University of Chinese Academy of Sciences

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 计算机网络简史
  - 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 电信网：电话电报 |
| 1963 | J. C. R. Licklider proposed the concept of Intergalactic Computer Network | A general idea of computer networks 计算机网络思想 |
| 1969 | First message sent on ARPANET 阿帕网 (50 Kbps = 50 Kilo bits per second) | Message passing, packet switching, interface HW 信息传递 分组交换 |
| 1974 | TCP/IP | Internetworking (Internet) 因特网 with telnet, ftp, email applications |
| 1989 | World Wide Web 万维网 | More applications enabled by global-scale hypertexting 超文本、超链接 |
| 2000 | Network science, 网络科学，网格计算 grid, cloud computing 云计算 | Various networks as the object of scientific inquiry, utility computing |
| 2007 | Apple iPhone 苹果公司智能手机 | Mobile Internet 移动互联网 |
| 2008 | Bitcoin 比特币 | Blockchain, network of trust 区块链 |

# Internet history is a history of social impact
# 互联网产生越来越大的社会影响

- 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 互联网规模增长：历史与展望

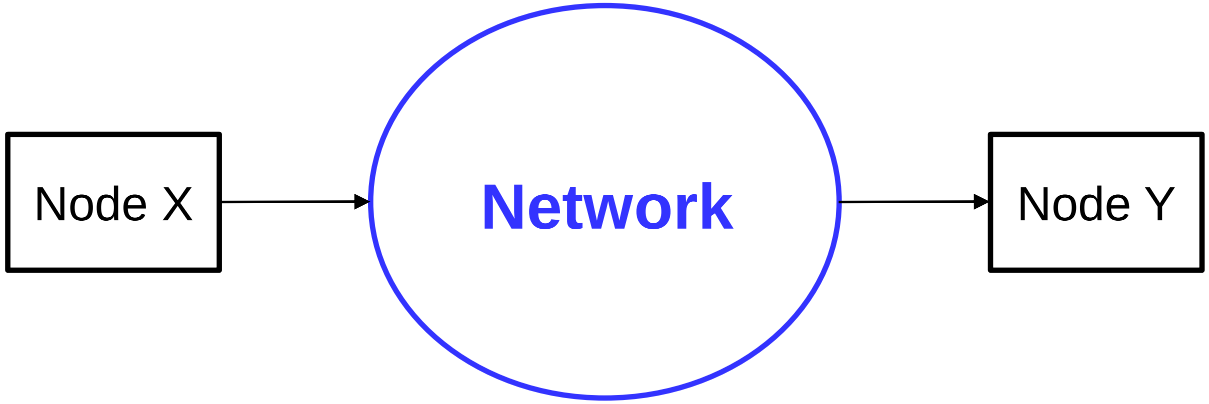
| **Time 时间** | **# Nodes 节点数** | **Exemplar Techniques 标志性技术** |
|---|---|---|
| 1960s | A few 数个 | Packet Switching Network 分组交换网 |
| 1970s | Thousands 数千个 | TCP/IP, Ethernet 因特网、以太网 |
| 1980s | 100 thousands 数十万 | Client-Server Computing 客户-服务器计算 |
| 1990s | Millions 数百万 | World Wide Web 万维网 |
| 2000s | 100 Millions 数亿 | Cloud Computing 云计算 |
| 2010s | Billions 数十亿 | Smartphones, Mobile Internet 移动互联网 |
| 2020-2050 | Trillions 数万亿 | Internet of Human-Cyber-Physical Systems 人机物融合的智能互联 |

# 5. Network laws 网络定律

- Here, the “laws” refer to observations, phenomenon, principles, and viewpoints stated by experts
  - More like Moore’s law than Newton’s laws of mechanics
  - 网络定律是像摩尔定律一样的观察，不是物理学定律
- They mainly relate to impact of networks to society
- We discuss the following
  - A network’s latency and bandwidth 网络的延迟与带宽
  - Network effect 网络效应
    - Metcalfe’s law 梅特卡夫定律
    - Reed’s law 里德定律
  - The Viral marketing phenomenon 病毒市场现象

# 5.1 Latency and bandwidth

- We focus on one node sending a message to another node over a network 考虑最简单的网络
  - Node X sends a message of *m* bytes to node Y
    - What is the total time $t$ to transmit the message?
- Hockney's formula: $t = t_0 + m/\, r_\infty$
  - Extreme values　极端值
    - 最小延迟 Minimal latency: $t_0$; 最大带宽 maximal bandwidth: $r_\infty$
  - User experienced values 用户体验值
    - User experienced latency: $t$; User experienced bandwidth $m/t$



# 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 $r_\infty$ | Time $t$ to Transmit 1 GB | | Time $t$ to Transmit 1 KB | |
|---|---|---|---|---|---|
| | | $t_0 = 1\ \mu s$ | $t_0 = 1\ ms$ | $t_0 = 1\ \mu s$ | $t_0 = 1\ ms$ |
| 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 $\mu s$ $\quad t = m/ r_\infty$
  - 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 $ps$ $\quad t = m/ r_\infty$

| Time of Experiment | Maximal Bandwidth Achieved $r_\infty$ | 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 $\mu s$ $\quad t = m/ r_\infty$
  - 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 $ps$ $\quad t = m/ r_\infty$
  - 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!

空消息传输时间 $\neq$ 0！

| Time of Experiment | Maximal Bandwidth Achieved $r_\infty$ | 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 使用$t = t_0 + m / r_\infty$
  - Q1: How much time is needed to transmit a movie file of 1GB over the hero network of 2013?
    - A1: If $\boldsymbol{t_0} = 1\ \boldsymbol{\mu s}$, $\boldsymbol{t}$ = 1E-06 + 8 Gb / 818 Tbps = 10.78E-06 = 11 $\boldsymbol{\mu s}$
      If $\boldsymbol{t_0} = 1\ \mathbf{ms}$, $\boldsymbol{t}$ = 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 $\boldsymbol{t_0} = 1\ \boldsymbol{\mu s}$, $\boldsymbol{t}$ = 1E-06 + 8 Kb / 818 Tbps = 1E-06 = 1 $\boldsymbol{\mu s}$
      If $\boldsymbol{t_0} = 1\ \mathbf{ms}$, $\boldsymbol{t}$ = 1E-03 + 8 Kb / 818 Tbps = 1E-03 = 1 $\mathbf{ms}$
    - 用户体验带宽：***m*** / ***t*** = 1KB / 1ms = 8 Mbps，远低于818 Tbps
      - 短消息带宽低

| Time of Experiment | Maximal Bandwidth Achieved $r_\infty$ | 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 | 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? 从电信公司买了1-Gbps，只得到5 Mbps。为什么？
  - 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. 只有接入是1-Gbps
  - I am sharing the 1-Gbps connection with other students. 1-Gbps接入不是独占，而是与其他用户分享
  - I am accessing a lot of small files, resulting in transmissions of many short messages. Thus, the user experienced bandwidth is smaller than the maximal bandwidth 1-Gbps. 用户传输大量短消息，实际体验到的带宽远低于最大带宽1-Gbps

# Compression 数据压缩

- Data compression: Technique to reduce file size
  - To save storage space and transmission time
- Lossless compression 无损压缩
  - 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 有损压缩
  - 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** ($V \propto n^2$) 梅特卡夫定律
    - Value $V$ of a network of $n$ nodes is proportional to $n^2$
  - **Reed's law** ($V \propto 2^n$) 里德定律
    - Value $V$ of a network of $n$ nodes can scale exponentially with $n$, because the network can form $2^n$ subgroups
- Viral marketing 病毒市场现象
  - 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
# 脸书网与腾讯网实例

- Real data from Facebook and Tencent annual reports (2003-2019)
  - Facebook's Value $= 9.69 \times 10^{-9} \times n^2$ USD, 均方根差 RMSD = 4.58 Billion USD
  - Tencent's Value $= 9.67 \times 10^{-9} \times n^2$ USD, 均方根差 RMSD = 4.30 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