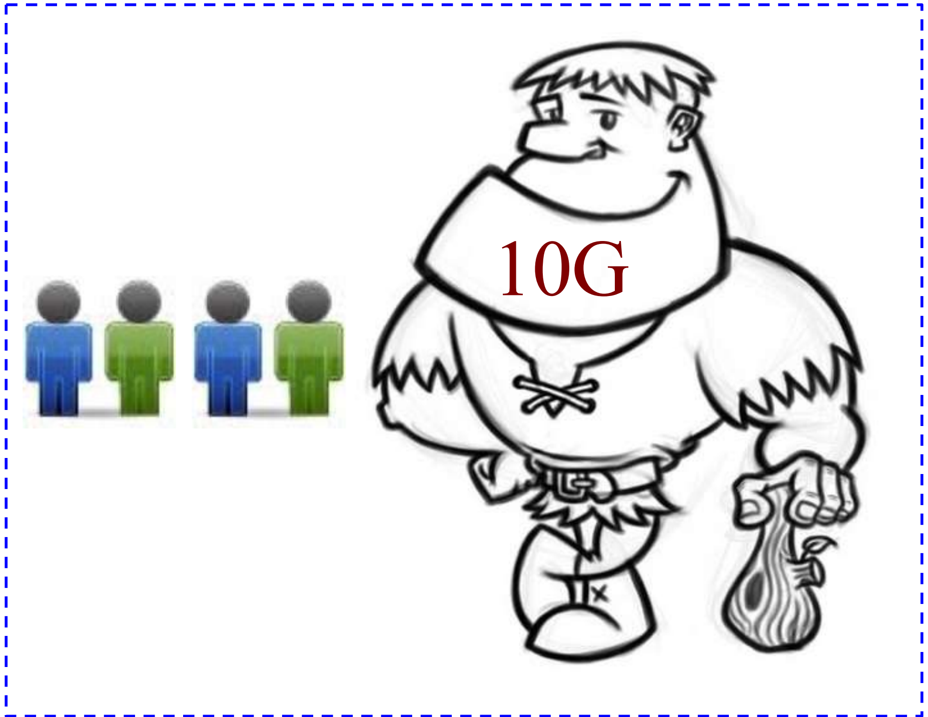
	circuit switching	packet switching
resource usage		
reservation/setup		
resource contention		
charging		
header		
fast path processing		

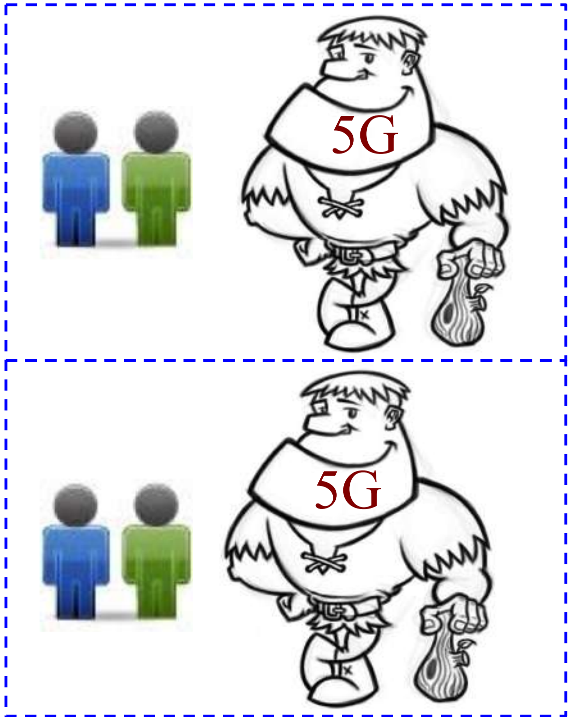
Circuit Switching vs. Packet Switching

	circuit switching	packet switching
resource usage	use a single partition bandwidth	use whole link bandwidth
reservation/setup	need reservation (setup delay)	no reservation
resource contention	busy signal (session loss)	congestion (long delay and packet losses)
charging	time	packet
header	no per-pkt header	per packet header
fast path processing	fast	per packet processing

Key Issue to be Settled

- A key issue: what is the efficiency of resource partition?





- Tool used to analyze the issue: queueing theory
  - Some basic results of queueing theory can be quite useful in many systems settings

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  - *M/M queues and statistical multiplexing*

Queueing Theory

- Strategy:
  - model system state
    - if we know the fraction of time that the system spends at each state, we can get answers to many basic questions: how long does a new request need to wait before being served?
- System state changes upon events:
  - introduce state transition diagram
  - focus on equilibrium: state trend neither growing nor shrinking (key issue: how to define equilibrium)

- Our approach: We are not interested in extremely precise modeling, but want quantitative intuition

Warm up: Analysis of Circuit-Switching Blocking (Busy) Time

- Assume a link has only a finite number of N circuits
- Objective: compute the percentage of time that a new session (call) is blocked
- Analogy in a more daily-life scenario?
- Key parameters?