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CS101

Network Thinking

Network Laws

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Outline

- What is network thinking?
- Network terms
- Connectivity
  - Naming
  - Topology
- Protocol stack
  - The Web over TCP/IP stack
  - Web programming
- Network laws
  - Performance metrics
  - Network effect
- Responsible computing

These slides acknowledge sources for additional data not cited in the textbook

History of computer networks, revisited

- A brief history of computer networks
  - Note the never-stopping changes and evolution of
    - what are connected and what are passed (communicated)

Start Time	Milestone	Main Functions
Late 1800's	Telecommunication networks	Telephony, telegraph
1963	J. C. R. Licklider proposed the concept of Intergalactic Computer Network	A general idea of computer networks
1969	First messages sent over ARPANET (50 Kbps = 50 Kilo bits per second)	Message passing, packet switching, interface HW
1974	TCP/IP	Internetworking (Internet) with telnet, ftp, email applications
1989	World Wide Web	Even more applications enabled by global-scale hypertexting
2000	Network science, grid, cloud computing	Various networks as the object of scientific inquiry, utility computing
2007	Apple iPhone	Mobile Internet
2008	Bitcoin	Blockchain, network of trust

Internet history is a history of social impact

- With technology advances comes increasing social impact
  - The size of the global Internet has grown exponentially
    - The trend is likely to continue till 2050
  - Most of nodes are hosts (edge nodes), not networking devices

Evolution of Internet

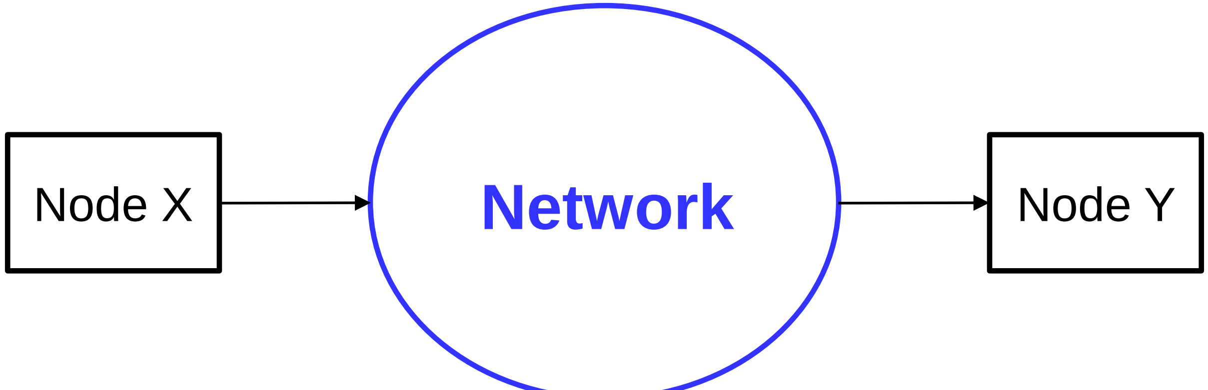
Time	# Nodes	Exemplar Techniques
1960s	A few	Packet Switching Network
1970s	Thousands	TCP/IP, Ethernet
1980s	100 thousands	Client-Server Computing
1990s	Millions	World Wide Web
2000s	100 Millions	Cloud Computing
2010s	Billions	Smartphones, Mobile Internet
2020-2050	Trillions	Internet of Human-Cyber-Physical Systems

5. Network laws

- Here, the "laws" refer to observations, phenomenon, principles, and viewpoints stated by experts
  - More like Moore's law than Newton's laws of mechanics
- They mainly relate to impact of networks to society
- We discuss the following
  - A network's latency and bandwidth
  - Network effect
    - Metcalfe's law
    - Reed's law
  - The Viral marketing phenomenon

5.1 Latency and bandwidth

- We focus on one node sending a message to another node over a network
  - Node X sends a message of *m* bytes to node Y
    - What is the total time $\boldsymbol{t}$ to transmit the message?
- Hockney's formula: $t = t_0 + m/\, r_\infty$
  - Extreme values
    - Minimal latency: $\boldsymbol{t_0}$; maximal bandwidth: $\boldsymbol{r_\infty}$
  - User experienced values
    - User experienced latency: $\boldsymbol{t}$; User experienced bandwidth $\boldsymbol{m/t}$



Example: network hero experiments data

- 1-minute quiz
  - Q1: How much time is needed to transmit a movie file of 1GB over the hero network of 2013?
  - Q2: How much time is needed to transmit a text file of 1KB over the hero network of 2013?

Time of Experiment	Maximal Bandwidth Achieved r_∞	Time t to Transmit 1 GB		Time t to Transmit 1 KB	
		$t_0 = 1$ μs	$t_0 = 1$ ms	$t_0 = 1$ μs	$t_0 = 1$ ms
1975	4.50E+07 bps, or 45 Mbps				
1984	1.00E+09 bps, or 1 Gbps				
1993	1.53E+11 bps, or 153 Gbps				
2002	1.00E+13 bps, or 10 Tbps				
2013	8.18E+14 bps, or 818 Tbps	?	?	?	?

Example: network hero experiments data

- 1-minute quiz
  - Q1: How much time is needed to transmit a movie file of 1GB over the hero network of 2013?
    - A1: 8 Gb / 818 Tbps = 9.78E-06 = 9.78 $\mathbf{\mu s}$
  - Q2: How much time is needed to transmit a text file of 1KB over the hero network of 2013?
    - A2: 8 Kb / 818 Tbps = 9.78E-12 = 9.78 $\mathbf{ps}$

Time of Experiment	Maximal Bandwidth Achieved r_∞	Time t to Transmit 1 GB		Time t to Transmit 1 KB	
		$t_0 = 1\ \mu s$	$t_0 = 1\ ms$	$t_0 = 1\ \mu s$	$t_0 = 1\ ms$
2013	8.18E+14 bps, or 818 Tbps	?	?	?	?

Example: network hero experiments data

- 1-minute quiz
  - Q1: How much time is needed to transmit a movie file of 1GB over the hero network of 2013?
    - A1: 8 Gb / 818 Tbps = 9.78E-06 = 9.78 μs
  - Q2: How much time is needed to transmit a text file of 1KB over the hero network of 2013?
    - A2: 8 Kb / 818 Tbps = 9.78E-12 = 9.78 $\mathbf{ps}$
  - What is wrong with these answers?
    - Did not consider t_0, the startup overhead
    - The time to transmit a 0-byte message is not 0 second!

Time of Experiment	Maximal Bandwidth Achieved r_∞	Time t to Transmit 1 GB		Time t to Transmit 1 KB	
		$t_0 = 1\ \mu s$	$t_0 = 1$ ms	$t_0 = 1\ \mu s$	$t_0 = 1$ ms
2013	8.18E+14 bps, or 818 Tbps	?	?	?	?

Example: network hero experiments data

- 1-minute quiz: correct answers
  - Q1: How much time is needed to transmit a movie file of 1GB over the hero network of 2013?
    - A1: If $\boldsymbol{t_0} = 1\ \mathbf{\mu s}$, 1E-06 + 8 Gb / 818 Tbps ≈ 10.78E-06 ≈ 11 $\mathbf{\mu s}$
      If $\boldsymbol{t_0} = 1\ \mathbf{ms}$, 1E-03 + 8 Gb / 818 Tbps ≈ 1E-03 = 1 $\mathbf{ms}$
  - Q2: How much time is needed to transmit a text file of 1KB over the hero network of 2013?
    - A2: If $\boldsymbol{t_0} = 1\ \mathbf{\mu s}$, 1E-06 + 8 Kb / 818 Tbps ≈ 1E-06 = 1 $\mathbf{\mu s}$
      If $\boldsymbol{t_0} = 1\ \mathbf{ms}$, 1E-03 + 8 Kb / 818 Tbps ≈ 1E-03 = 1 $\mathbf{ms}$

Time of Experiment	**Maximal Bandwidth Achieved r_∞**	**Time t to Transmit 1 GB**		**Time t to Transmit 1 KB**	
		$\boldsymbol{t_0} = \mathbf{1\ \mu s}$	$\boldsymbol{t_0} = \mathbf{1\ ms}$	$\boldsymbol{t_0} = \mathbf{1\ \mu s}$	$\boldsymbol{t_0} = \mathbf{1\ ms}$
2013	8.18E+14 bps, or 818 Tbps	11 μs	1 ms	1 μs	1 ms

Example: network hero experiments data

- Lessons learned regarding $t = t_0 + m/r_\infty$
  - For a short message, the first term $\boldsymbol{t_0}$ often dominates
  - For a long message, the second term $\boldsymbol{m/r_\infty}$ often dominates
  - User experienced latency is $\boldsymbol{t}$, not $\boldsymbol{m/r_\infty}$
  - User experienced bandwidth is $\boldsymbol{m/t}$, not $\boldsymbol{r_\infty}$
    - To transmit a 1-KB message over a network with $r_\infty = 1$ Gbps and $t_0 = 1\ ms$, the user experienced bandwidth is m/t = 7.9 Mbps, 125 times smaller than the maximal bandwidth $r_\infty = 1$ Gbps

Time of Experiment	Maximal Bandwidth Achieved $\boldsymbol{r_\infty}$	Time $\boldsymbol{t}$ to Transmit 1 GB		Time $\boldsymbol{t}$ to Transmit 1 KB	
		$\boldsymbol{t_0 = 1\ \mu s}$	$\boldsymbol{t_0 = 1\ ms}$	$\boldsymbol{t_0 = 1\ \mu s}$	$\boldsymbol{t_0 = 1\ ms}$
1975	4.50E+07 bps, or 45 Mbps	178 s	178 s	0.2 ms	1.2 ms
1984	1.00E+09 bps, or 1 Gbps	8 s	8 s	9 μs	1 ms
1993	1.53E+11 bps, or 153 Gbps	52 ms	53 ms	1.1 μs	1 ms
2002	1.00E+13 bps, or 10 Tbps	0.8 ms	1.8 ms	1 μs	1 ms
2013	8.18E+14 bps, or 818 Tbps	11 μs	1 ms	1 μs	1 ms

1-minute quiz

- Q: Paid for 1-Gbps and got only 5-8 Mbps. Why?
  - I subscribe to a fiber optical plan from a reputable ISP, which offers a 1-Gbps bandwidth connection to the Internet. However, I often only experience 5-8 Mbps bandwidth when accessing the Internet. Why this huge (up to 200 times) disparity?

1-minute quiz

- Q: Paid for 1-Gbps and got only 5-8 Mbps. Why?
  - I subscribe to a fiber optical plan from a reputable ISP, which offers a 1-Gbps bandwidth connection to the Internet. However, I often only experience 5-8 Mbps bandwidth when accessing the Internet. Why this huge (up to 200 times) disparity?
- A: The following are possible reasons
  - The 1-Gbps connection is only part of the full path from my laptop to the servers on the Internet. Some parts of the rest of the path are slower than 1-Gbps.
  - I am sharing the 1-Gbps connection with other students.
  - I am accessing a lot of small files, resulting in transmissions of many short messages. Thus, the user experienced bandwidth is much smaller than 1-Gbps.

Compression

- Data compression: Technique to reduce file size
  - To save storage space and transmission time
- Lossless compression
  - Reduce file size without losing information
    - > gzip fib-10 (2011793 bytes)
    - To obtain a compressed file fib-10.gz (709090 bytes)
    - > gzip Autumn.bmp (9144630 bytes)
    - The compressed file is Autumn.bmp.gz (8224455 bytes)
  - Original file can be recovered from compressed file
    - > gzip -d Autumn.bmp.gz
- Lossy compression
  - Reduce file size while losing information
  - Original file cannot be recovered from compressed file

Lossy compression

5971405
597384
92506

5.97 MB
597 KB
92.5 KB

- Original file

  > ls -l Autumn.png

  -rw-r--r-- 1 5971405 Autumn.png

- Reduce size ~10 times

  > pngquant --quality=1 Autumn.png

  > ls -l Autumn-fs8.png

  -rw-r--r-- 1 597384 Autumn-fs8.png

- Reduce size ~64 times

  > pngquant --quality=0 Autumn.png

  > ls -l Autumn-fs8.png

  -rw-r--r-- 1 92506 Autumn-fs8.png

5.2 Network effect

- Network laws

  n = number of nodes

  - **Metcalfe's law** ($V \propto n^2$)
    - Value *V* of a network of *n* nodes is proportional to n^2
  - **Reed's law** ($V \propto 2^n$)
    - Value *V* of a network of *n* nodes can scale exponentially with *n*, because the network can form 2^n subgroups
- Viral marketing
  - Markets grow wide and fast, like biologic viruses
  - Why?
    - Connected and 0-cost
      - Zero purchasing price
      - Zero usage cost
      - Zero propagation cost

Social networks example

- Real data from Facebook and Tencent annual reports (2003-2019)
  - $\text{Facebook's Value} = 9.69 \times 10^{-9} \times n^2 \text{ USD}, \qquad \text{RMSD} = 4.58 \text{ Billion USD}$
  - $\text{Tencent's Value} = 9.67 \times 10^{-9} \times n^2 \text{ USD}, \qquad \text{RMSD} = 4.30 \text{ Billion USD}$
  - Number of nodes *n* is measured by the Monthly Active Users (MAUs)
    Value is measured by the annual revenue

- Per-user revenue (amount in USD) growth trends of Facebook and Tencent from 2003 to 2018