Complex Networks

Lecture 4a: Internet

-- Topology and Modeling

EE 6605

Instructor: G Ron Chen

Most pictures on this ppt were taken from
un-copyrighted websites on the web with thanks

QQ Networking

Internet

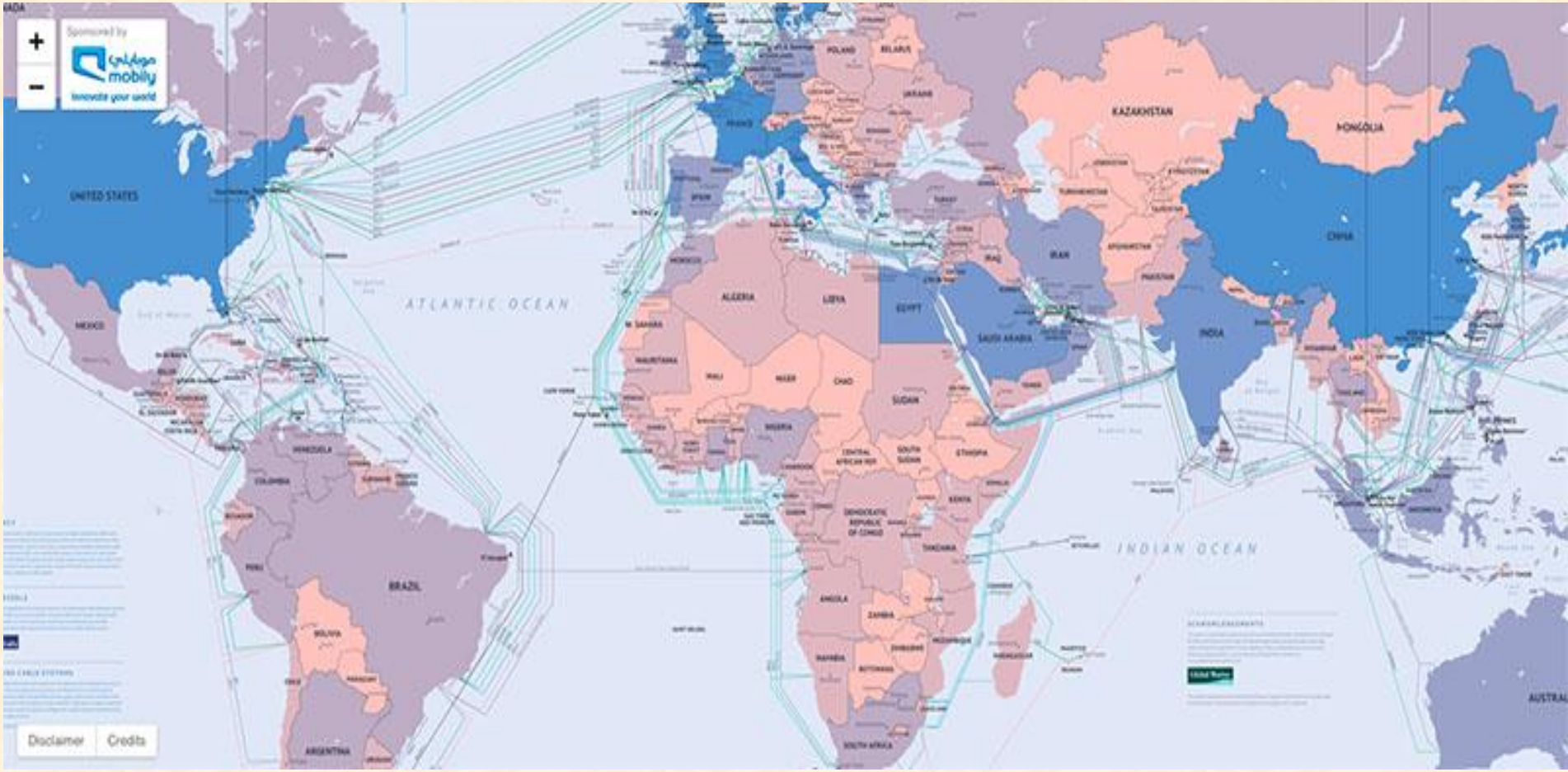
- **Internet is a global system of interconnected computer networks that use the standard Internet Protocol Suite (TCP/IP) to serve billions of users worldwide** (Wikipedia)

- **Structure:**
  - **Autonomous Systems (AS)**
  - **Wide Area Network (WAN)**
  - **Metropolitan Area Network (MAN)**
  - **Local Area Network (LAN)**
- **Software:**
  - **Transmission Control Protocol (TCP)**
  - **Internet Protocol (IP)**
  - **Other protocols at the application level:**
    - **Internet Control Message Protocol (ICMP)**
    - **File Transfer Protocol (FTP)**
    - **Simple Mail Transfer Protocol (SMTP)**

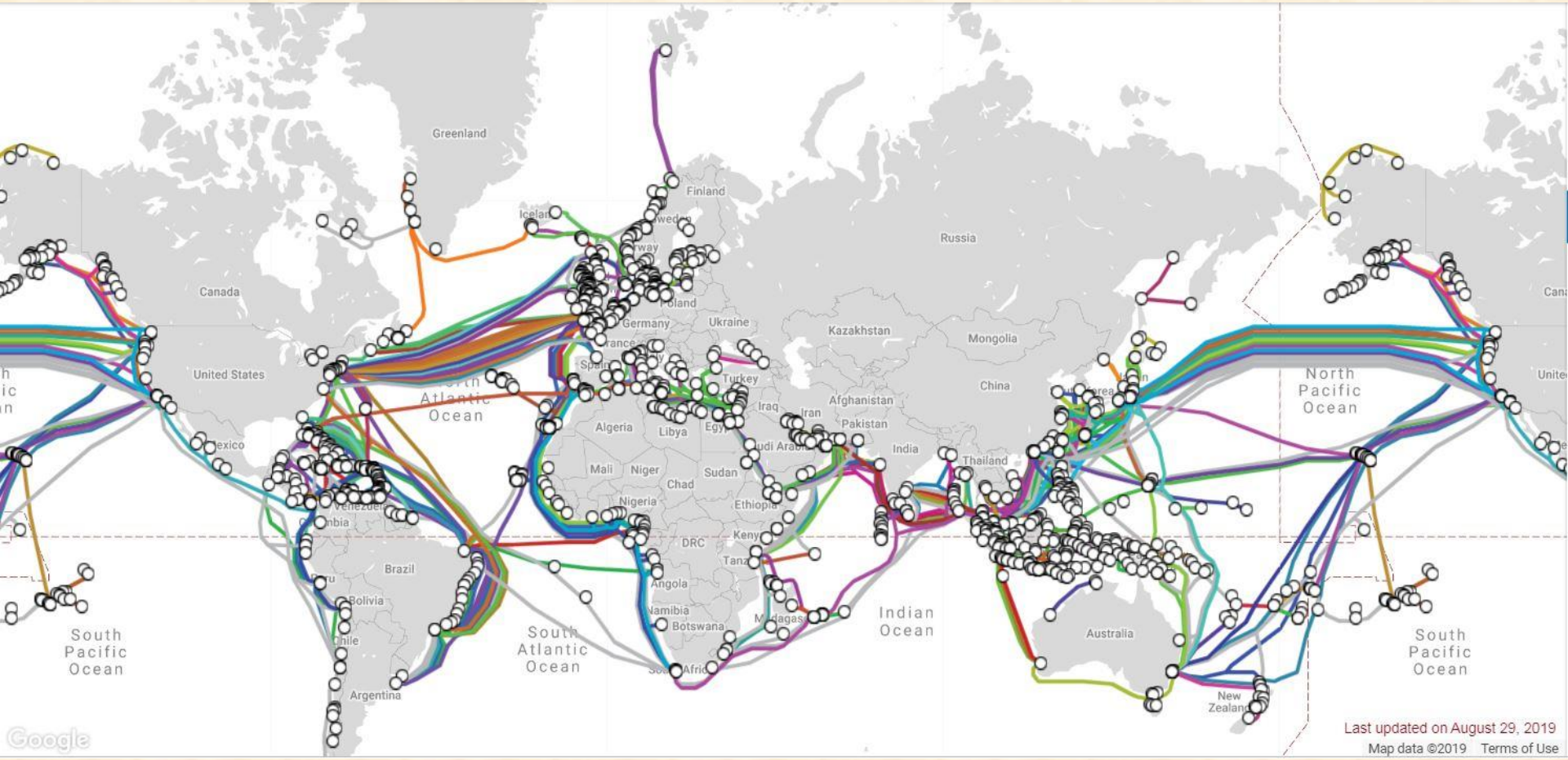
Internet is a network of networks
(structure)

- Internet is the inter-connection of networks:
  - Internet Service Provider (ISP) networks
  - Corporate networks (e.g. Cisco and Microsoft)
  - Campus networks (e.g. CityU)
  - Mobile operator networks (e.g. one2free)
  - Government networks
  - Internet Exchanges (e.g. HKIX)
- through optical fibers (telephone lines)

Submarine Cables in the World

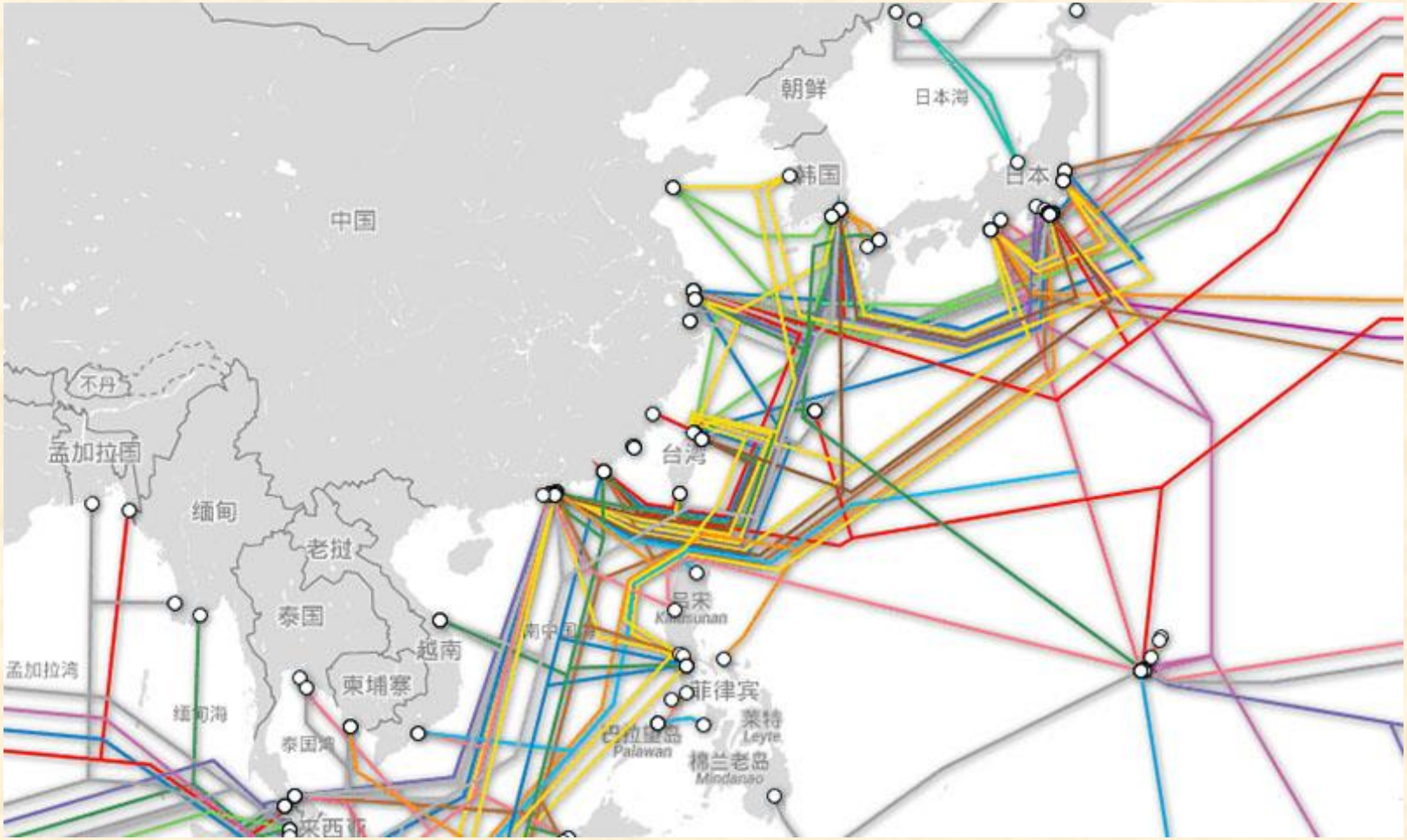


TeleGeography



TeleGeography

Submarine Cables near China



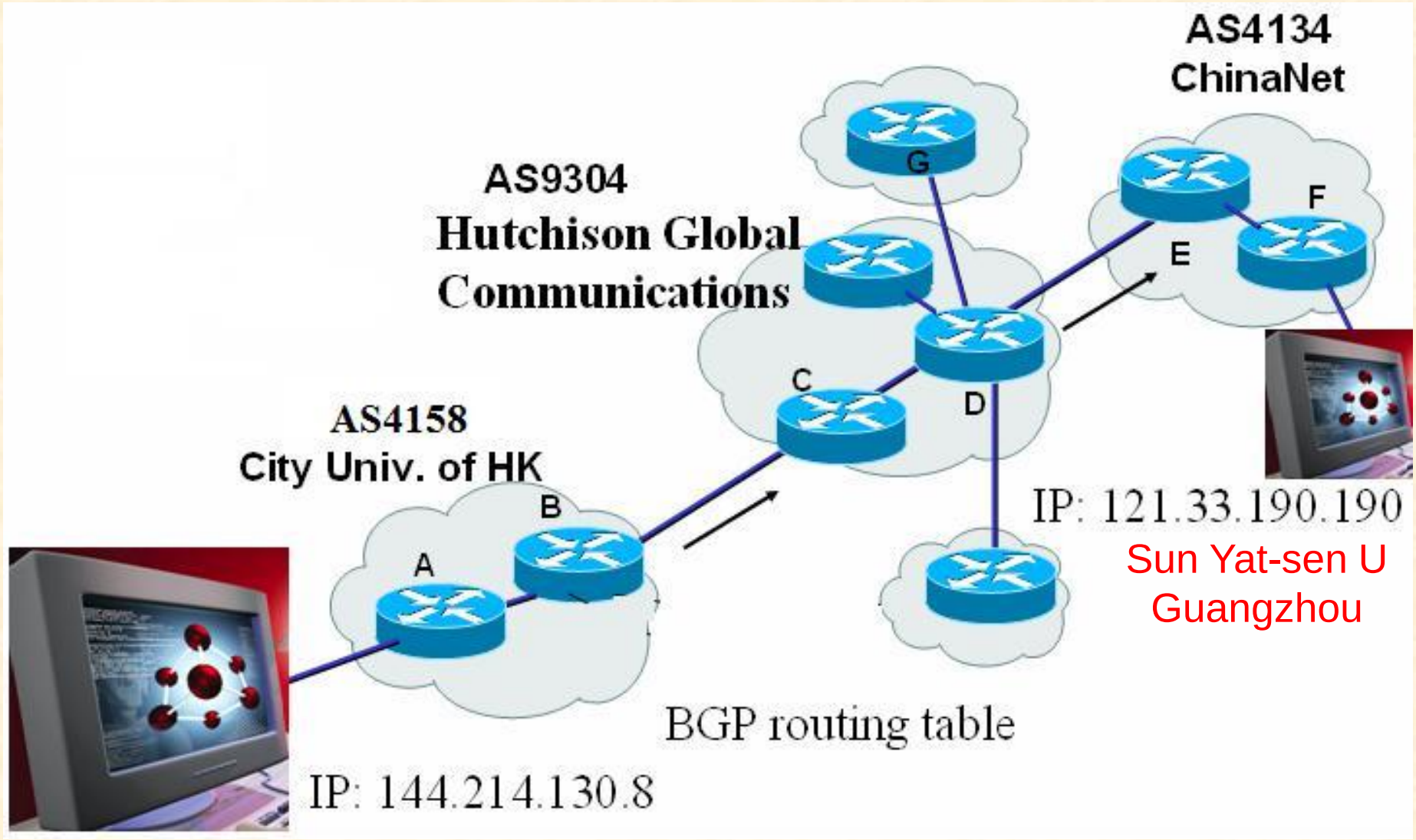
TeleGeography

中国超大容量光传输系统获突破：一根光纤135亿人同时通话

近日，烽火科技在国内首次实现560Tb/s超大容量波分复用及空分复用的光传输系统实验，可以实现一根光纤上67.5亿对人（135亿人）同时通话。

2017年2月5日

A Real Example



Brief History of the Internet

- **1968** - DARPA (Defense Advanced Research Projects Agency) contracts with BBN (Bolt, Beranek & Newman) to create ARPAnet
- **1970** - First ARPAnet had 5 Nodes:

  UCLA
  Stanford
  UC Santa Barbara
  U of Utah
  BBN

DARPA

Leonard Kleinrock (1934 -)

1961 MIT PhD Thesis:

Information Flow in Large Communication Nets

(on queuing theory and packet-switching networks)

Leonard Kleinrock conducted early research in queuing theory, which proved important in packet switching, and he later played a leading role in building and managing the world's first packet-switched network - ARPAnet

In the Press | About | Publications | History | Twitter | Students

Leonard Kleinrock

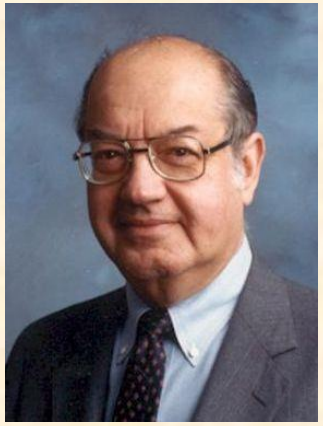
Distinguished Professor
UCLA
Computer Science Department
3732G Boelter Hall
Los Angeles, California 90095
Phone (310) 825-2543
Fax (310) 825-7578
E-mail: lk@cs.ucla.edu

Professor Leonard Kleinrock is Distinguished Professor of Computer Science at UCLA. He developed the mathematical theory of packet networks, the technology underpinning the Internet, while a graduate student at MIT in the period from 1960-1962. The birth of the Internet occurred in his UCLA laboratory (3420 Boelter Hall) when his Host computer became the first node of the Internet in September 1969 and it was from there that he directed the transmission of the first message to pass over the Internet on October 29, 1969.

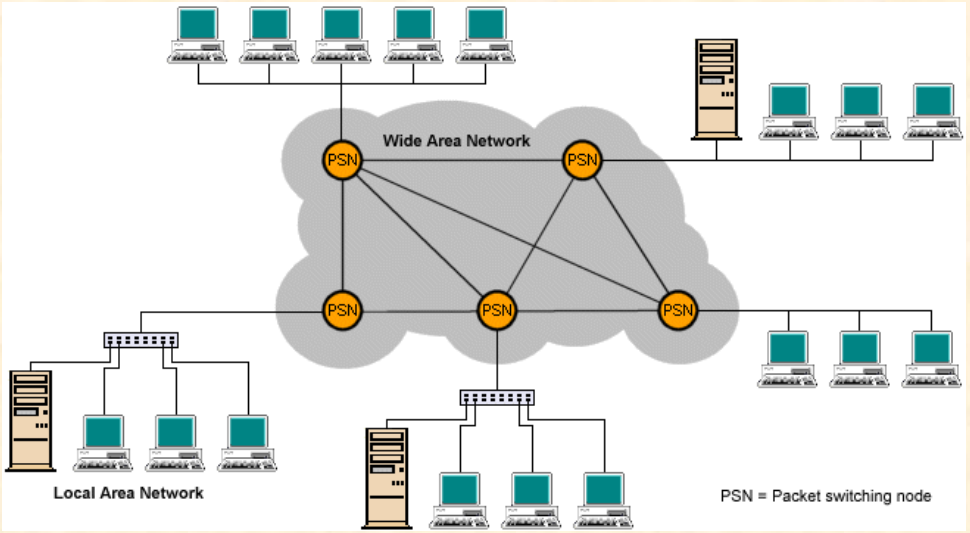
Dr. Kleinrock received his Ph.D. from MIT in 1963. He has served as a Professor of Computer Science at the University of California, Los Angeles since then, serving as Chairman of the department from 1991-1995. He received his BEE degree from CCNY in 1957. and his MS degree from MIT in 1959. He is also the recipient of a number of Honorary Doctorates. He was the first President and Co-founder of Linkabit Corporation, the co-founder of Nomadix, Inc., and Founder and Chairman of TTI/Vanguard, an advanced technology forum organization. He has published over 250 papers and authored six books on a wide array of subjects, including packet switching networks, packet radio networks, local area networks, broadband networks, gigabit networks, nomadic computing, intelligent software agents, performance evaluation, and peer-to-peer networks. During his tenure at UCLA, Dr. Kleinrock has supervised the research for 48 Ph.D. students and numerous M.S. students. These former students now form a core group of the world's most advanced networking experts.

Dr. Kleinrock is a member of the National Academy of Engineering, a member of the American Academy of Arts and Sciences, an IEEE fellow, an ACM fellow, an INFORMS fellow, an IEC fellow a Guggenheim fellow, and a founding member of the Computer Science and Telecommunications Board of the National Research Council. He is recipient of the 2007 National Medal of Science, the L.M. Ericsson Prize, the NAE Charles Stark Draper Prize, the Marconi International Fellowship Award, the Dan David Prize, the Okawa Prize, the IEEE Internet Millennium Award, the ORSA Lanchester Prize, the ACM SIGCOMM Award, the NEC Computer and Communications Award, the Sigma Xi Monie A. Ferst Award, the CCNY Townsend Harris Medal, the CCNY Electrical Engineering Award, the UCLA Outstanding Faculty Member Award, the UCLA Distinguished Teaching Award, the UCLA Faculty Research Lecturer, the INFORMS President's Award, the ICC Prize Paper Award, the IEEE Leonard G. Abraham Prize Paper Award, and the IEEE Harry M. Goode Award.

Packet Switching is a digital networking communication method, which groups all transmitted data – regardless of their content, type or structure – into blocks, called packets

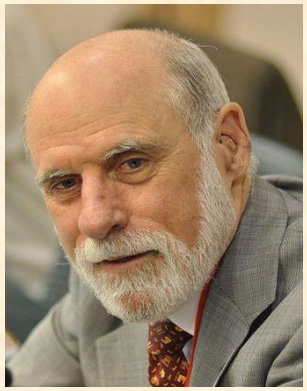


Paul Baran
(1926-2011)



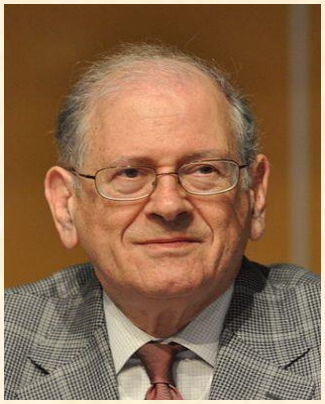
Donald Davies
(1924-2000)

The concept of **switching small blocks of data** was first explored independently by Paul Baran at the RAND Corporation in the US and by Donald Davies at the National Physical Laboratory (NPL) in the UK in the earlier 1960s



Vinton Gray Cerf

(1943 -)



Robert Elliot Kahn

(1938 -)

TCP (Transmission Control Protocol) was invented by Vint Cerf and Bob Kahn in 1974, which was split to TCP and **IP** (Internet Protocol) in 1978

DoD used TCP/IP to inter-connect all networks in 1982, thus the real Internet was considered to be born

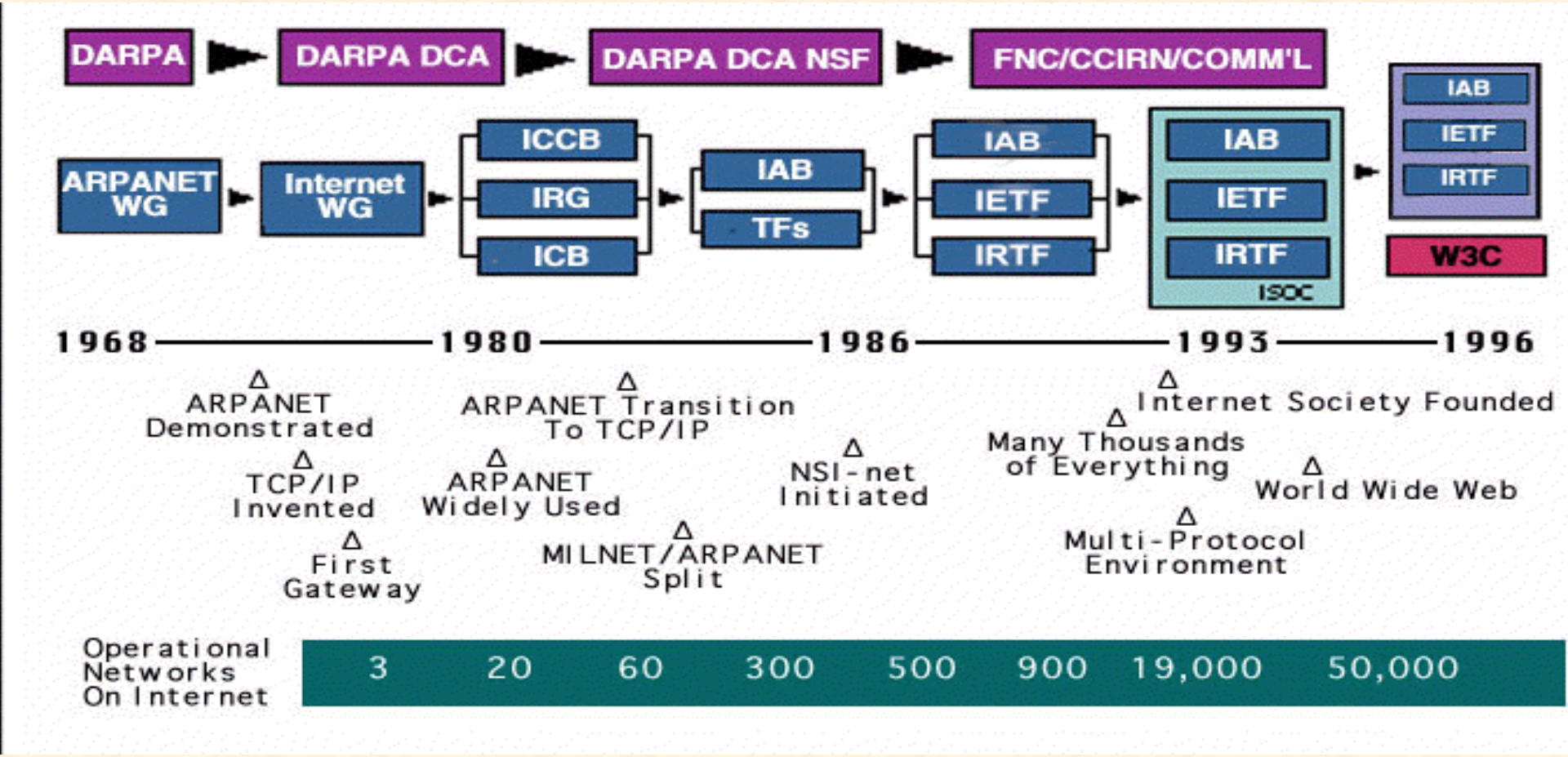
In 1967-1972, Vint Cerf was a graduate student in Kleinrock's lab, working on application level protocols for the ARPAnet (File Transfer Protocol, Telnet Protocol, etc.)

Protocols

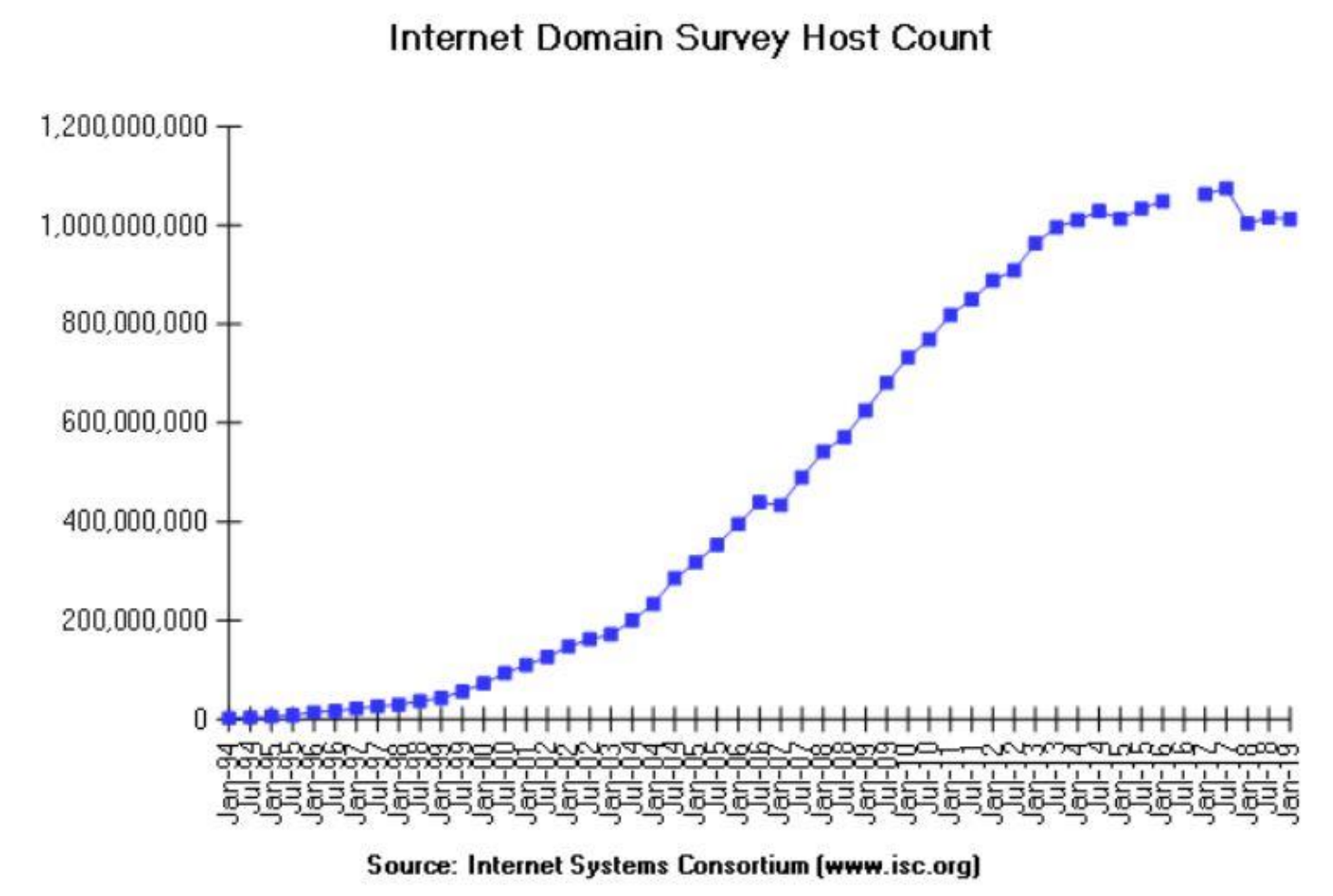
- **Protocol** originates from the Greek word *protocollon*, which was a piece of paper glued to a manuscript to describe its contents.
- In computing and communication systems, a protocol is a set of rules, a convention, or a standard, that controls the connection and data transfer between endpoints.
- **Telecommunication systems:**
  - data interchange protocols at the hardware device level
  - data interchange protocols at the application program level
- **Internet:**
  - Transmission Control Protocol (TCP), for exchanging messages with other Internet points at the information packet level
  - Internet Protocol (IP), for sending and receiving messages at the Internet address level
  - Other protocols: Hypertext Transfer Protocol (HTTP), File Transfer Protocol (FTP), Border Gateway Protocol (BGP), and Dynamic Host Configuration Protocol (DHCP), ...

Earlier History of Internet

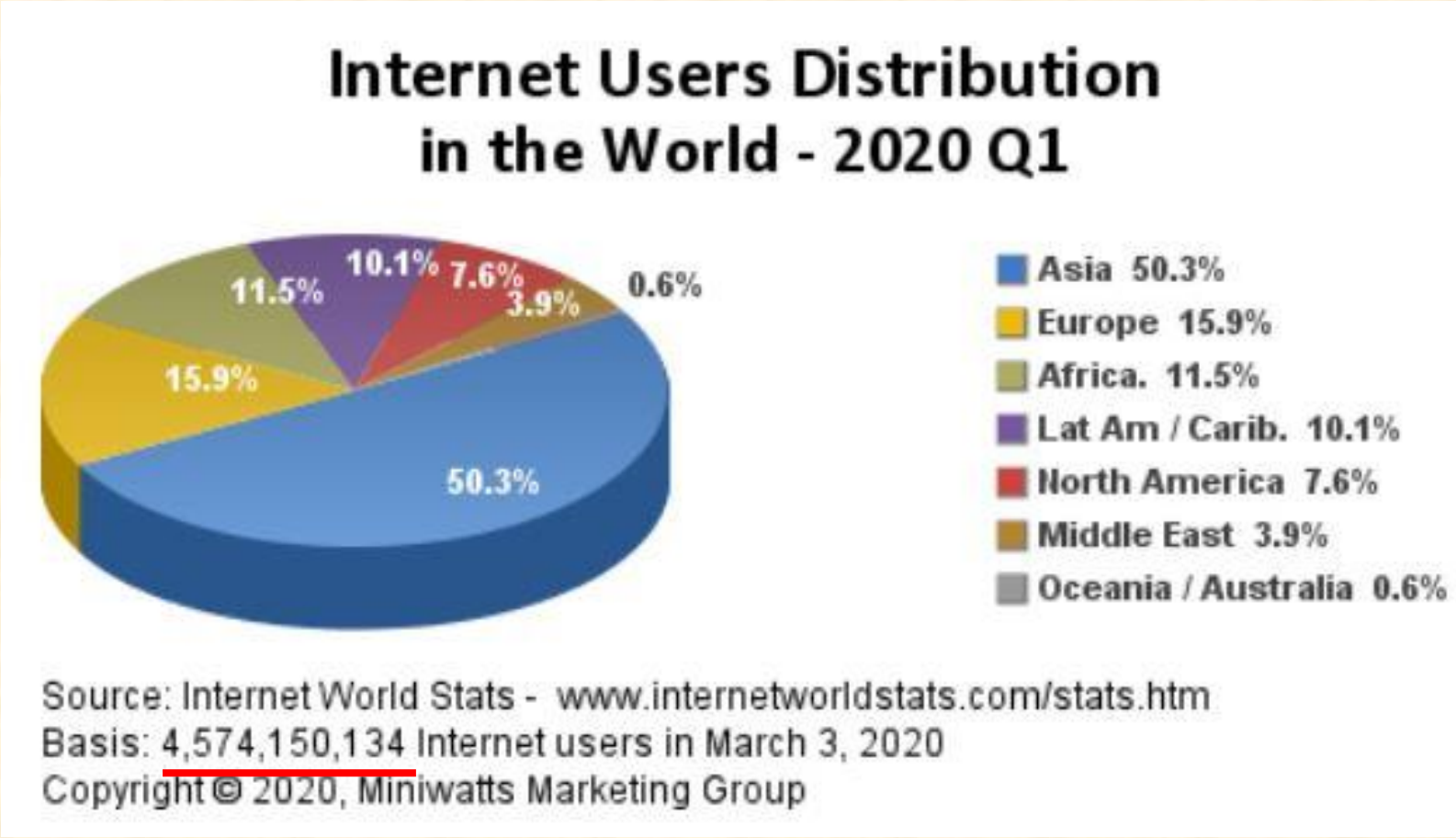
DARPA



Internet today

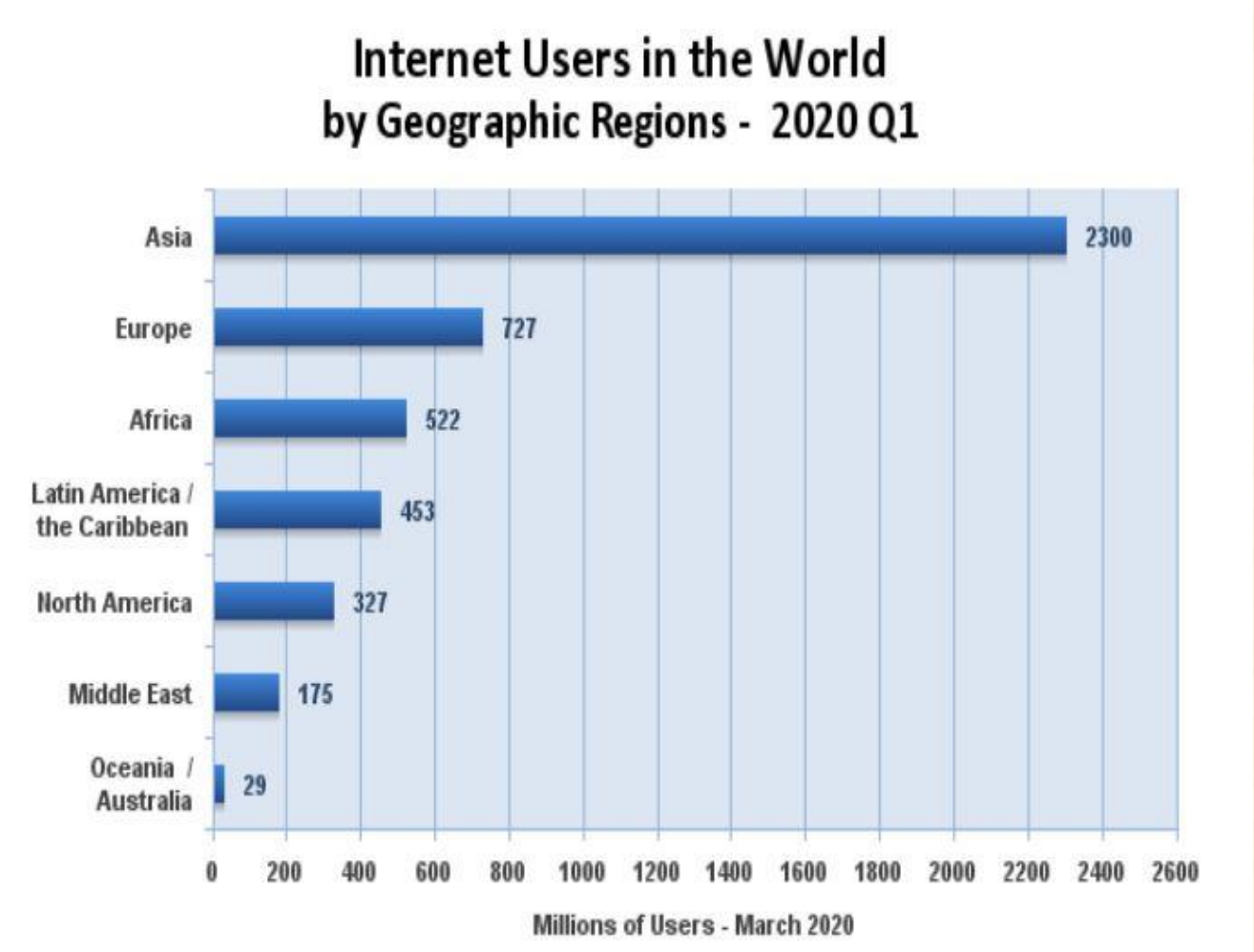


Data Source



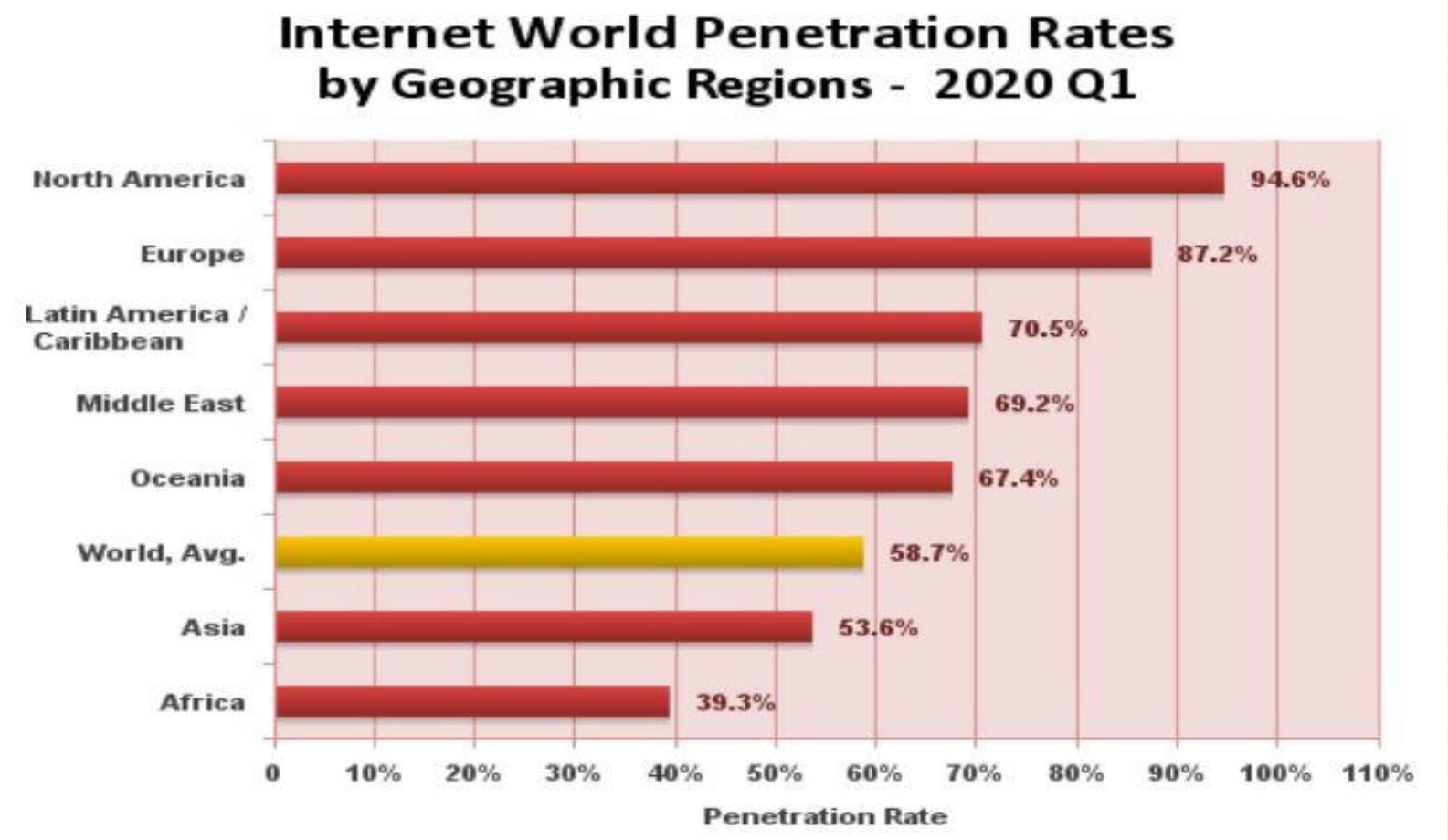
Internet Data

Recent Internet Statistics

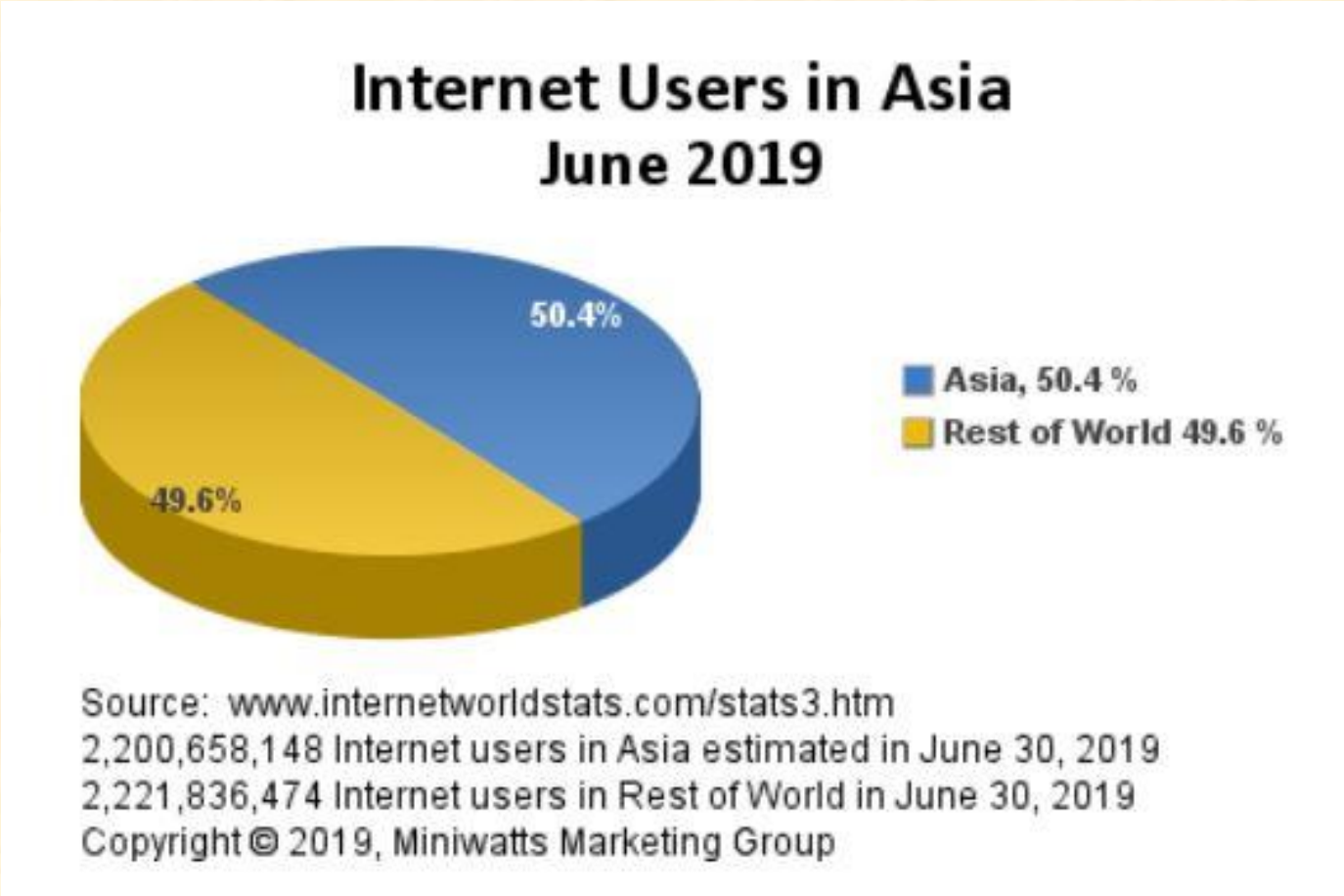


Internet Data

Recent Internet Statistics



Internet Data



Internet Data

Recent Internet Statistics

World Population: > 7,796,949,710

Number of Users: > 4,833,521,806 (62%)

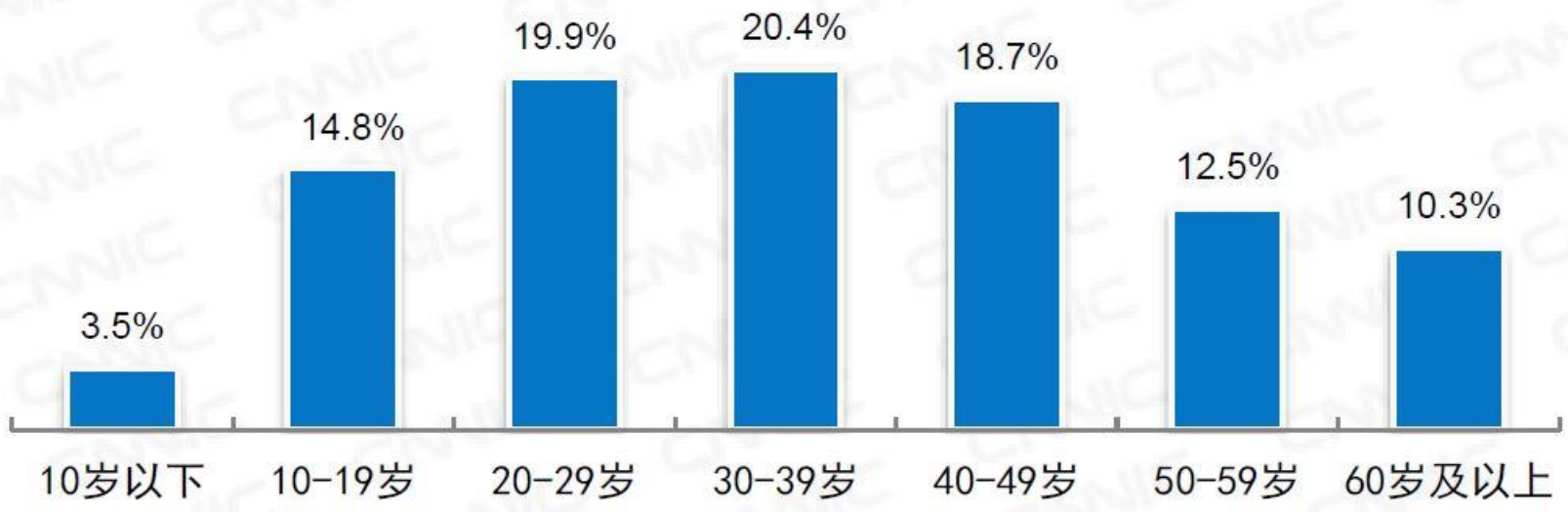
- Annual global IP traffic was 1.5 ZB per year or 122 EB per month in 2017, which will reach 4.8 ZB per year or 396 exabytes (EB) per month by 2022.
- Global IP traffic will increase threefold over the next 5 years, which will reach from 16 GB per capita in 2017 to 50 GB per capita by 2022.

China (in millions): **CNNIC**
Internet Users: 932
iPhone Internet Users: 930
IPv4 Addresses: 386
IPv6 Addresses: 50903 (#1 in world)
Domain Names: 2304

Recent Internet Statistics

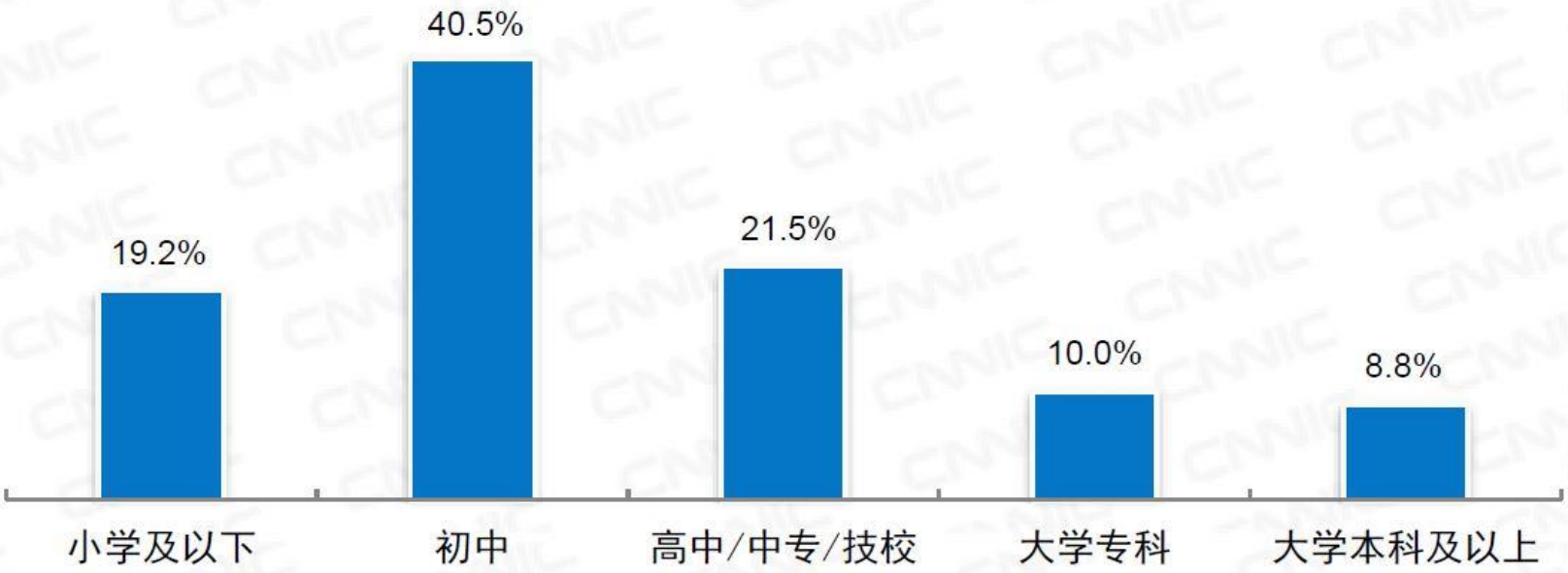

手机网民规模及其占网民比例
单位：万人
96.3%
97.5%
98.3%
98.6%
99.1%
99.3%
99.2%
72361
75265
78774
81698
84681
89690
93236
2017. 6
2017. 12
2018. 6
2018. 12
2019. 6
2020. 3
2020. 6
手机网民规模
手机网民占整体网民比例
来源：CNNIC 中国互联网络发展状况统计调查
2020.6

网民年龄结构



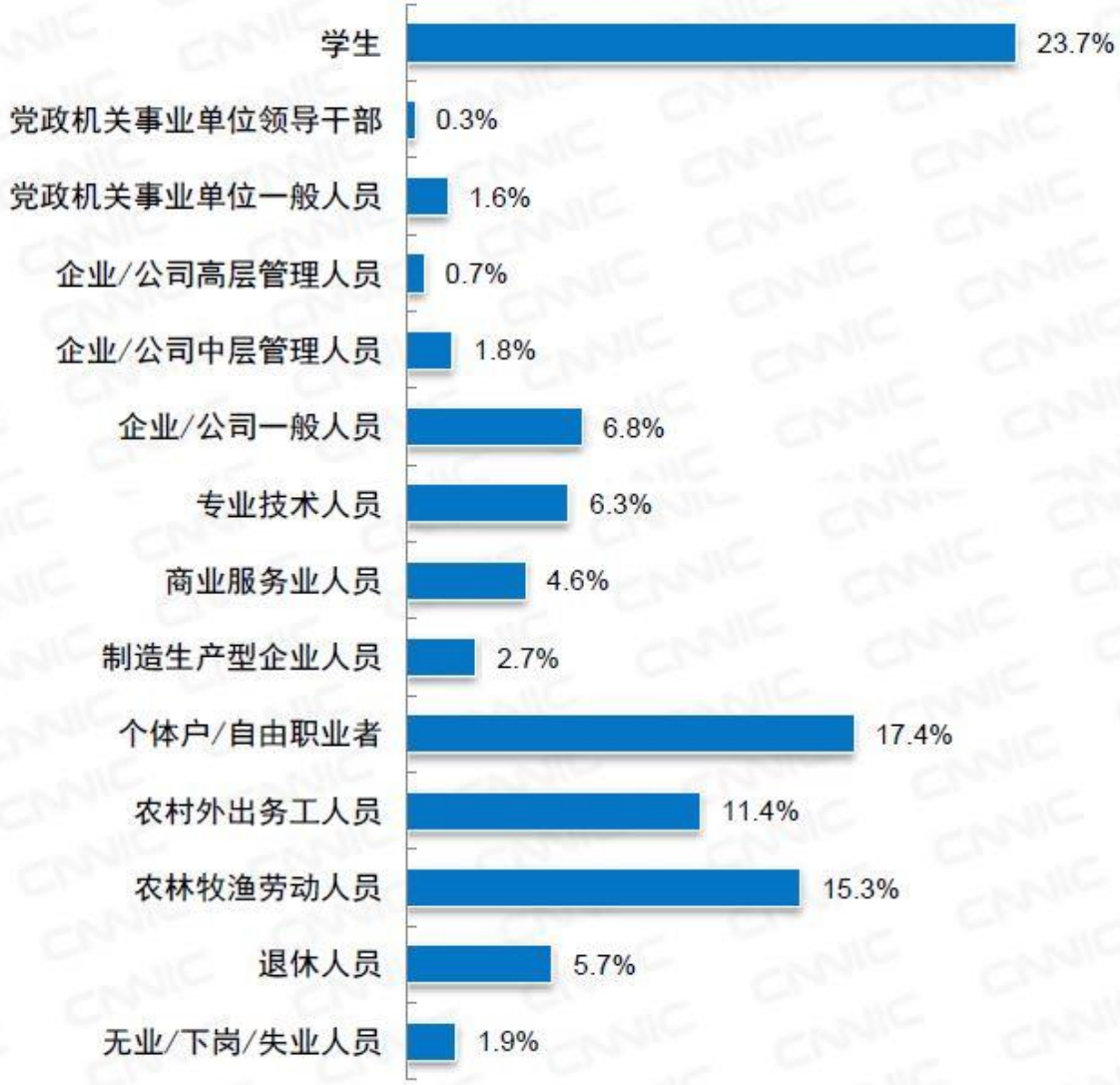
来源：CNNIC 中国互联网络发展状况统计调查 2020.6

网民学历结构



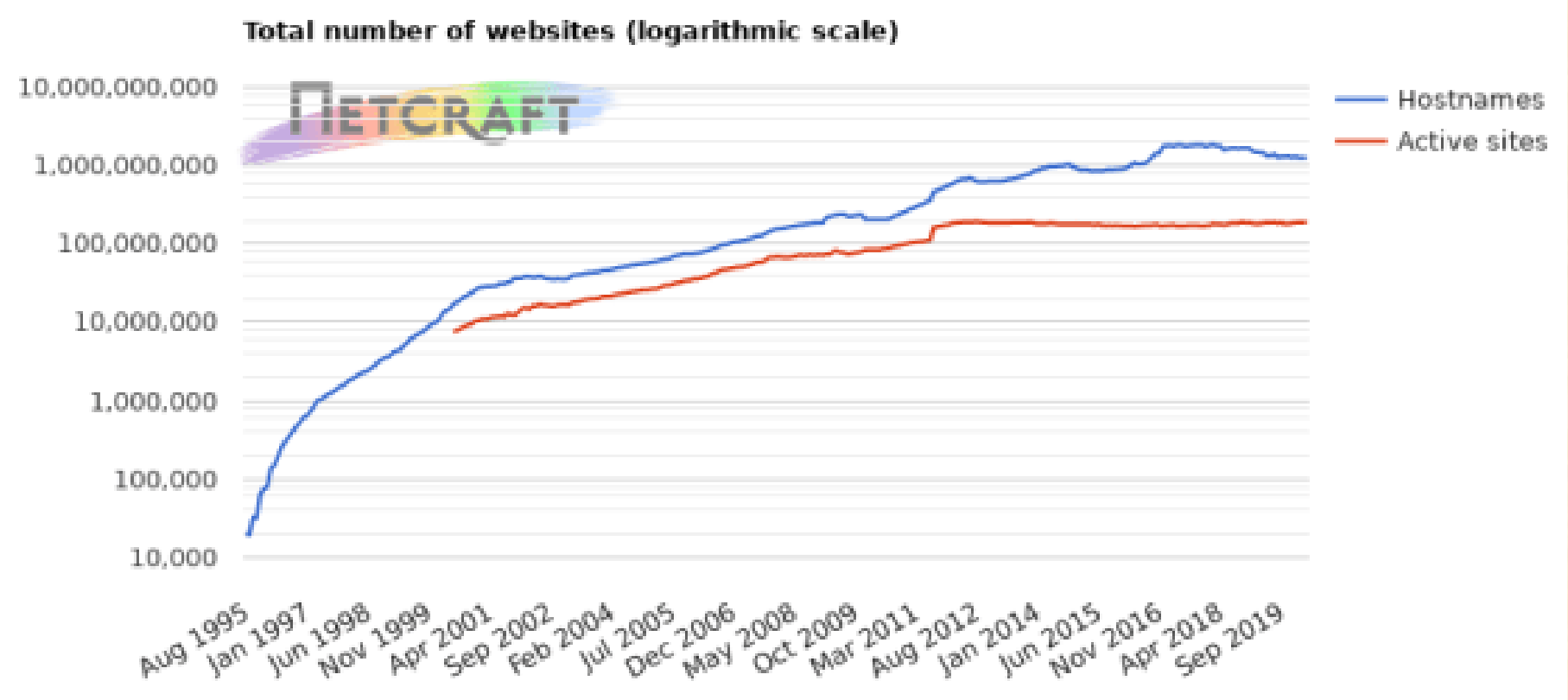
来源：CNNIC 中国互联网络发展状况统计调查 2020.6

网民职业结构



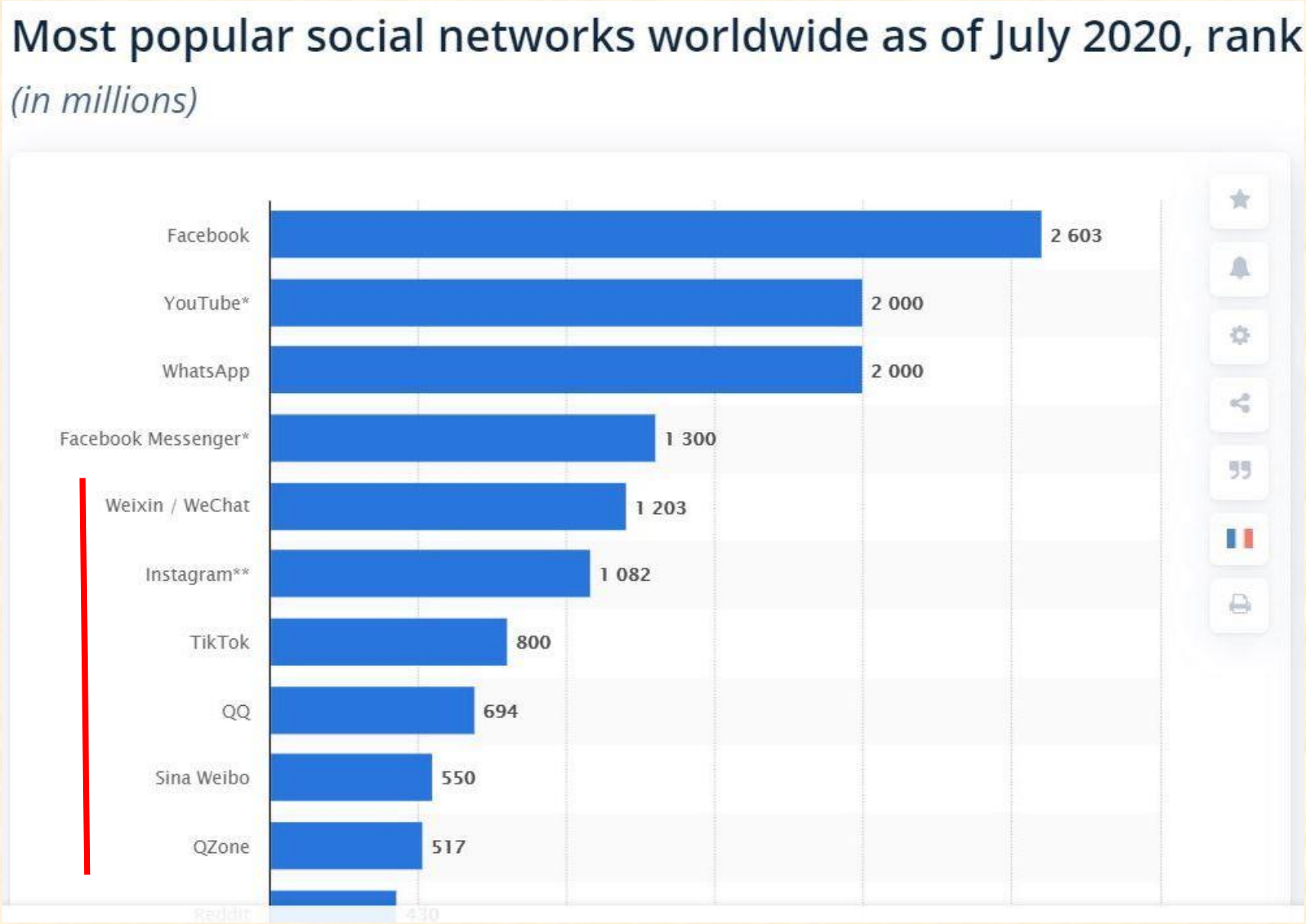
来源：CNNIC 中国互联网络发展状况统计调查 2020.6

Internet Websites

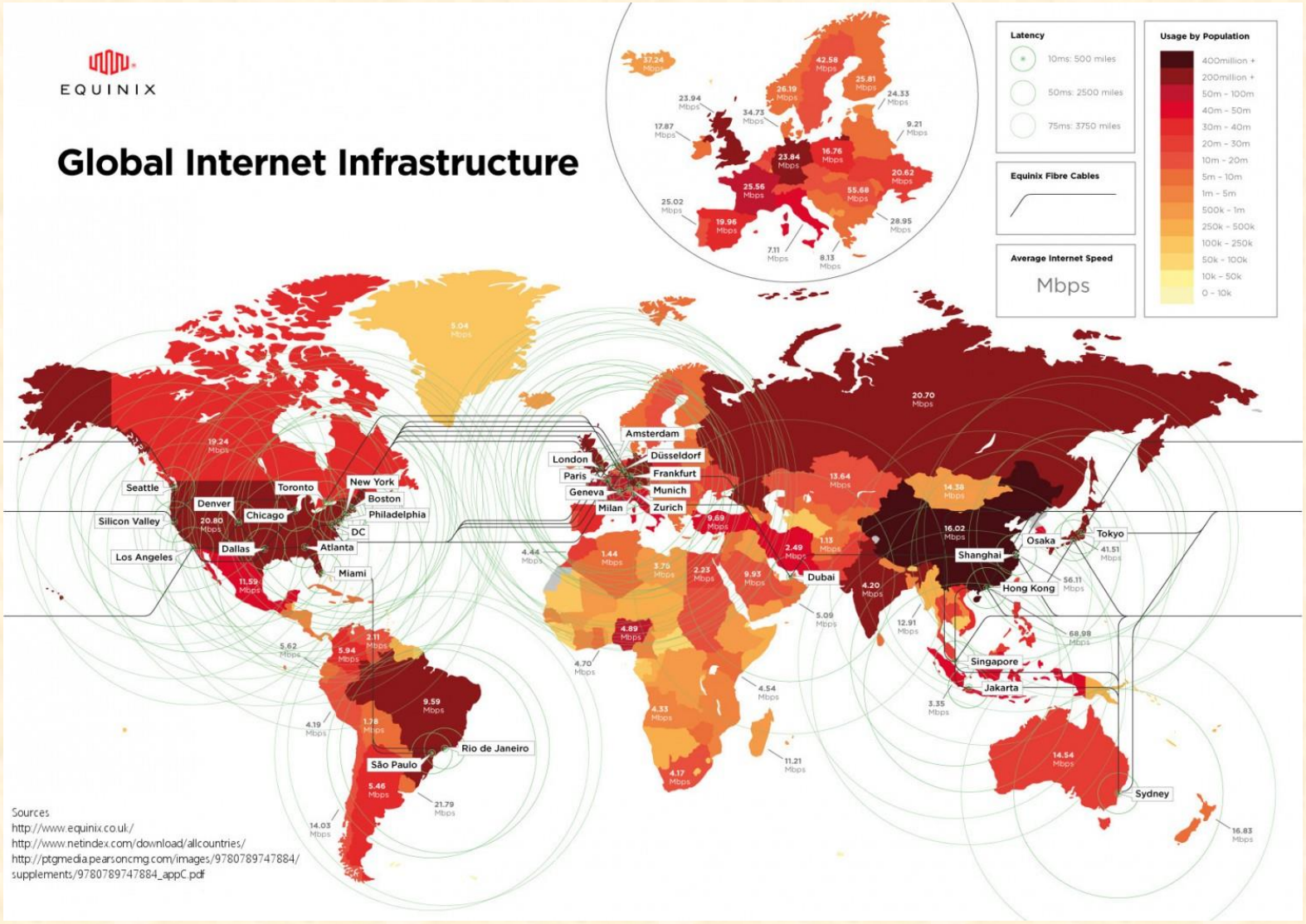


Netcraft Websites online right now > 1.7 billion today

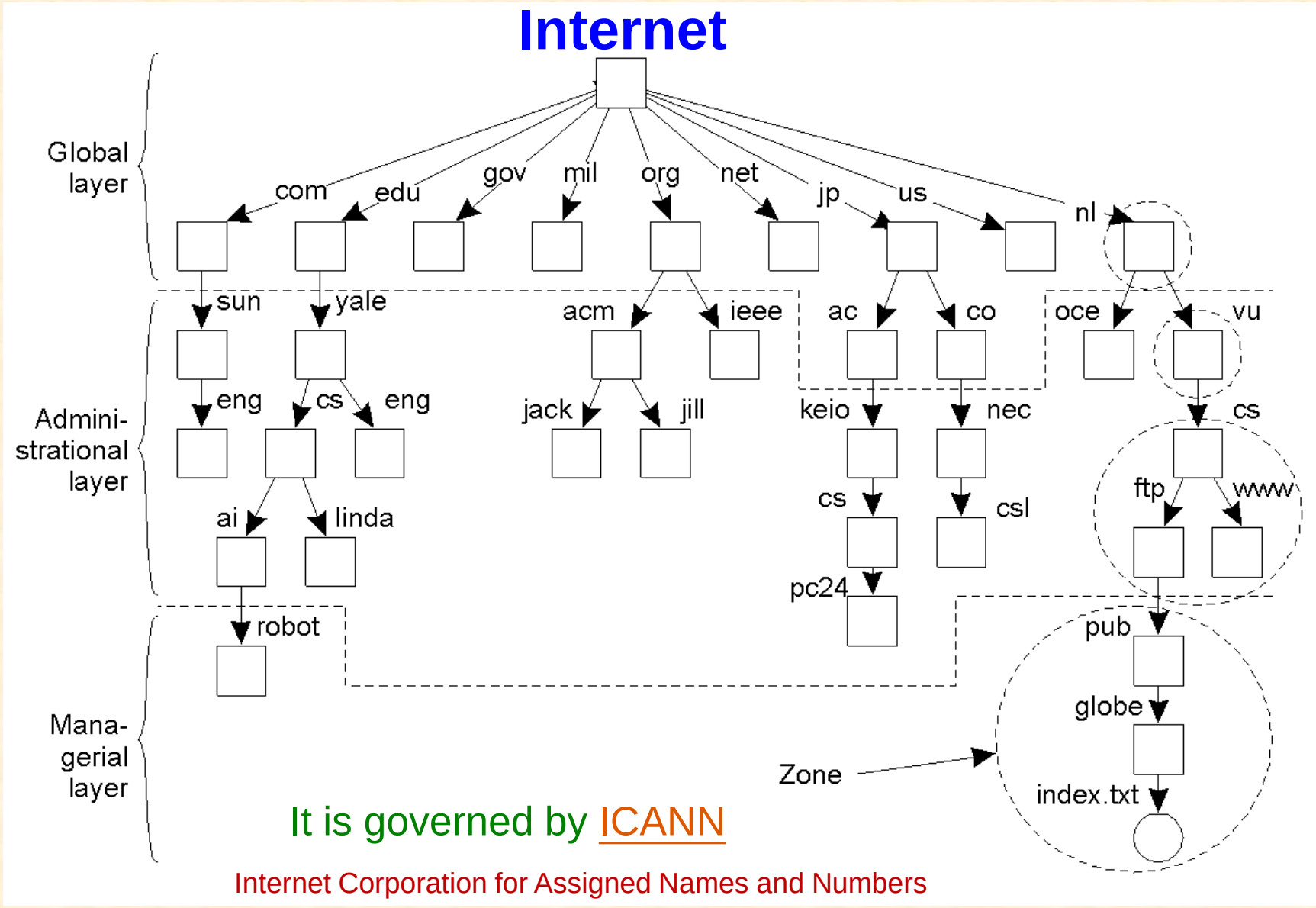
Internet Social Media Websites



Internet Topology



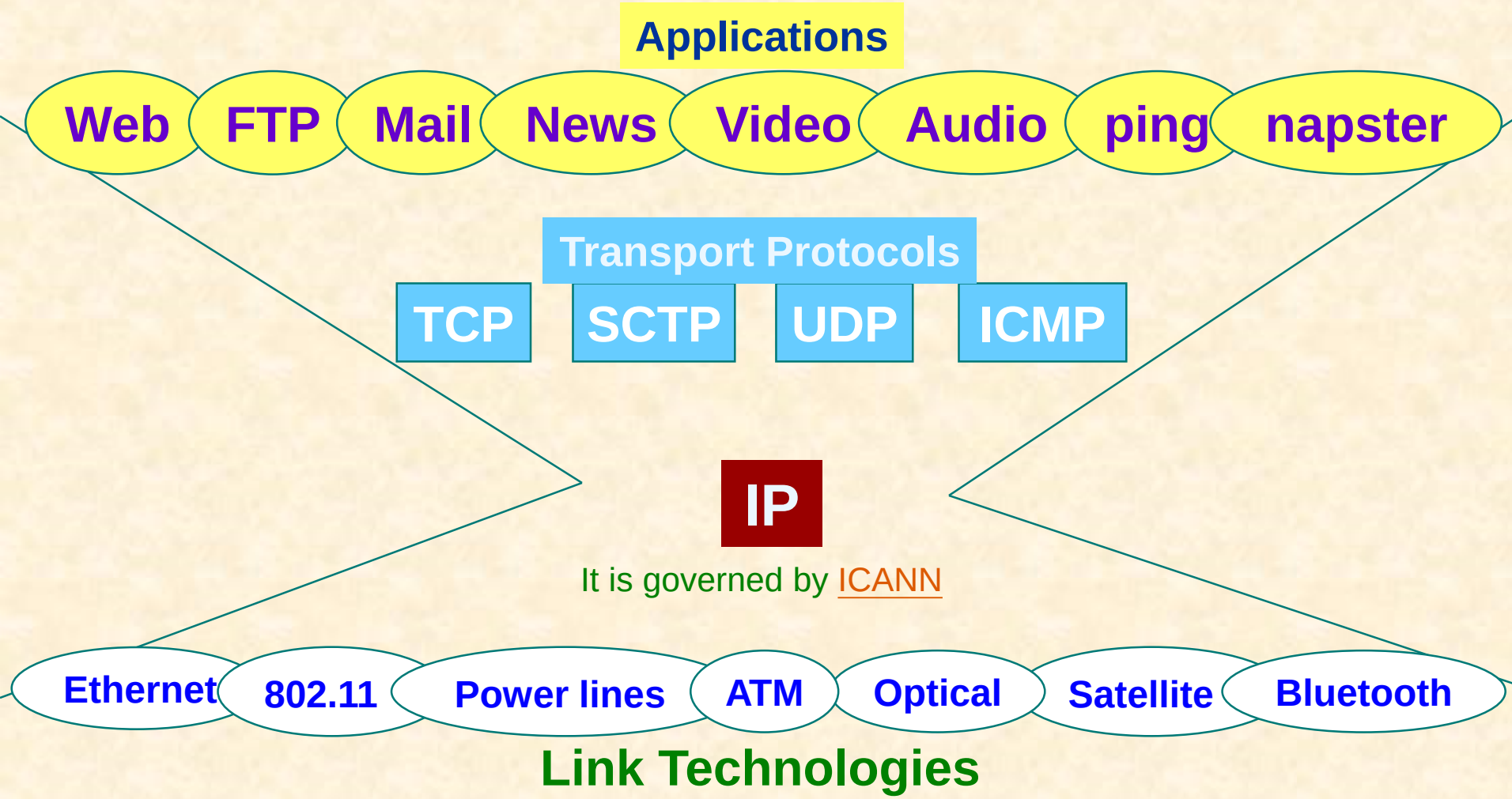
Internet Structure



It is governed by ICANN

Internet Corporation for Assigned Names and Numbers

Internet

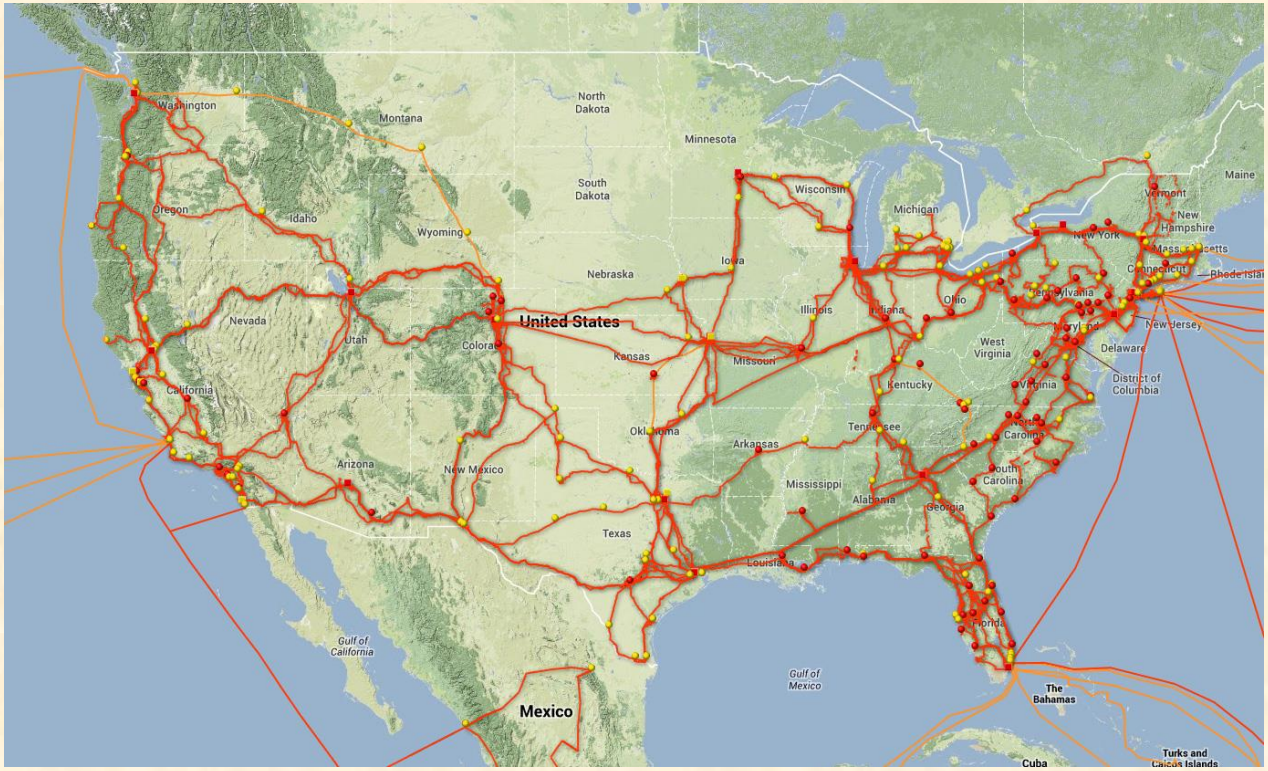

Applications
Web
FTP
Mail
News
Video
Audio
ping
napster
Transport Protocols
TCP
SCTP
UDP
ICMP
IP
It is governed by ICANN
Ethernet
802.11
Power lines
ATM
Optical
Satellite
Bluetooth
Link Technologies

Internet

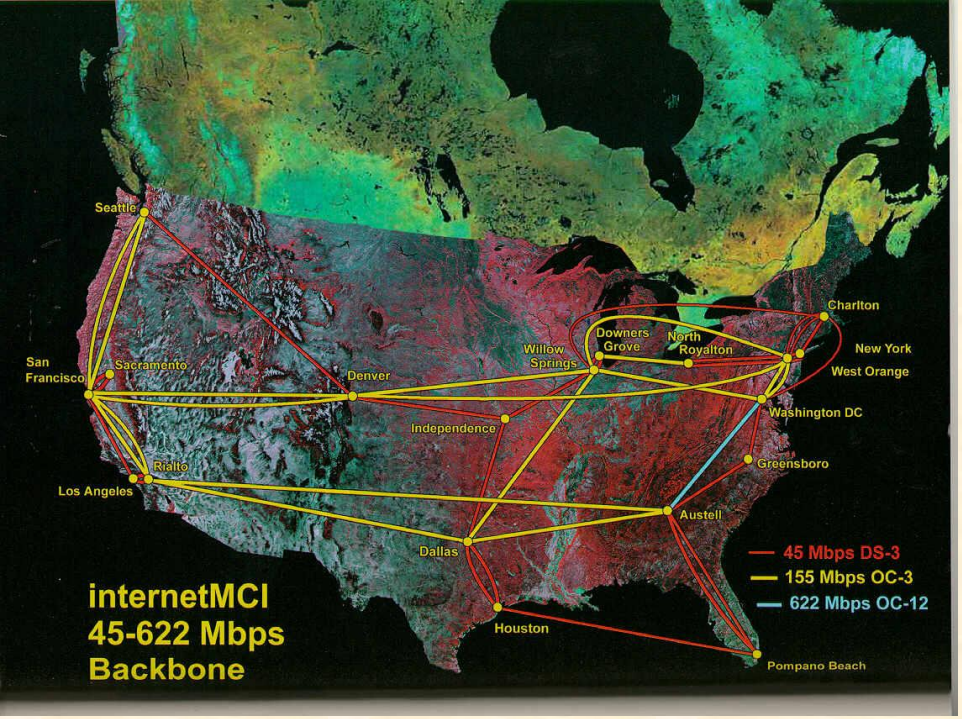
USA Backbone

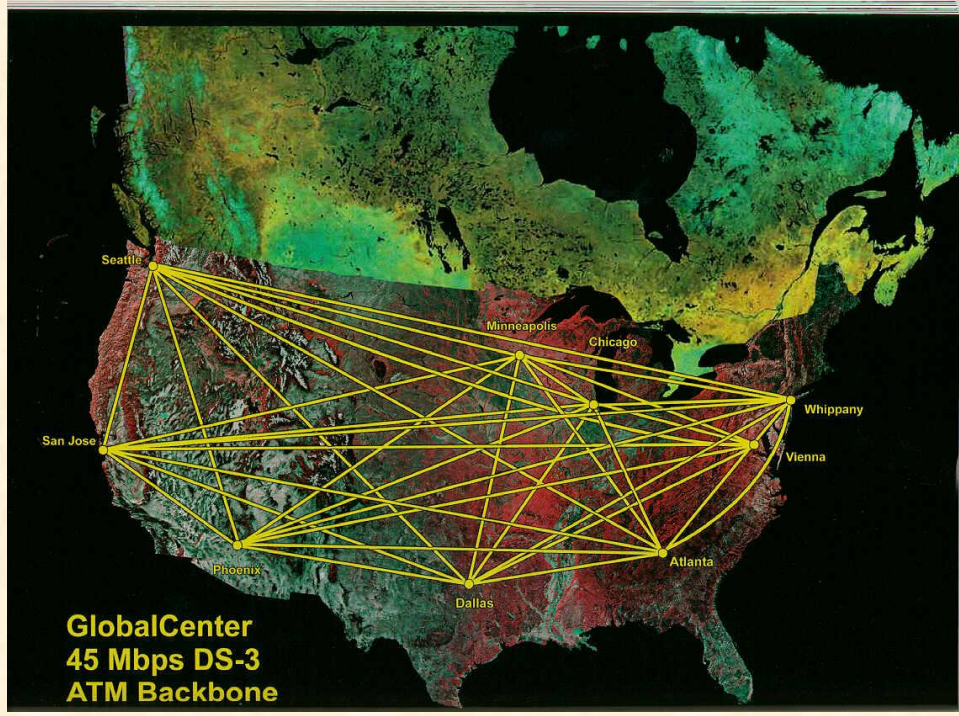
(2001) Shares in USA:

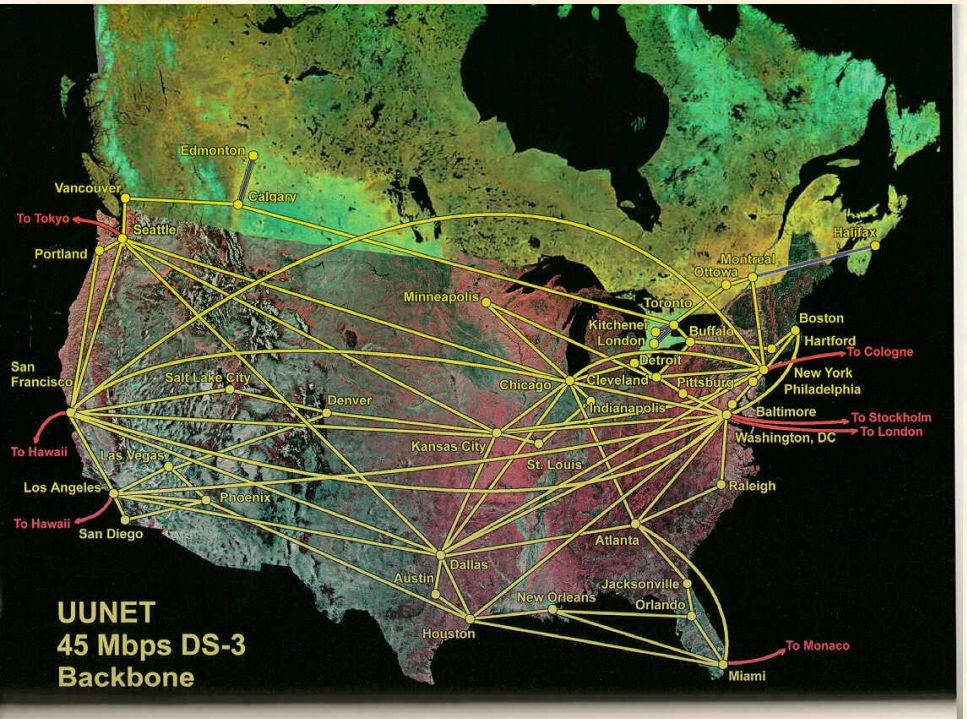
27.9% - UUNET/WorldCom/MCI
10.0% - AT&T
6.5% - Sprint
6.3% - Genuity
4.1% - PSINet
3.5% - Cable & Wireless
2.8% - XO Communications
2.6% - Verio
1.5% - Qwest
1.3% - Global Crossing

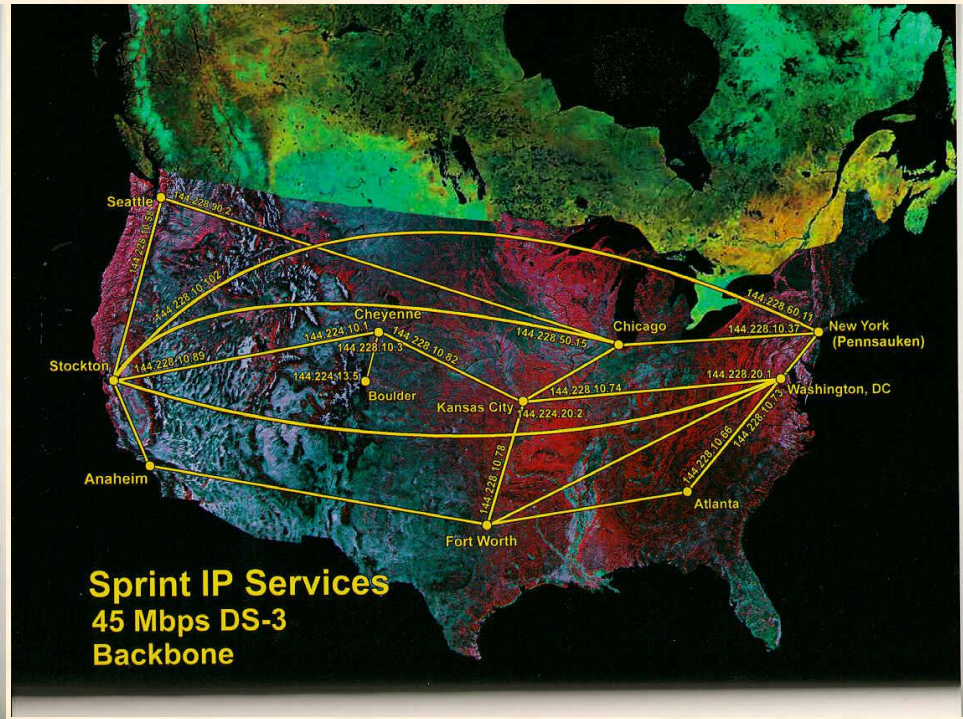


Today: UUNET, Level 3, Verizon, AT&T, Qwest, Sprint, IBM, …

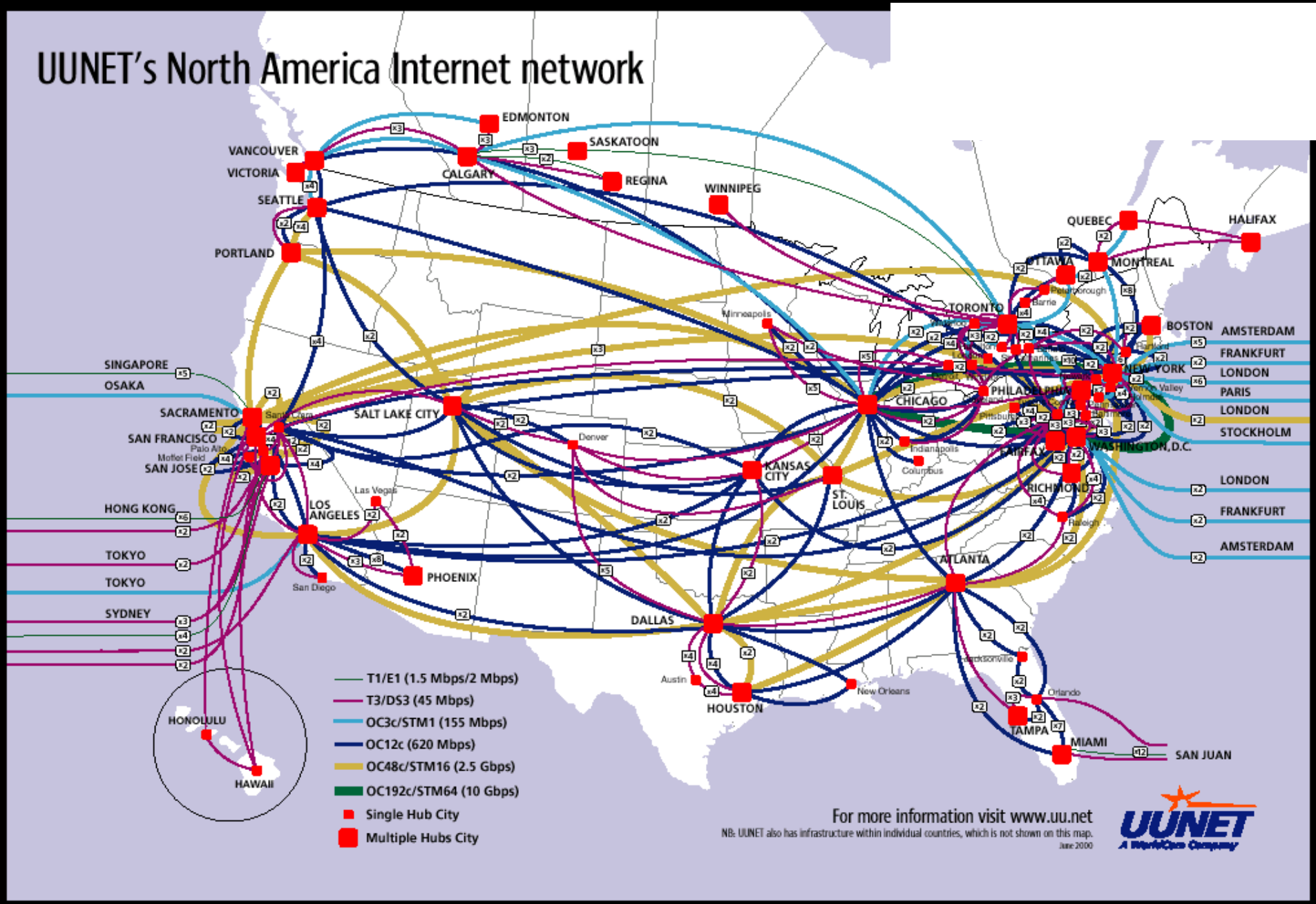

Seattle
San Francisco
Sacramento
Denver
Willow Springs
Downers Grove
North Royalton
Charlton
New York
West Orange
Washington DC
Independence
Greensboro
Rialto
Los Angeles
Austell
Dallas
Houston
Pompano Beach
45 Mbps DS-3
155 Mbps OC-3
622 Mbps OC-12
internetMCI
45-622 Mbps
Backbone


Seattle
Minneapolis
Chicago
San Jose
Whippany
Vienna
Phoenix
Atlanta
Dallas
GlobalCenter
45 Mbps DS-3
ATM Backbone

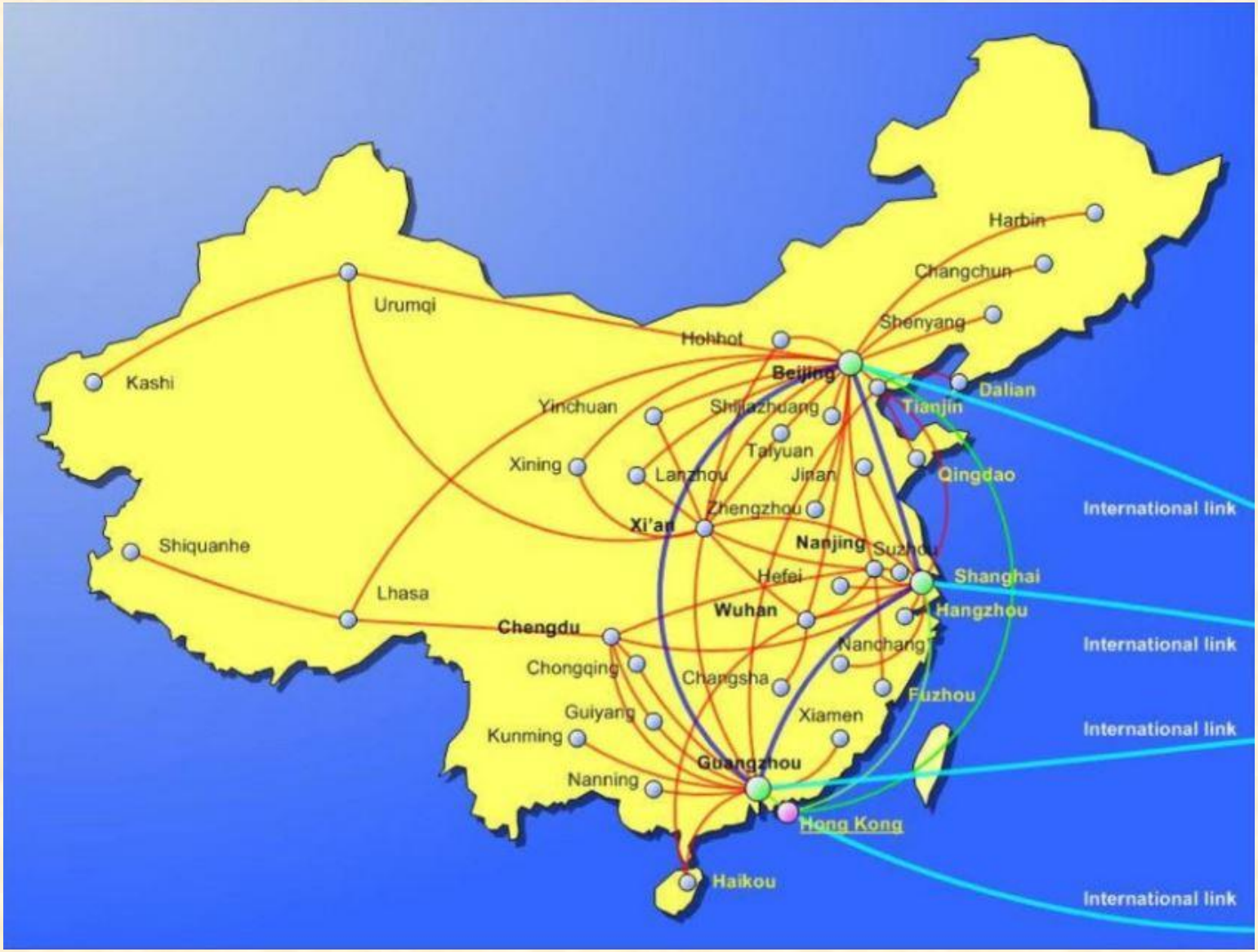

Edmonton
Vancouver
Calgary
To Tokyo
Seattle
Portland
Halifax
Montreal
Ottowa
Minneapolis
Toronto
Kitchener
London
Buffalo
Boston
Hartford
To Cologne
Detroit
New York
Philadelphia
San Francisco
Salt Lake City
Chicago
Cleveland
Pittsburg
Denver
Indianapolis
Baltimore
To Stockholm
To London
Washington, DC
To Hawaii
Las Vegas
Kansas City
St. Louis
Raleigh
Los Angeles
Phoenix
To Hawaii
San Diego
Atlanta
Dallas
Austin
Jacksonville
New Orleans
Orlando
Houston
To Monaco
Miami
UUNET
45 Mbps DS-3
Backbone


Seattle
144.228.90.2
144.228.10.102
144.228.10.89
Stockton
Cheyenne
144.224.10.1
144.228.10.3
144.224.13.5
Boulder
144.228.10.83
144.228.50.15
Chicago
144.228.60.11
144.228.10.37
New York
(Pennsauken)
144.228.20.1
Washington, DC
144.228.10.74
Kansas City
144.224.20.2
Anaheim
144.228.10.78
Fort Worth
144.228.10.66
144.228.10.18
Atlanta
Sprint IP Services
45 Mbps DS-3
Backbone

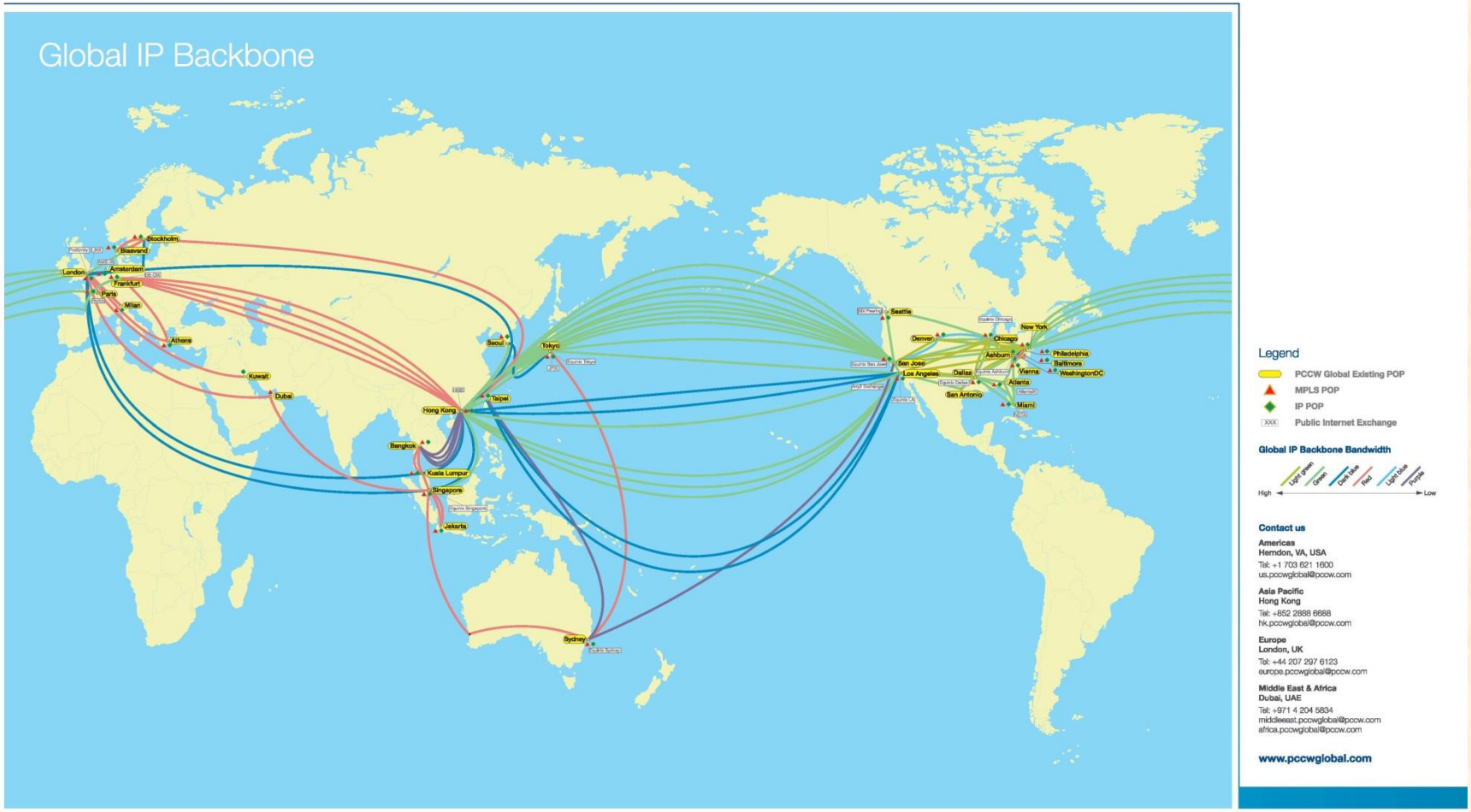
UUNET was founded in 1987: one of the largest Internet service providers and one of the nine Tier-1 networks



China

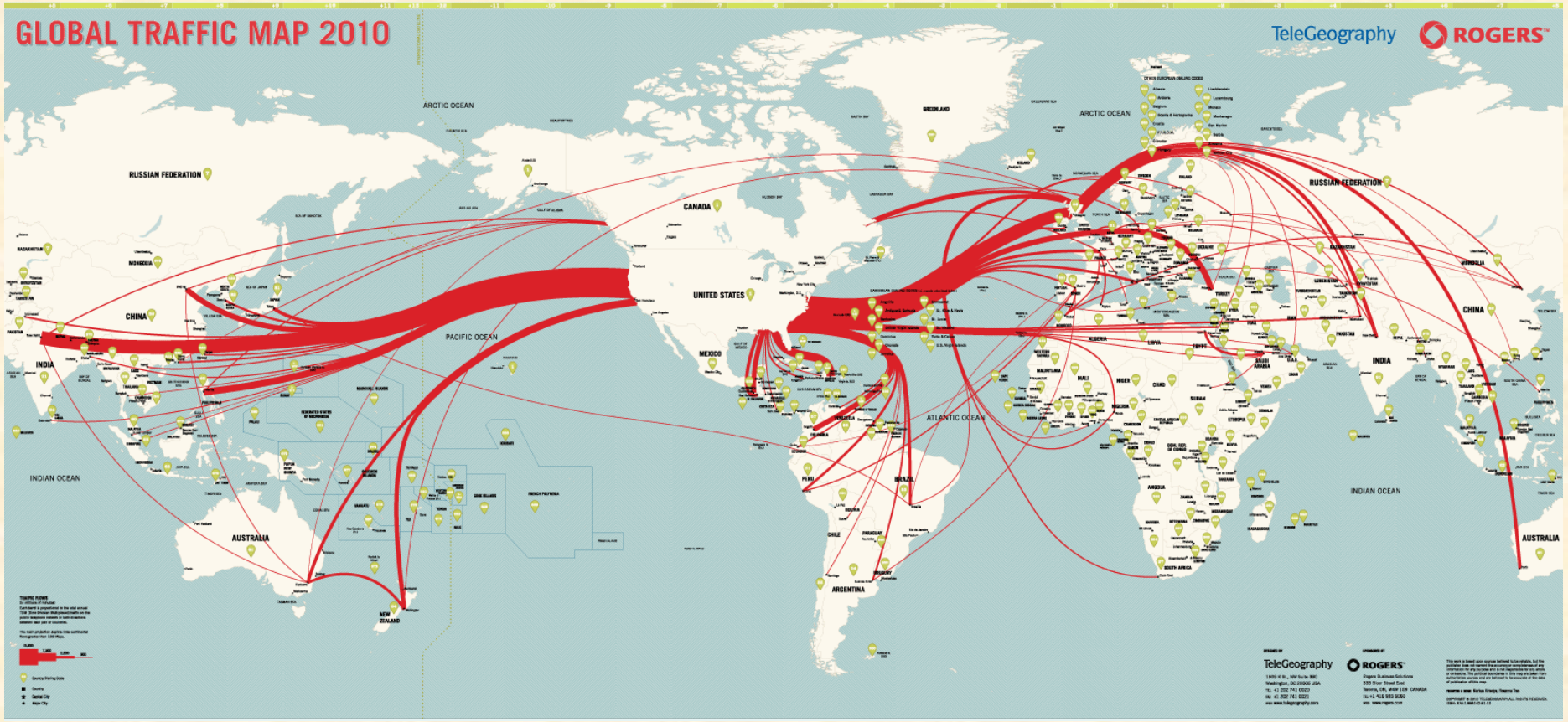

Harbin
Changchun
Shenyang
Urumqi
Hohhot
Beijing
Dalian
Kashi
Yinchuan
Shijiazhuang
Tianjin
Taiyuan
Xining
Lanzhou
Jinan
Qingdao
Zhengzhou
International link
Xi'an
Shiquanhe
Nanjing
Suzhou
Hefei
Shanghai
Lhasa
Wuhan
Hangzhou
Chengdu
Nanchang
International link
Chongqing
Changsha
Fuzhou
Guiyang
Xiamen
International link
Kunming
Guangzhou
Nanning
Hong Kong
Haikou
International link

Hong Kong



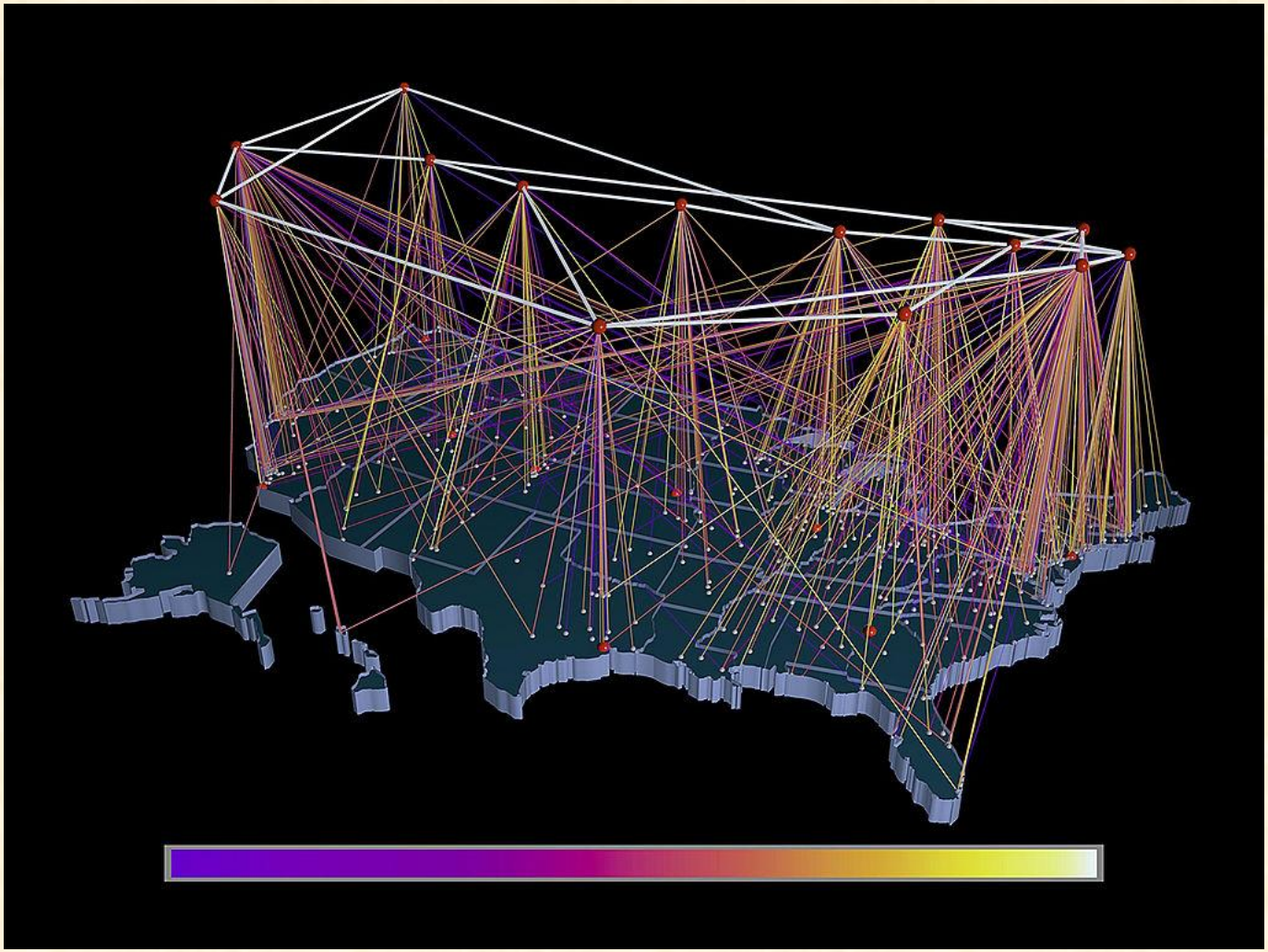
To Connect & Serve

PCCW Global



TeleGeography

NSFNET Traffic (1991)

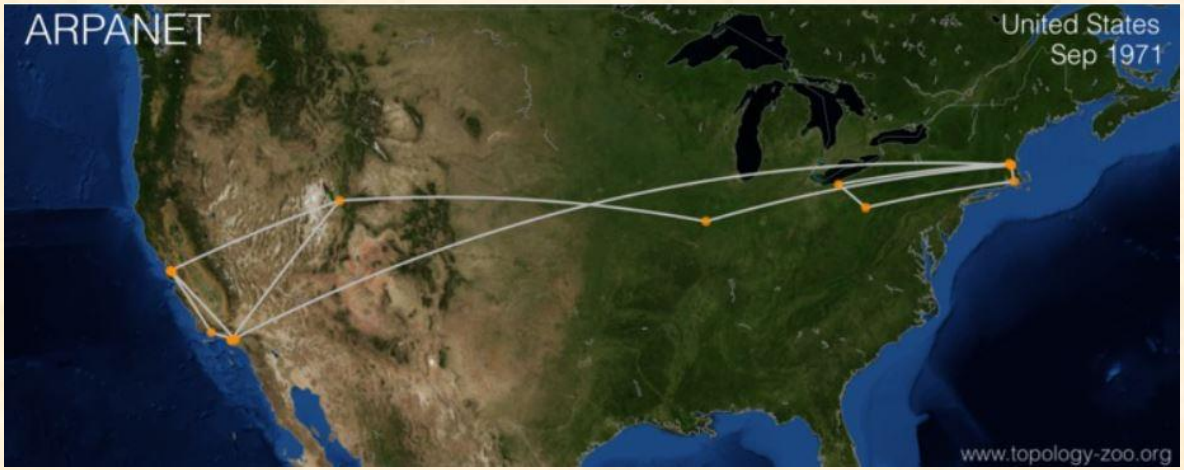


The Internet Topology Zoo

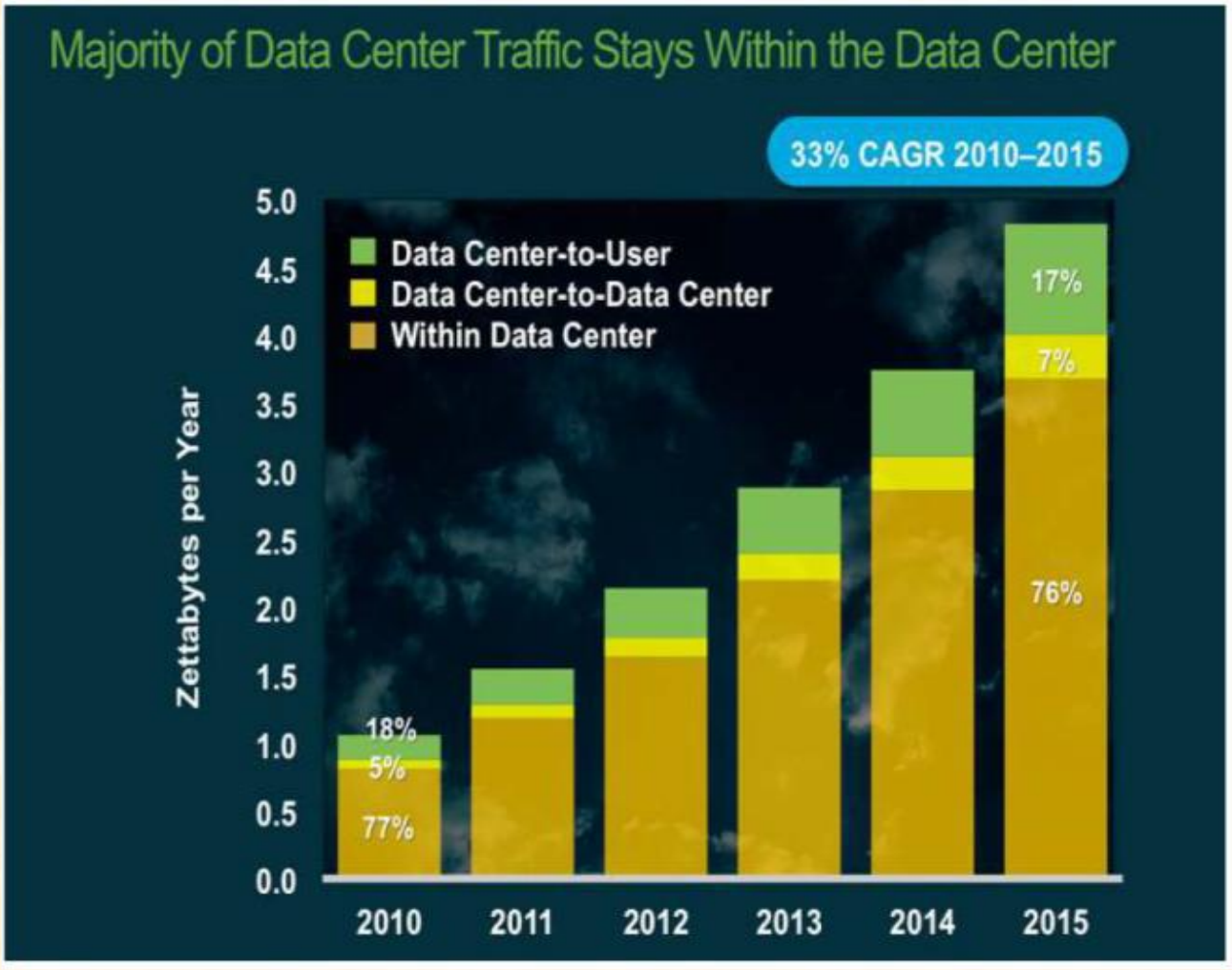
University of Adelaide, Australia

The Internet Topology Zoo is a store of network data created from the information that network operators make public.

As such it is the most accurate large-scale collection of network topologies available, and includes meta-data that couldn't have been measured.



Traffic within the Data Center



Data Centers in Hong Kong

Colocation Hong Kong

» Index » Hong Kong » Hong Kong

Currently there are **41** colocation data centers from Hong Kong (Hong Kong) in Hong Kong.
Save the trouble of contacting the providers, check out our **quote service**.

SunnyVision Data Center

SunnyVision Limited
18/F Well Tech Centre, 9 Pat Tat Street
00852 San Po Kong
HK, Hong Kong

» Visit website
» View profile

Short description:
Hong Kong Internet Data Center- With the ideal env
facilities, and professional services provided by the S
customers can concentrate on their business explora

*SunnyVision Limited is a **premium member** of*

Hong Kong Financial Data Center

NTT Communications Corporation

NA Hong Kong
Hong Kong

» Visit website
» View profile

Short description:
This is a Tier IV ready Data Center infrastructure in
and ultra-low latency network solution,

Hong Kong Kwai Chung Data Center

NTT Communications Corporation

NA Hong Kong
Hong Kong

» Visit website
» View profile

solana.hk

solana.hk
1 On Yip Street
Chaiwan Hong Kong
Hong Kong

» Visit website

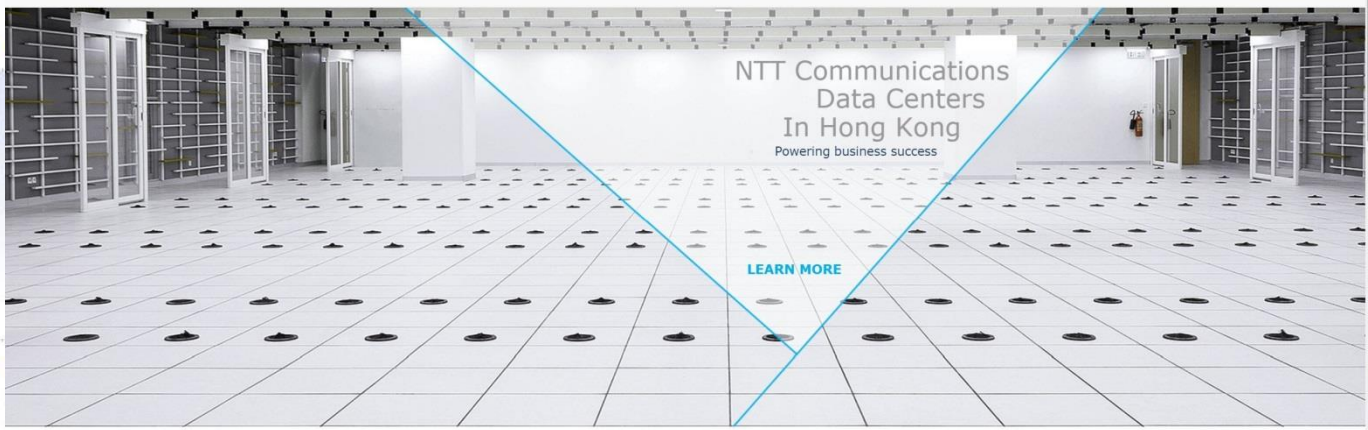
中華人民共和國香港特別行政區政府
The Government of the Hong Kong Special Administrative Region of the People's Republic of China

ENGLISH | 繁體版 | 简体版

HONG KONG

NTT Communications

ENG 中文

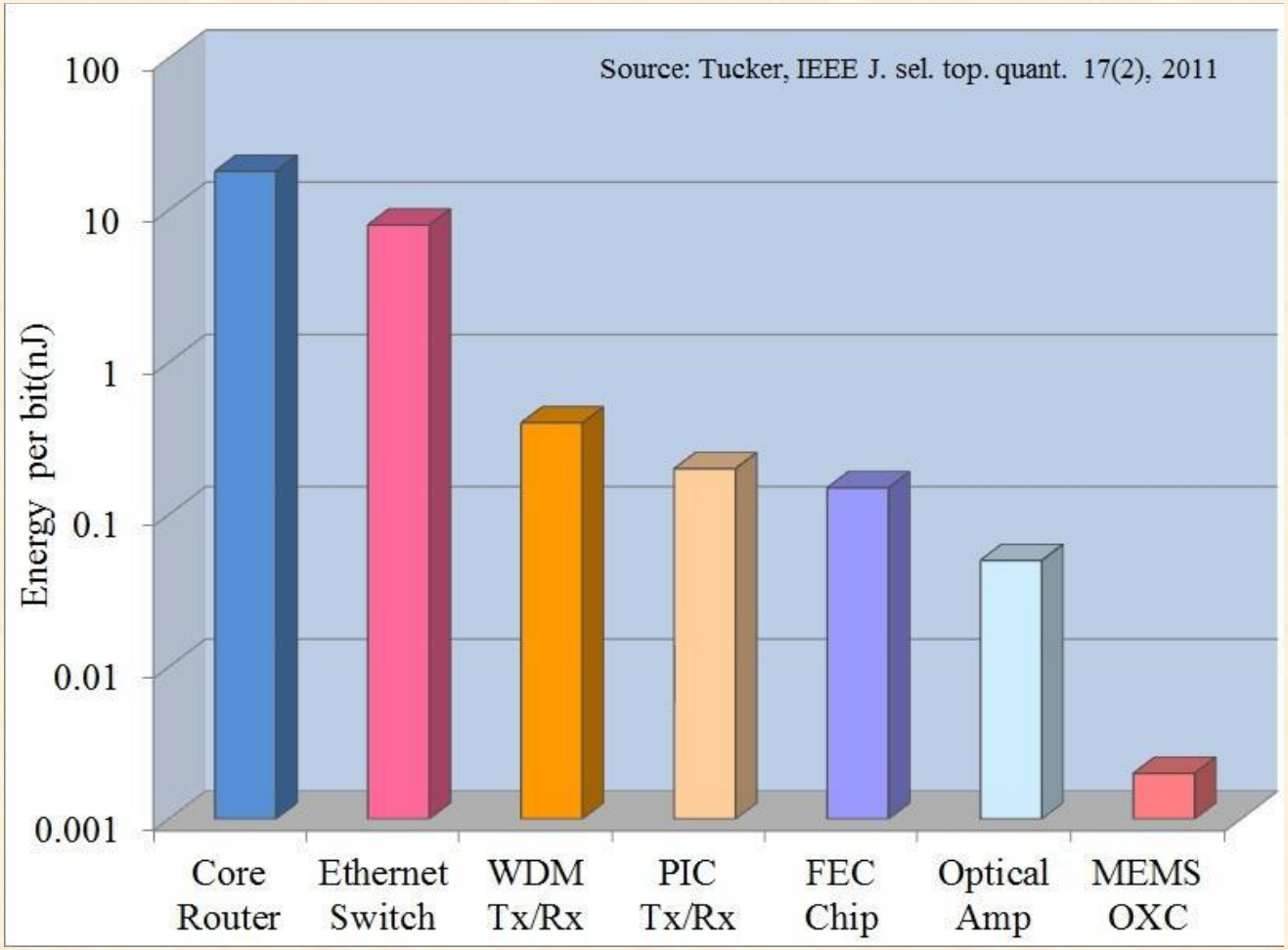


Data Centers in Hong Kong

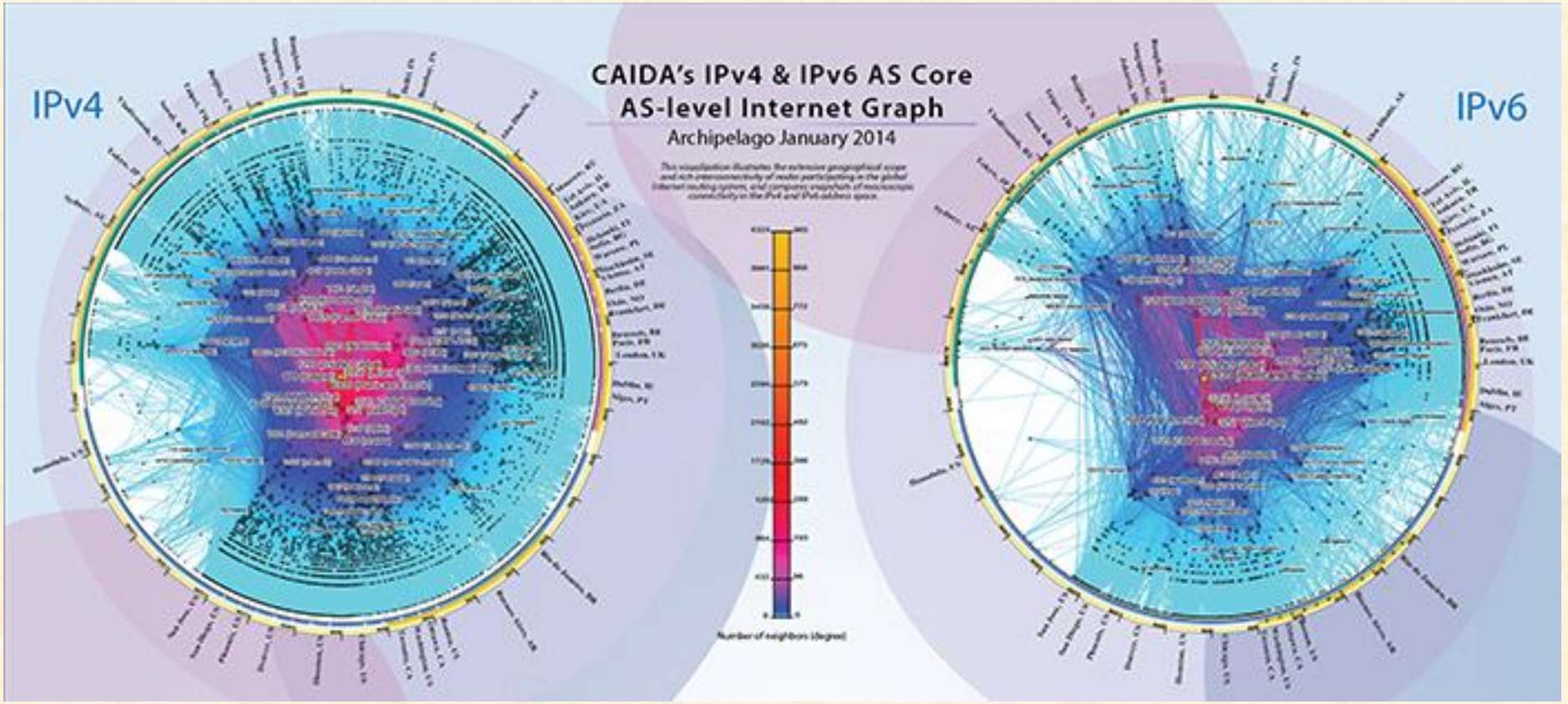
NTT Communications currently operates three data centers in Hong Kong, including Financial Data Center (FDC™), Tai Po Data Center and HKNet Data Center, each offering tailored services to best match with our client's diverse business needs.

NTT Communications
Data Centers in Hong Kong
Financial Data Center
Tai Po Data Center

Energy per bit consumed by 2010-era equipment

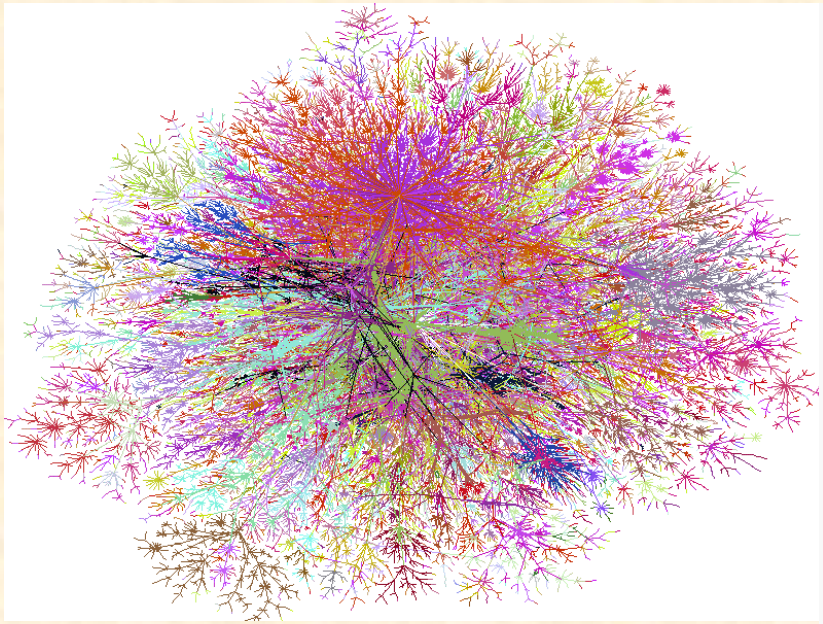


Internet Visualization



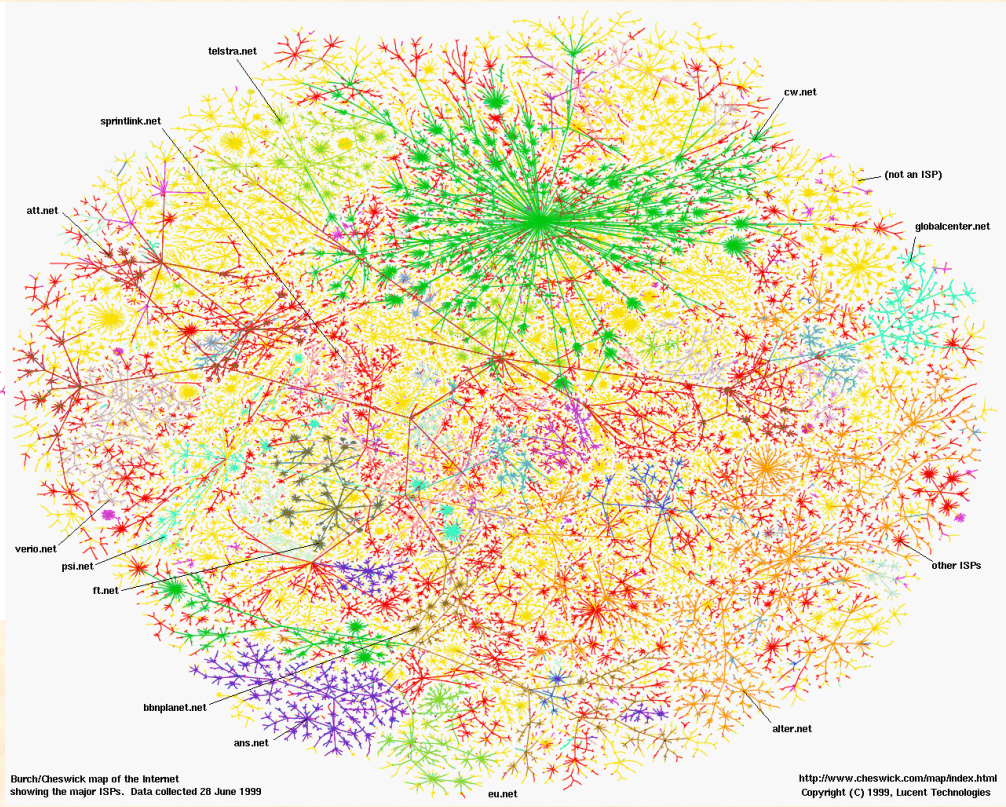
CAIDA Topology Mapping

Internet Visualization



1998

(William R. Cheswick)

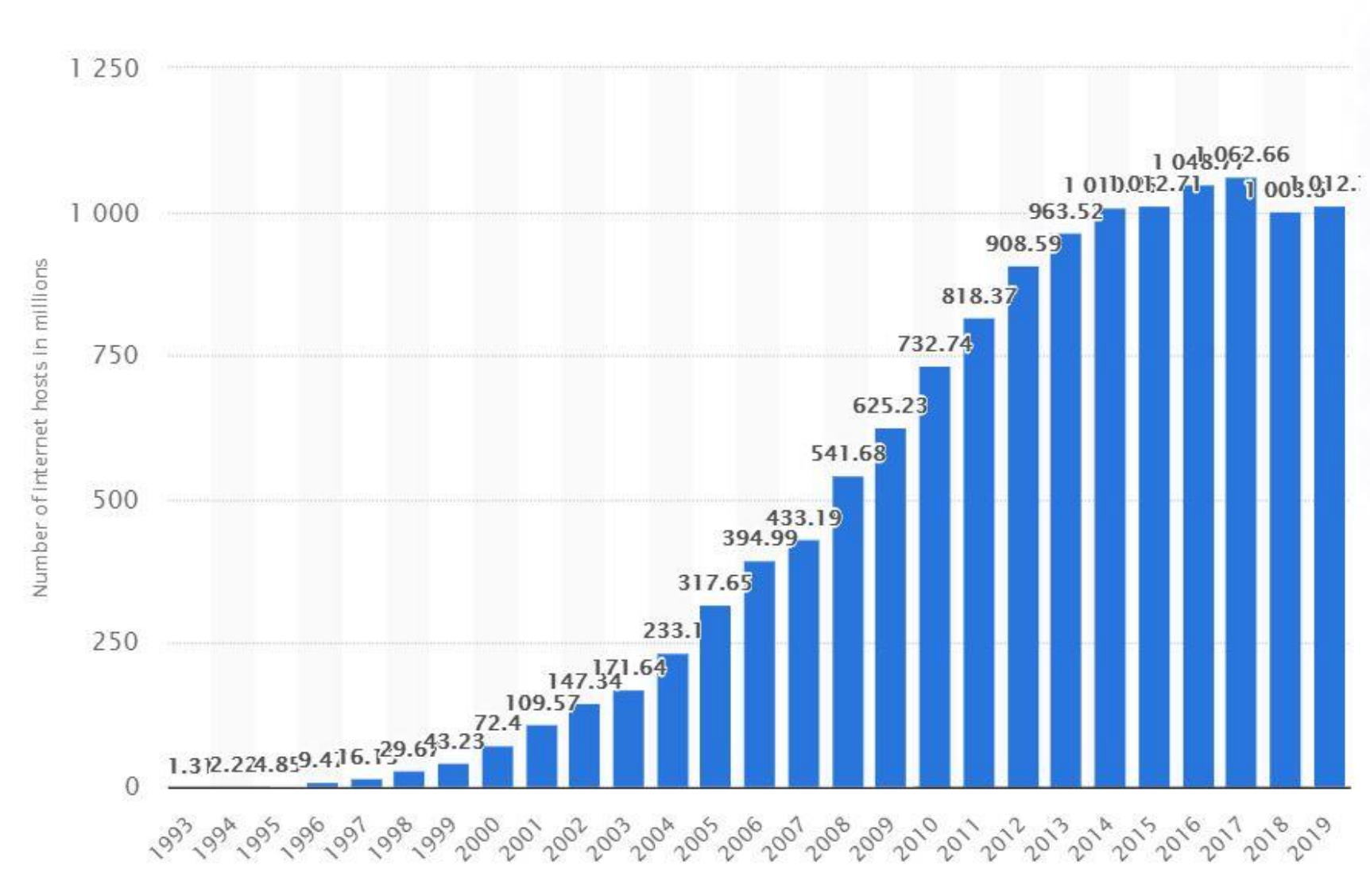


1999

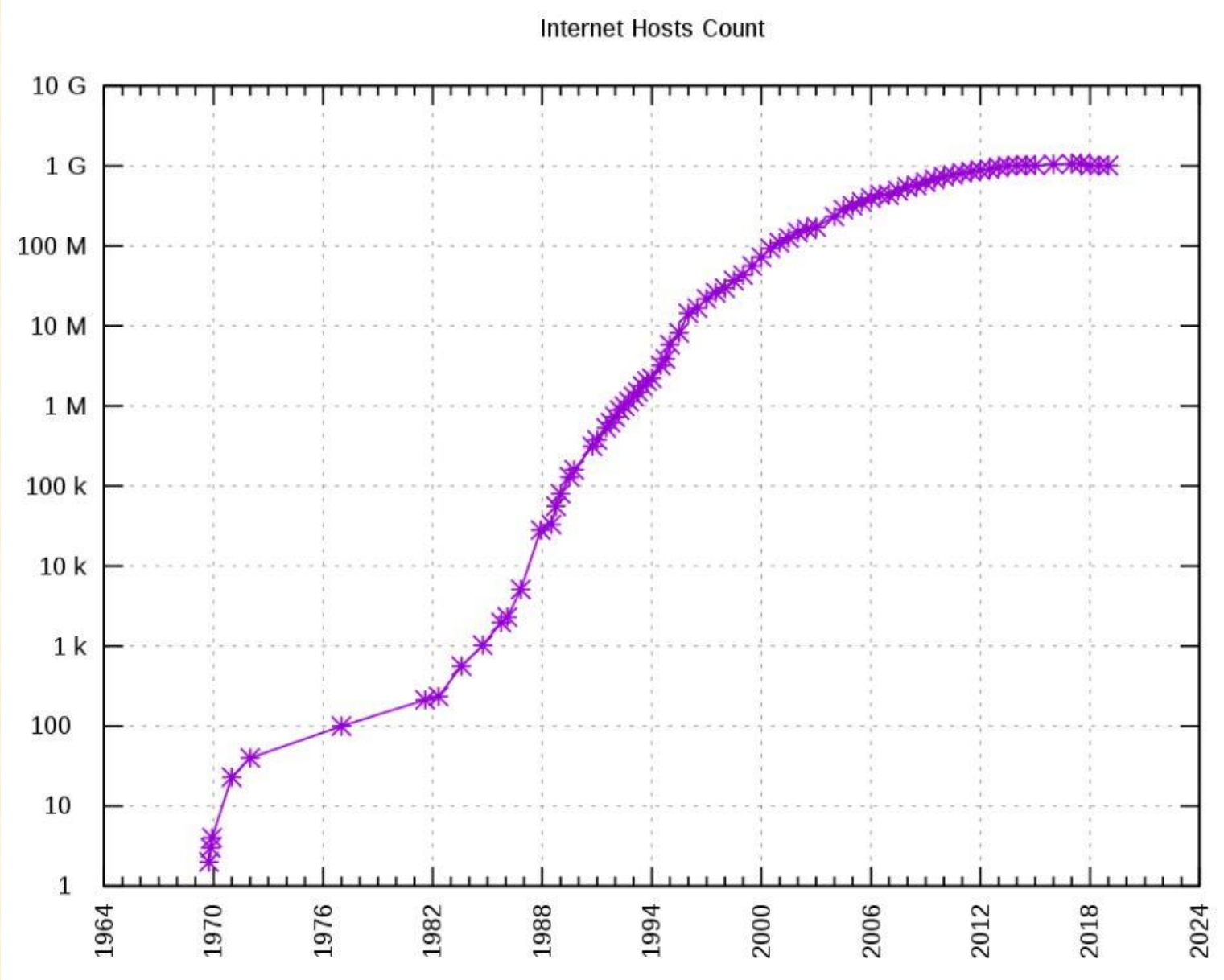
North American Internet Backbone Has 134,855 Routers in 2006

IP addresses (router level)

Growth of the Internet (AS-level)



Growth of the Internet (Hosts)



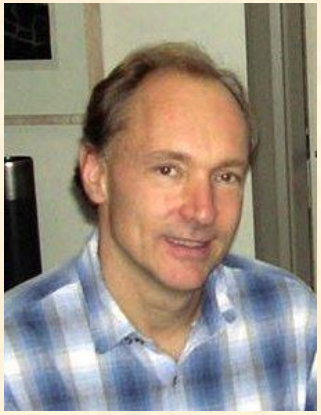
WWW

&

Facebook

on

Internet

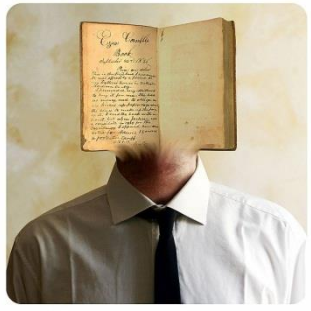


Sir Timothy John Berners-Lee
(1955 -)

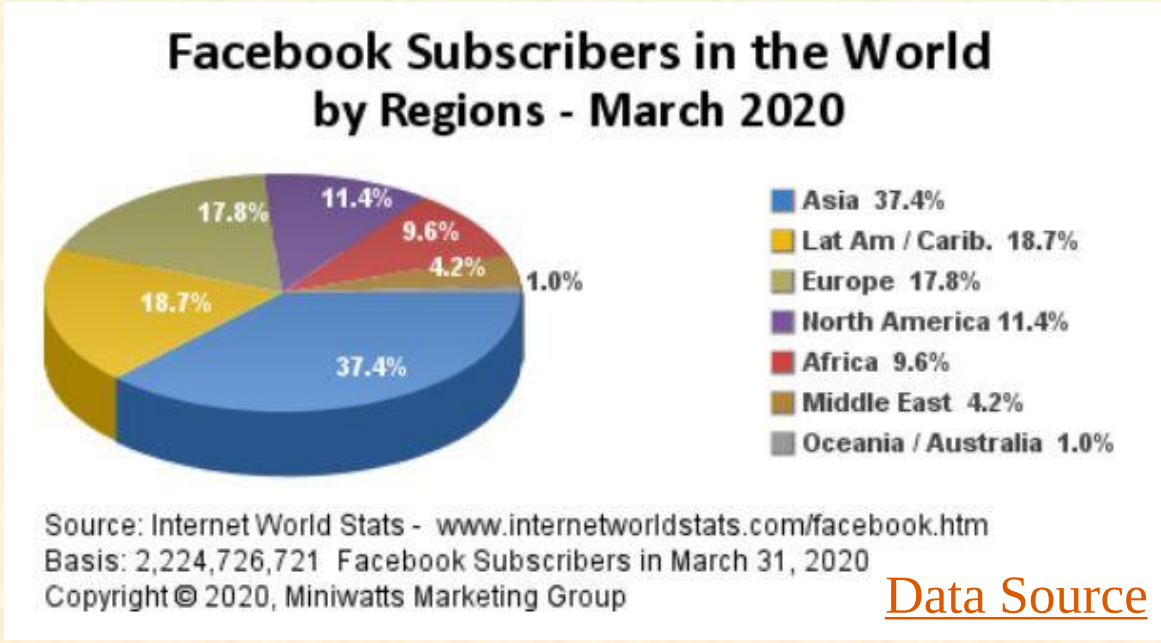
Tim Berners-Lee (“TimBL”) developed a hypertext system with initial versions of HTML and HTTP and first GUI web browser called World Wide Web in 1990

Tim Berners-Lee is the director of the World Wide Web Consortium (W3C) and he is also the founder of the World Wide Web Foundation, established at MIT in 1994

A Typical Application Example - Facebook



Mark Zuckerberg



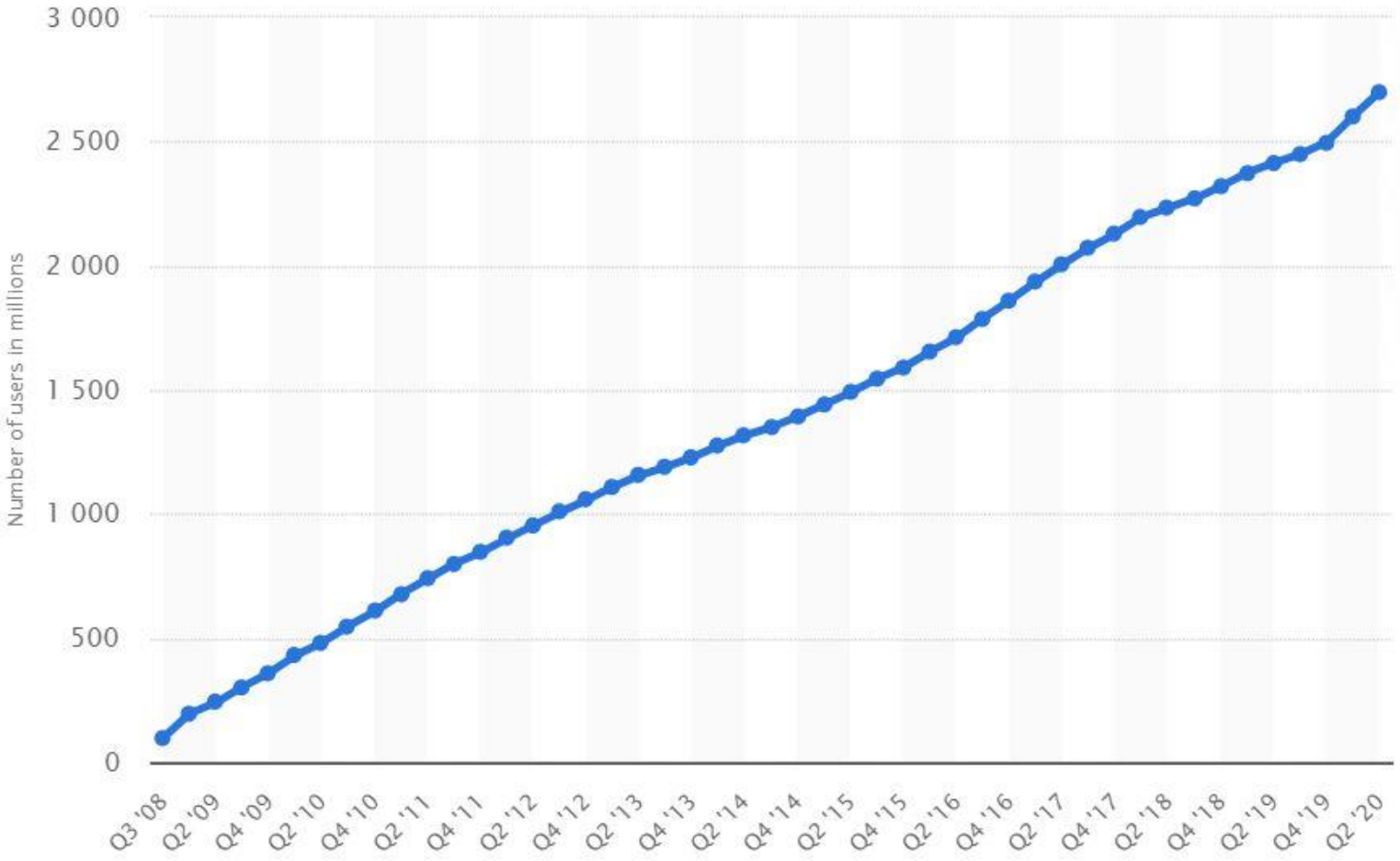
Data Source

www.bbc.co.uk

Number of monthly active Facebook users worldwide as

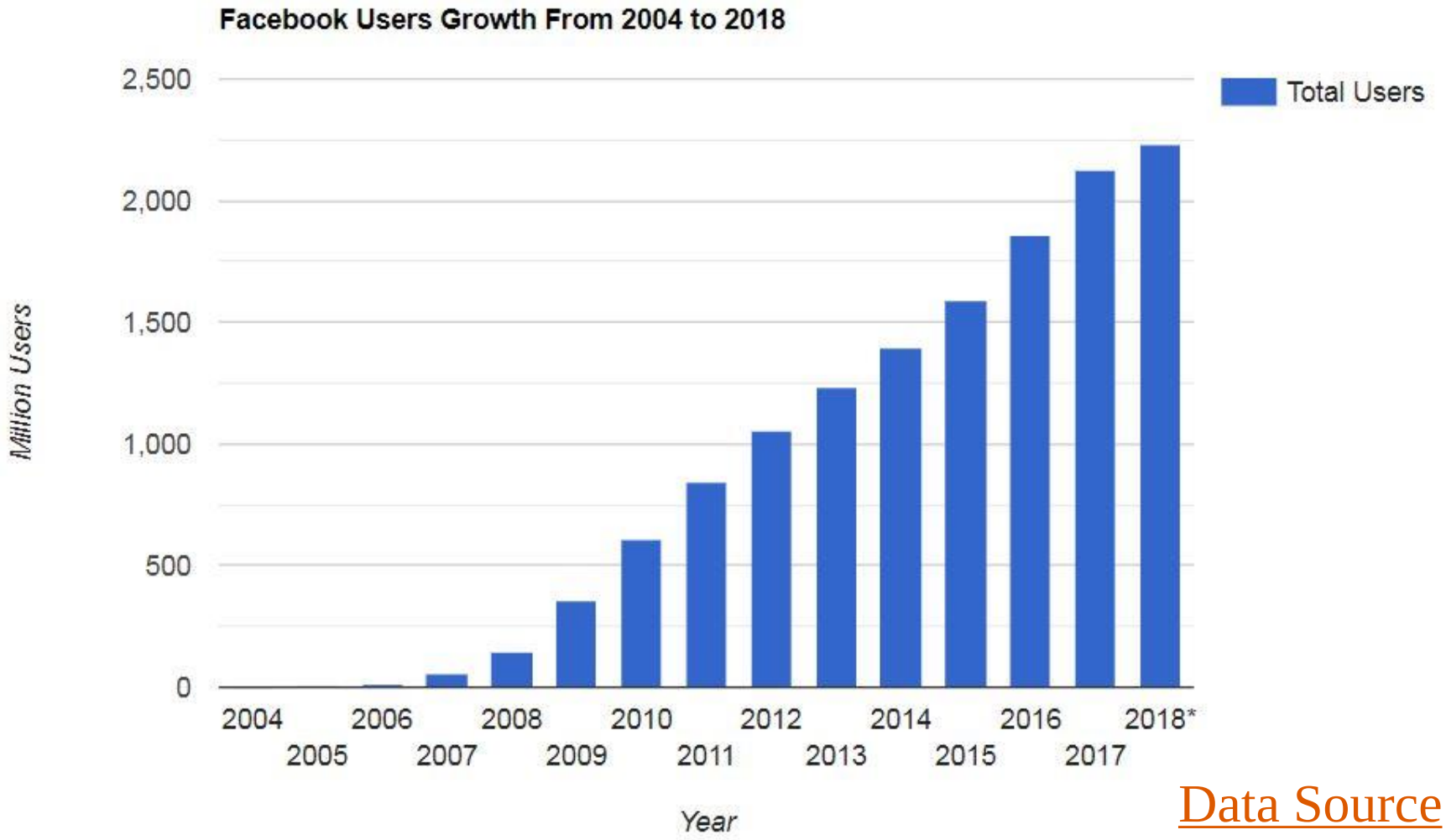
(in millions)

Zoomable Statistic: Select the range in the chart you want to zoom in on.



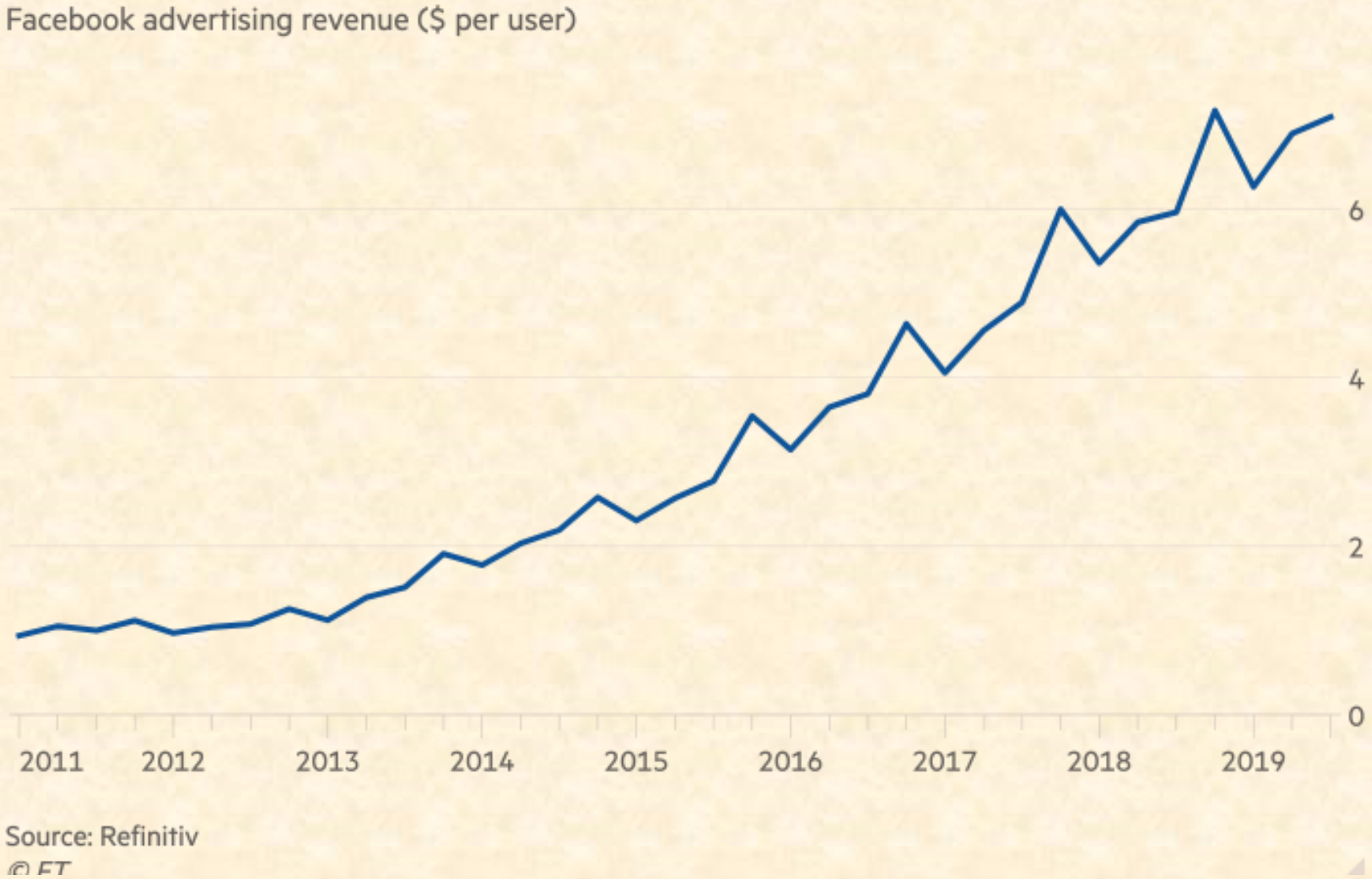
Facebook Users Distribution

Facebook Users Growth

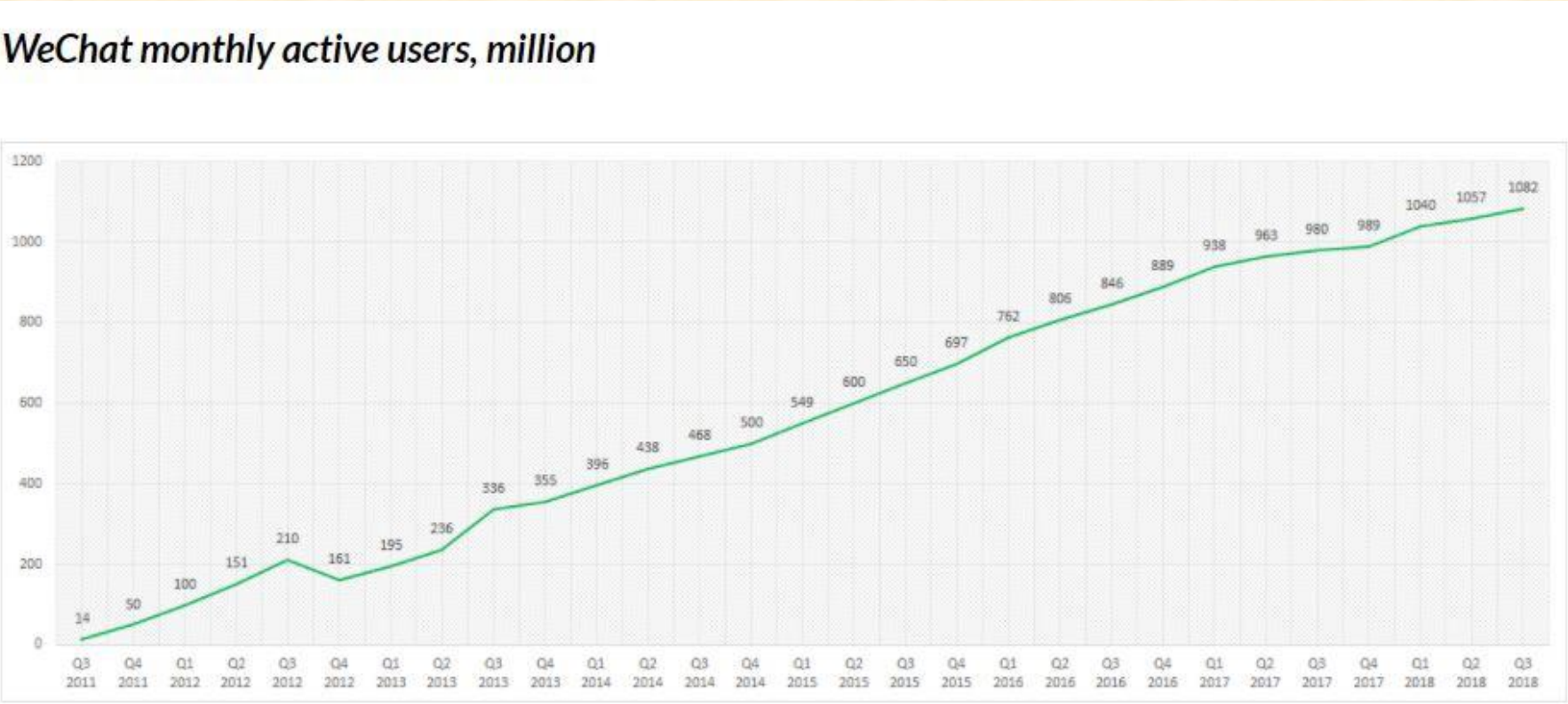


Data Source

Facebook Revenue Growth



WeChat



Data Source

China Beijing

China Internet Museum

WWW: Social Media

Global Social Media
Facebook
YouTube
Linkedin

Social Media in China
QQ 腾讯
Weibo 微博
Renren 人人
Kaixin 开心
Youku 优酷
Tudou 土豆

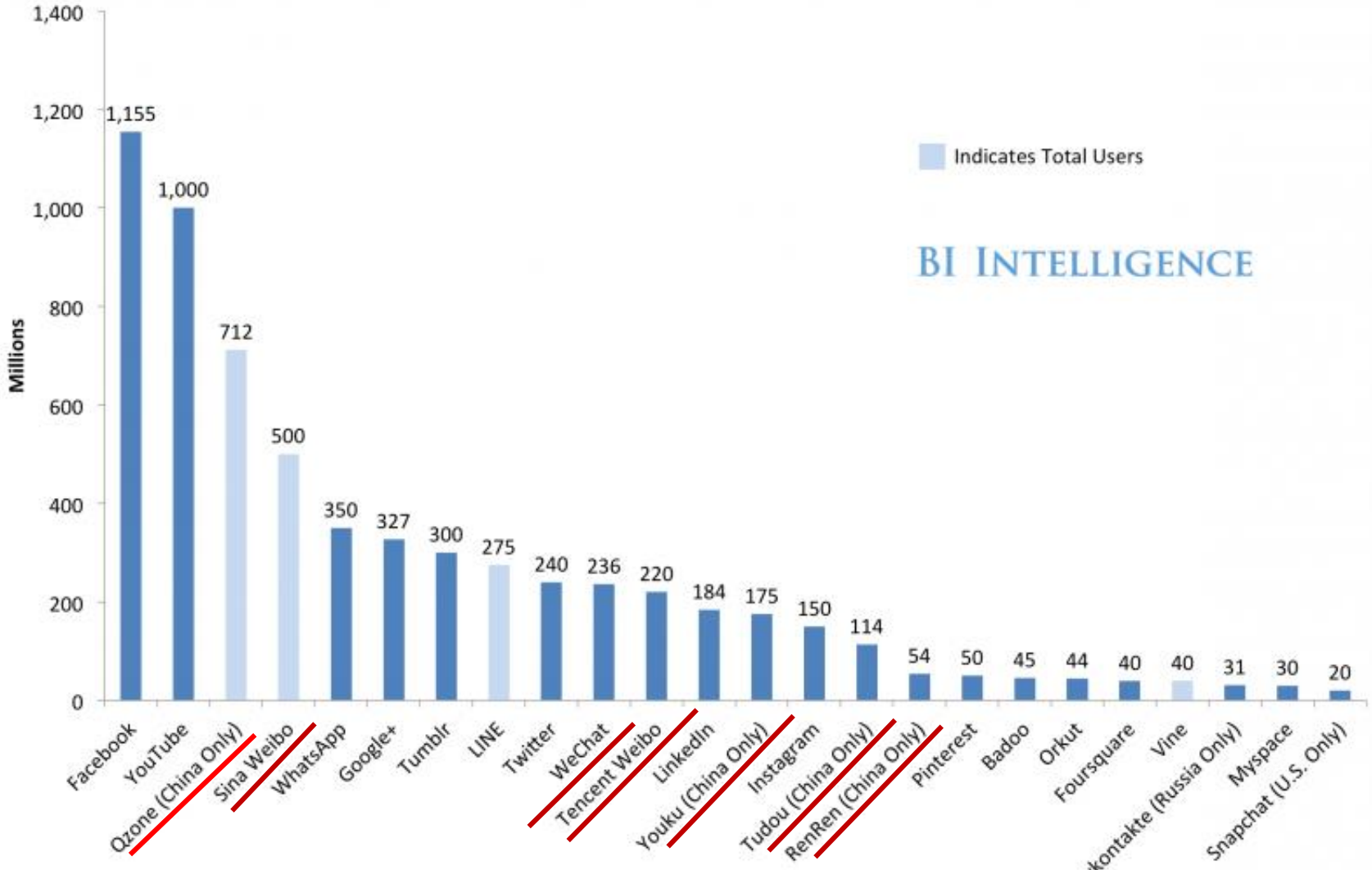
Search Engine Marketing
Google
Yahoo!
Baidu 百度

Total number of websites

Right Now !

Largest Social Networks In The World

Monthly Active Users (Unless Noted Otherwise)

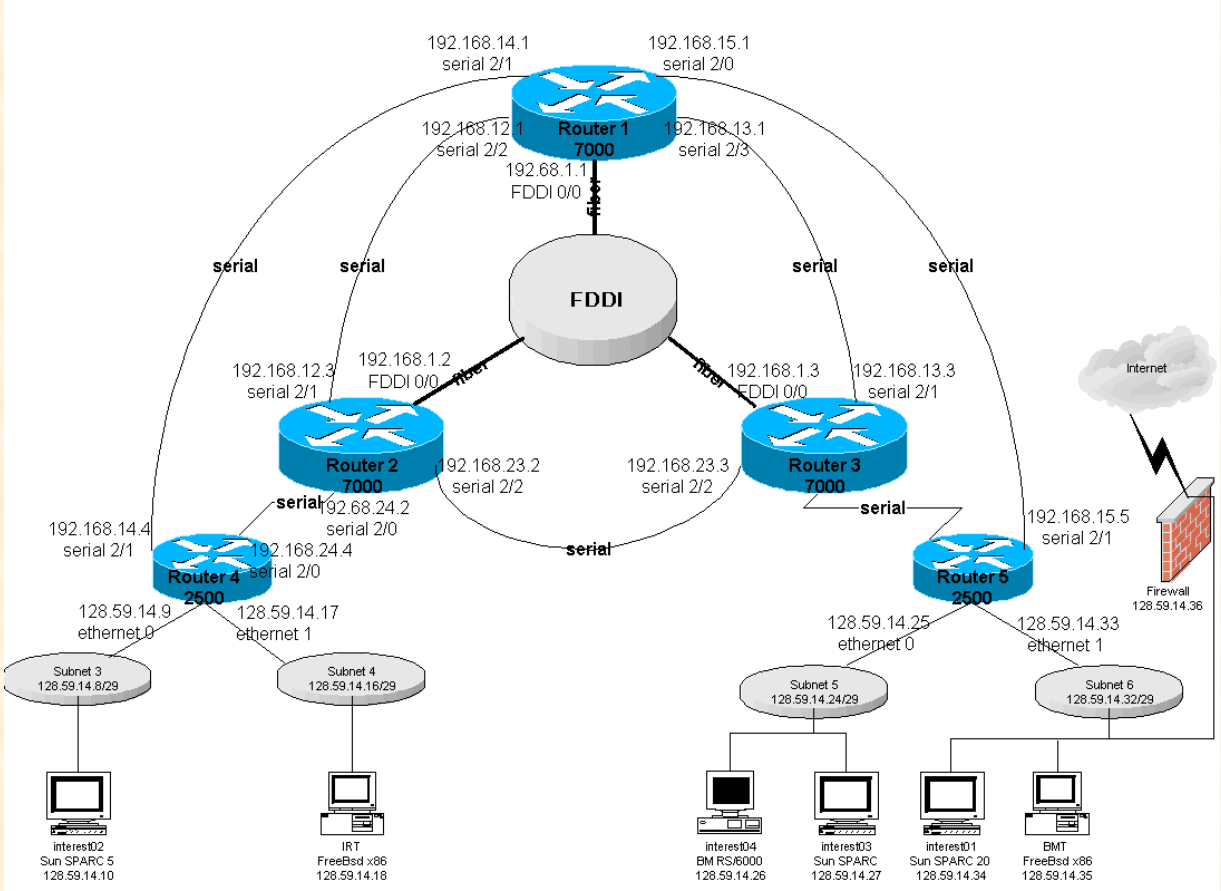


Source: Company Filings, News And Company Announcements, GlobalWebIndex

BREAK

10 minutes

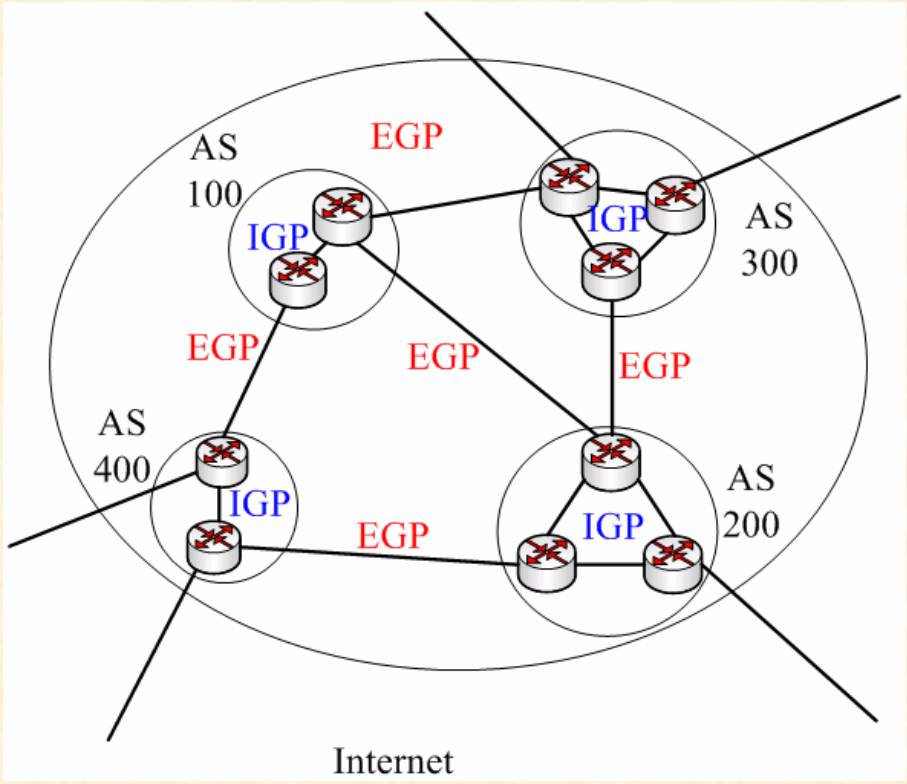
AS-Level Internet Topology



AS = Autonomous Systems

FDDI = Fiber Distributed Data Interface

Internet



Internet has more than 50,000 AS today

AS9444:
Hong Kong Telecom

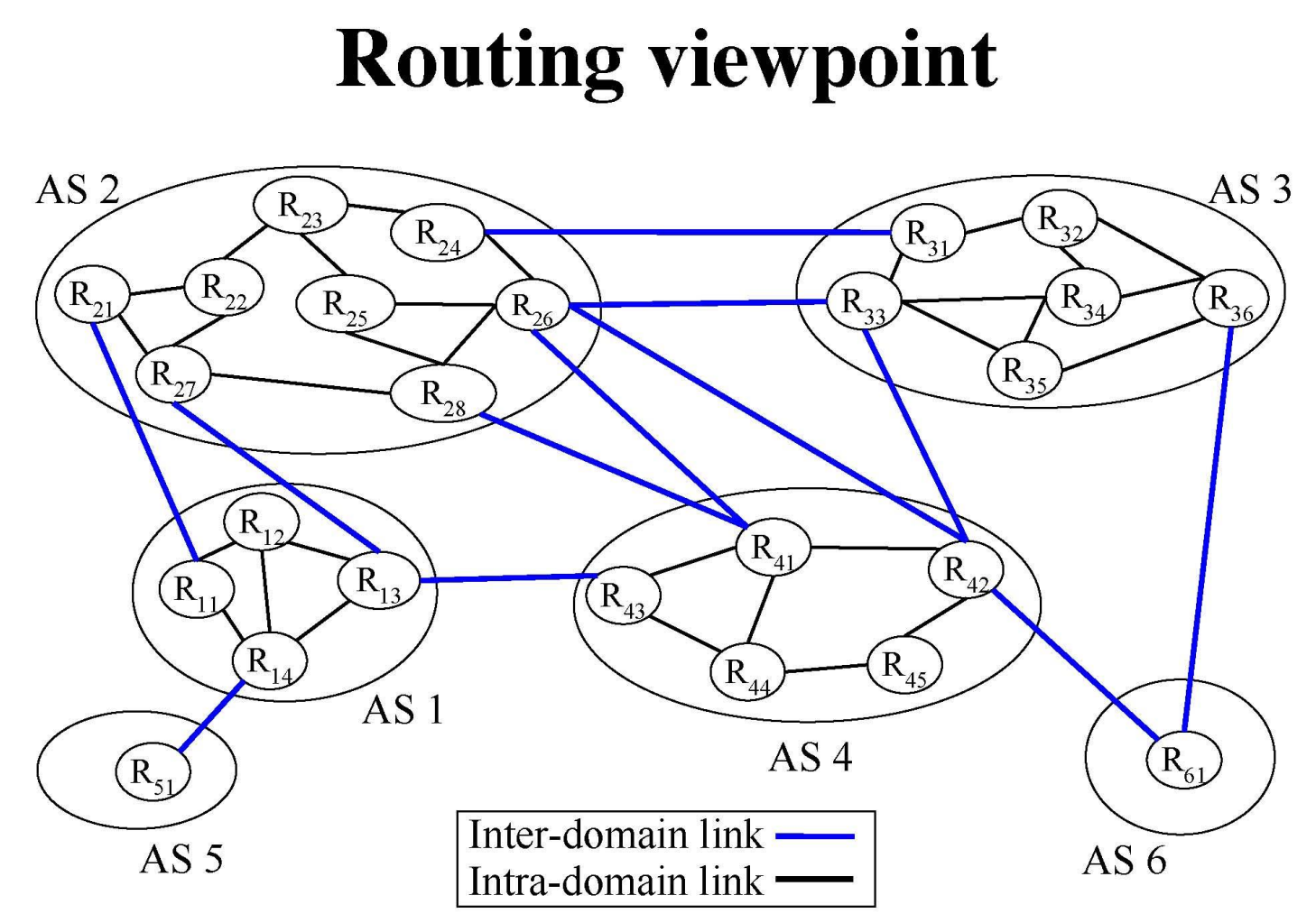
AS24112:
Standard Chartered Bank (HK) Limited

AS4158:
City Univ of Hong Kong

EGP – Exterior Gateway Protocol

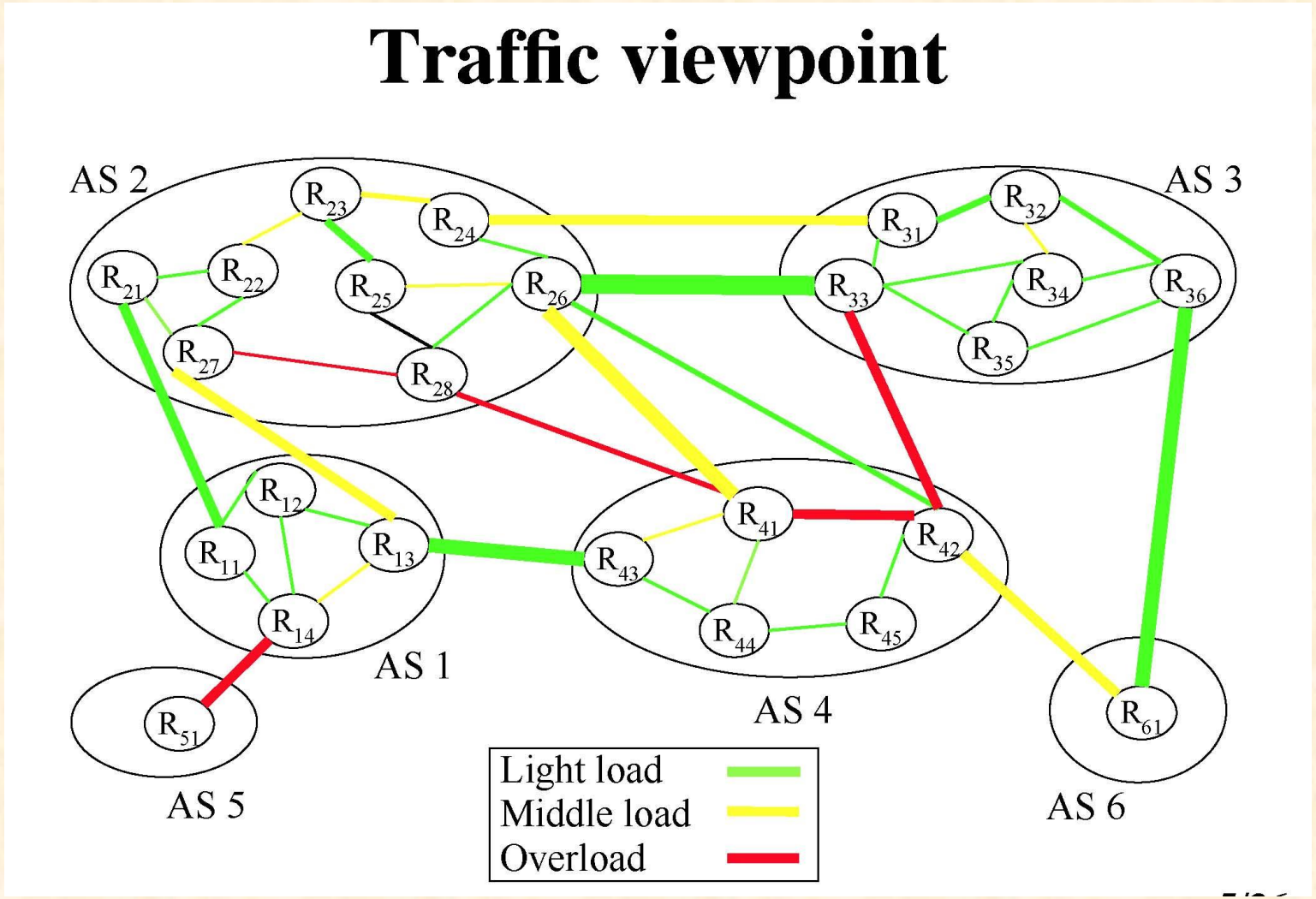
IGP – Interior Gateway Protocol

Internet at the AS Level



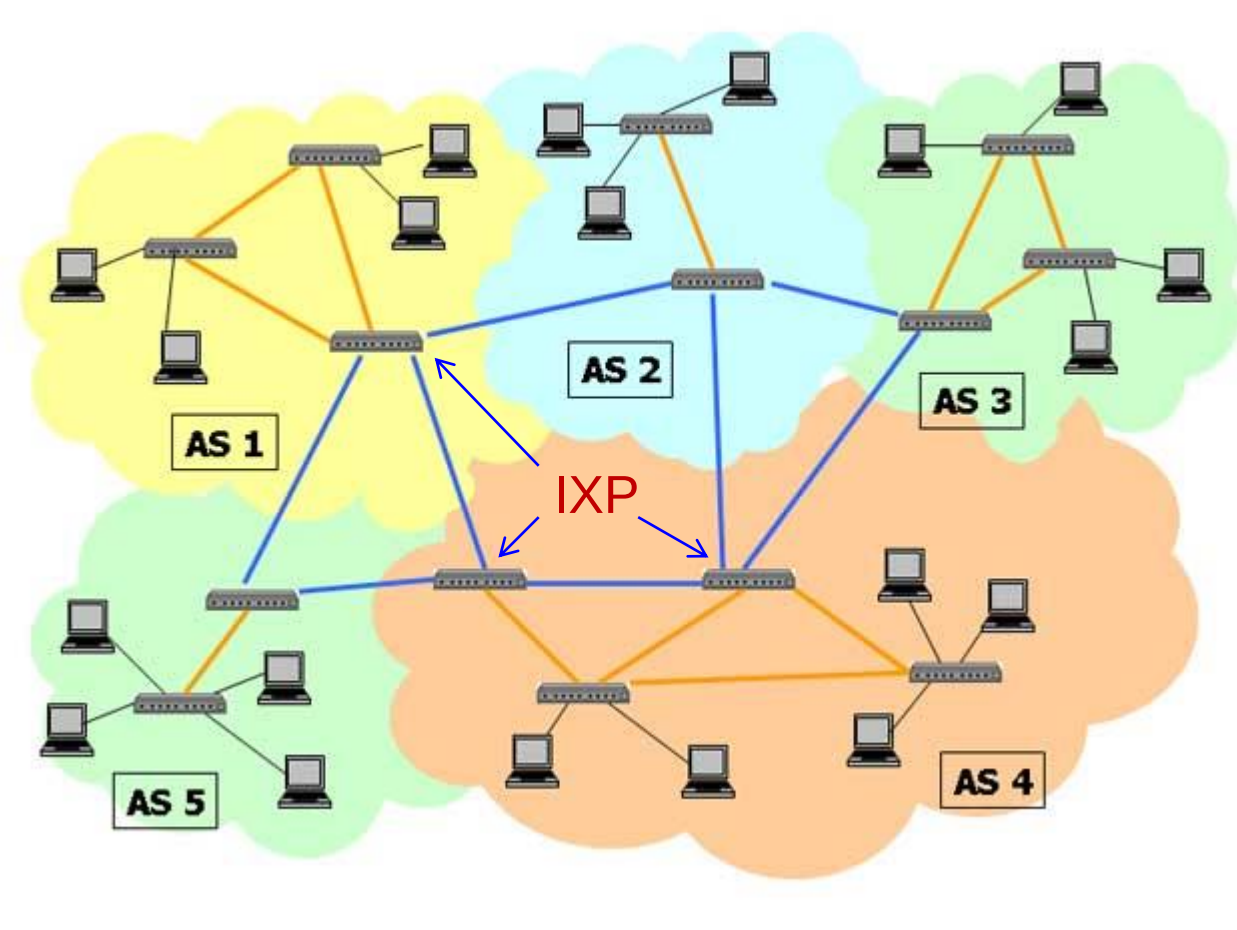
(Steve Uhlig)

Internet at the AS Level



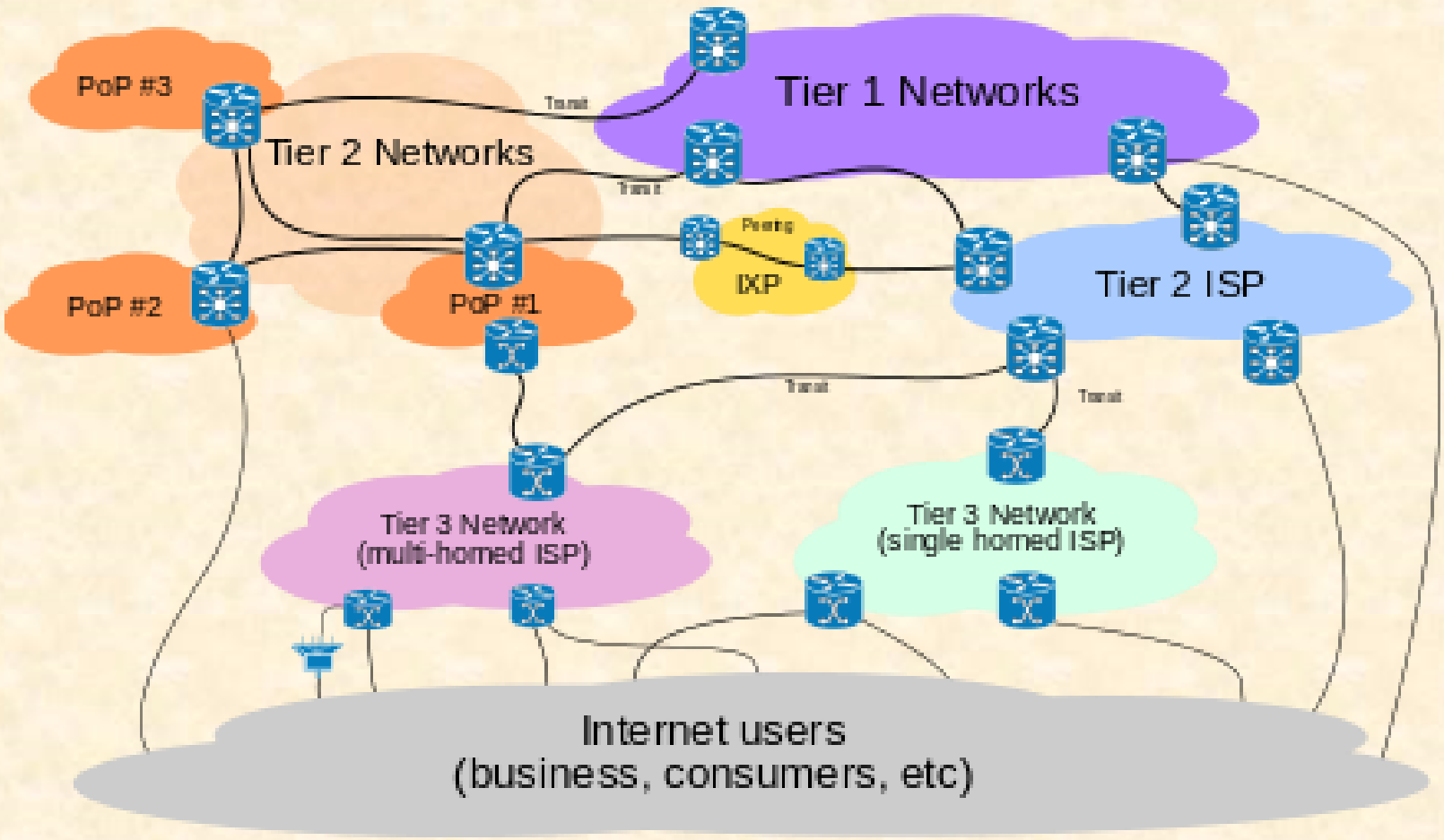
(Steve Uhlig)

Internet: AS and IXP

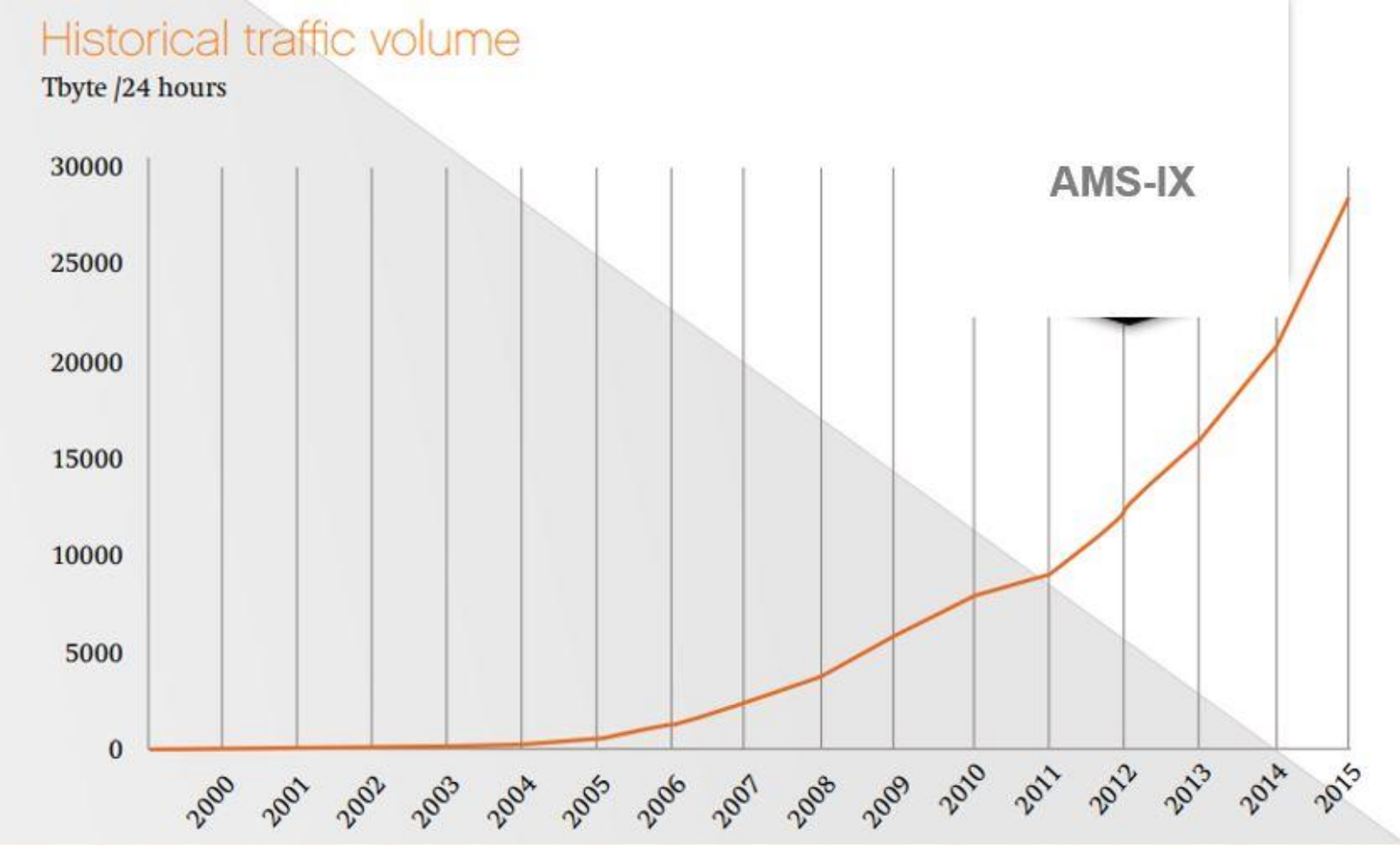


IXP = Internet Exchange Point

Internet: AS and IXP



There are > 400 IXPs today, providing services in > 100 countries/regions



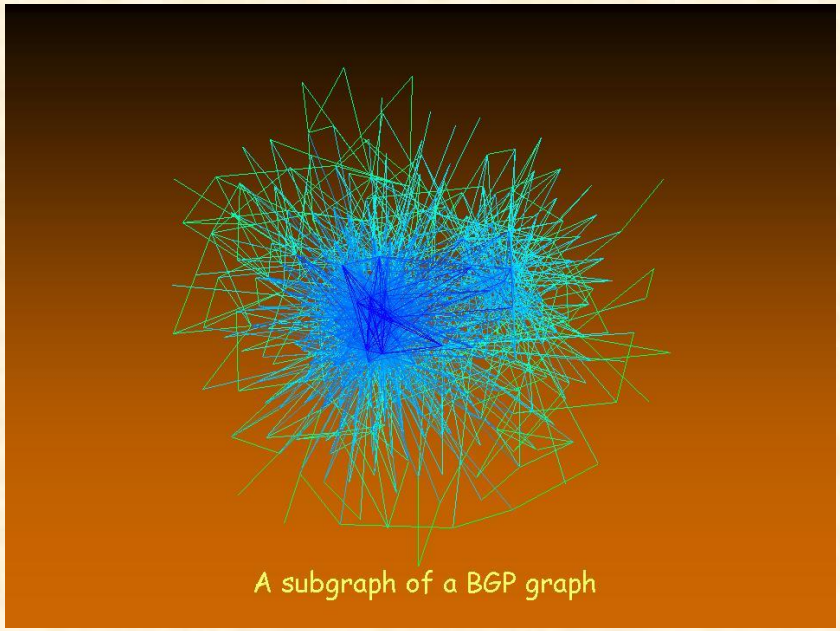
Internet Topology Generators

Three stages of development:

- First generation includes: random topology generators (in 1980s); representative - Waxman generator
- Second generation includes: structural topology generators (in 1990s); representatives - Tiers and Transit – Stub generators (with hierarchical and community structures)
- Third generation (since 2000), based on node degrees; representatives - BRITE and Inet, small-world and especially scale-free network models
- Open Source: **Net2Plan**

Internet Topological Properties and DATA

- Real AS-level Internet data can be obtained from the website of the Oregon Router Views Project, which was managed by the National Laboratory for Applied Network Research (NLANR), expired at the end of 2006, and now managed by the Cooperative Association for Internet Data Analysis (CAIDA)
- This website is being updated within hours daily by taking snapshots from the routing tables of the Border Gateway Protocol (BGP)

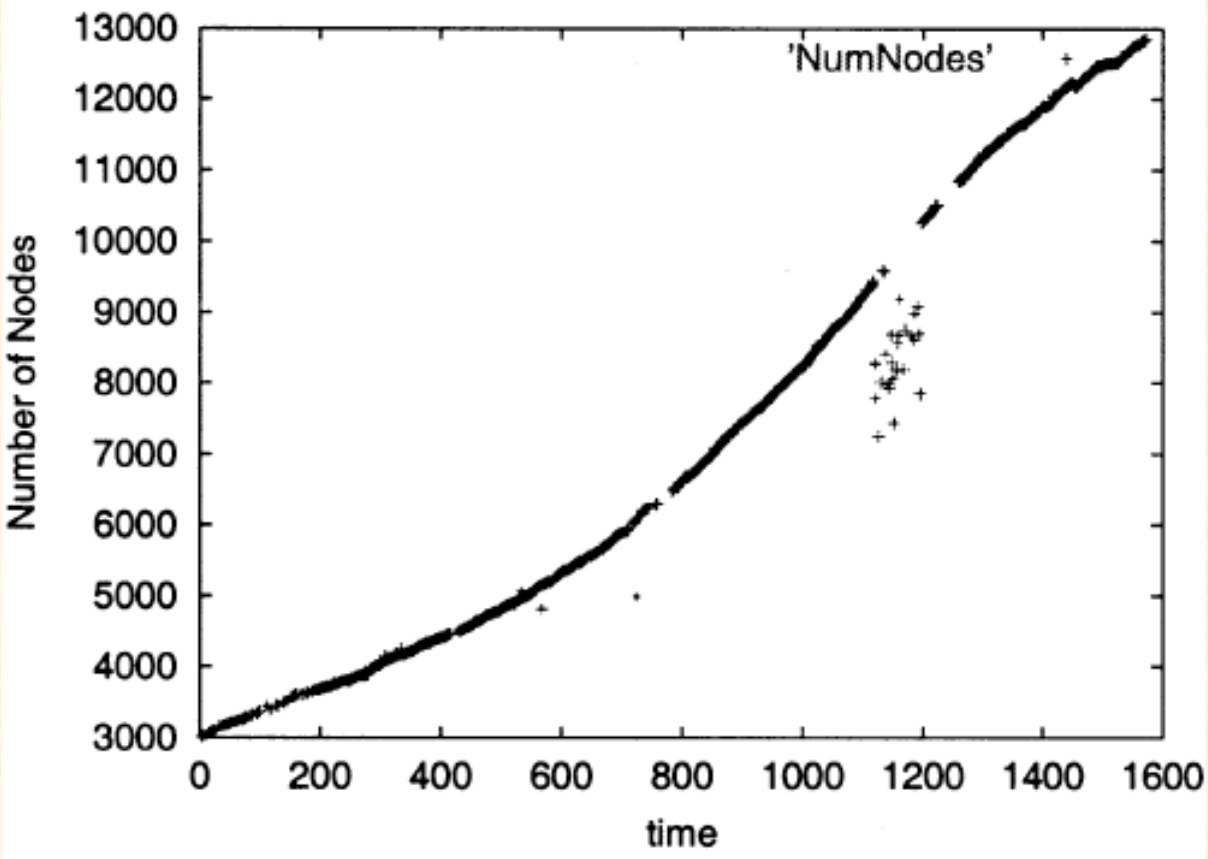


Internet Topological Properties

- Other useful data about the AS-level Internet:
- Skitter provides Internet topological measures by the CAIDA, using Traceroute (a computer network tool for determining the route taken by packets across an IP network.
- Whois is a domain search tool and data base, identifying the owners and IP addresses of all domains, but it is not automatically managed.
- RIPE NCC supports the infrastructure of the Internet and provides global Internet resources and related services (IPv4, IPv6 and AS Number resources) in Europe, Middle East and parts of Central Asia.

Real AS-Level Internet Data

Example



Numbers of Internet AS (Nov. 1997 – Feb. 2002)

(Siganos et al., 2003)

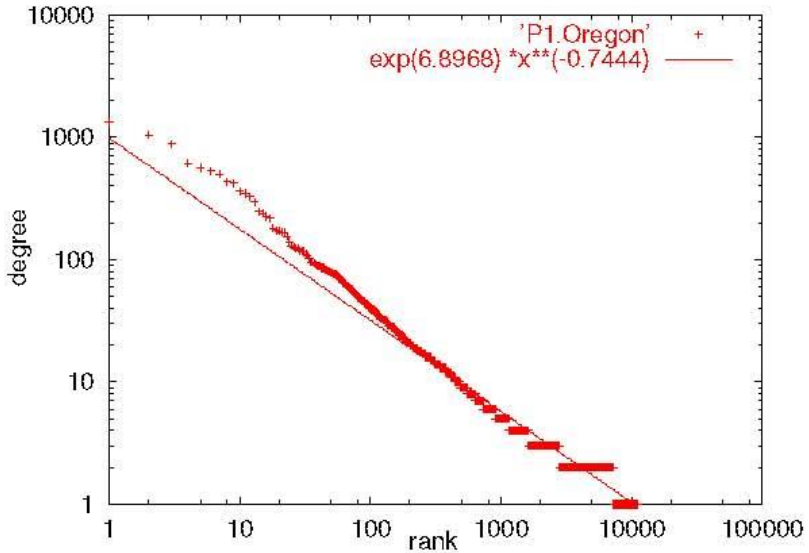
Power-Law Node-Degree Distributions

Faloutsos M, Faloutsos P, Faloutsos C.
On power-law relationships of the Internet topology.
ACM SIGCOMM Computer Communication Review, 1999, 29(4): 251-262

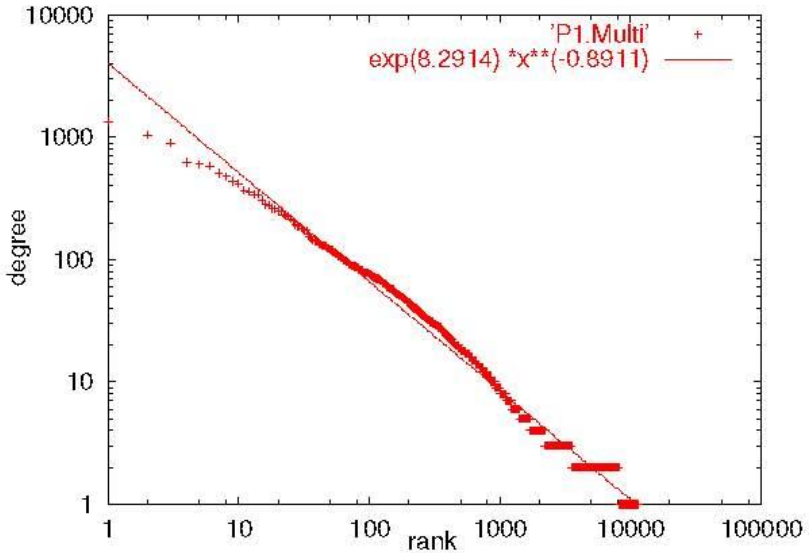


The Faloutsos Brothers

Power-Law Node-Degree Distribution



(a) Oregon



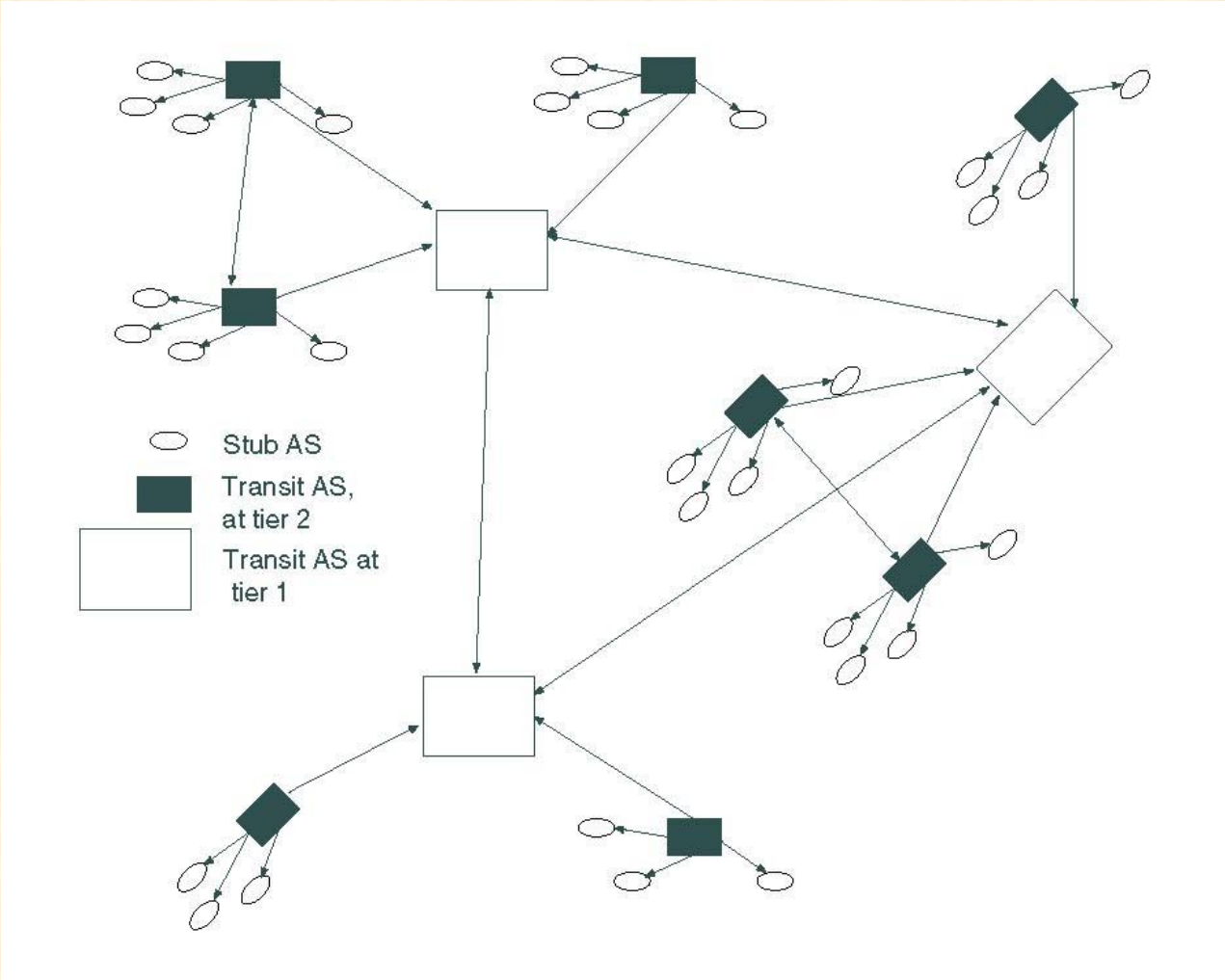
(b) Multi

Power law: $d_v \sim r_v^R$, where d_v is the degree of node v, r_v is the index of node v in the degree-decreasing ordering of all nodes, and $R < 0$ is a rank constant exponent.

Internet Hierarchical Structures

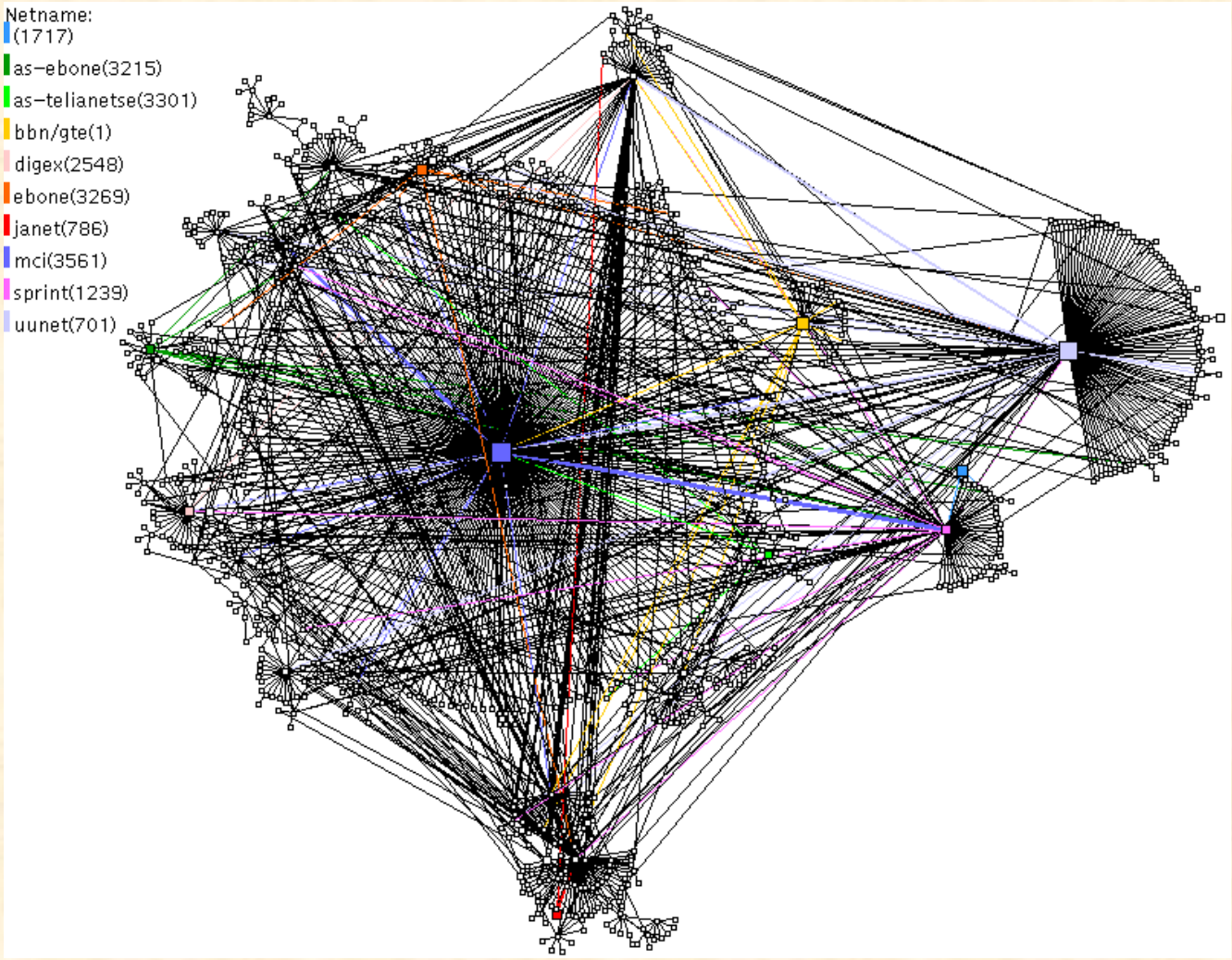
- Internet consists of a large number of interconnected AS
- AS may be considered as a *Stub domain* or a *Transit domain*
- Transit domain can be a Metropolitan Area Network (MAN) or a Wide Area Network (WAN), typically a regional or a national Internet Service Provider (ISP)
- Stub domain consists of campus networks or some other interconnected Local Area Networks (LAN)
- Transit domain is used to link many nearby Stub-domains together
- Stub domain usually processes the information starting and ending inside the domain, while a Transit domain has no such restriction

Internet Hierarchical Structures



AS-level Internet structure (Jaiswal et al., 2004)

Internet Hierarchical Structures



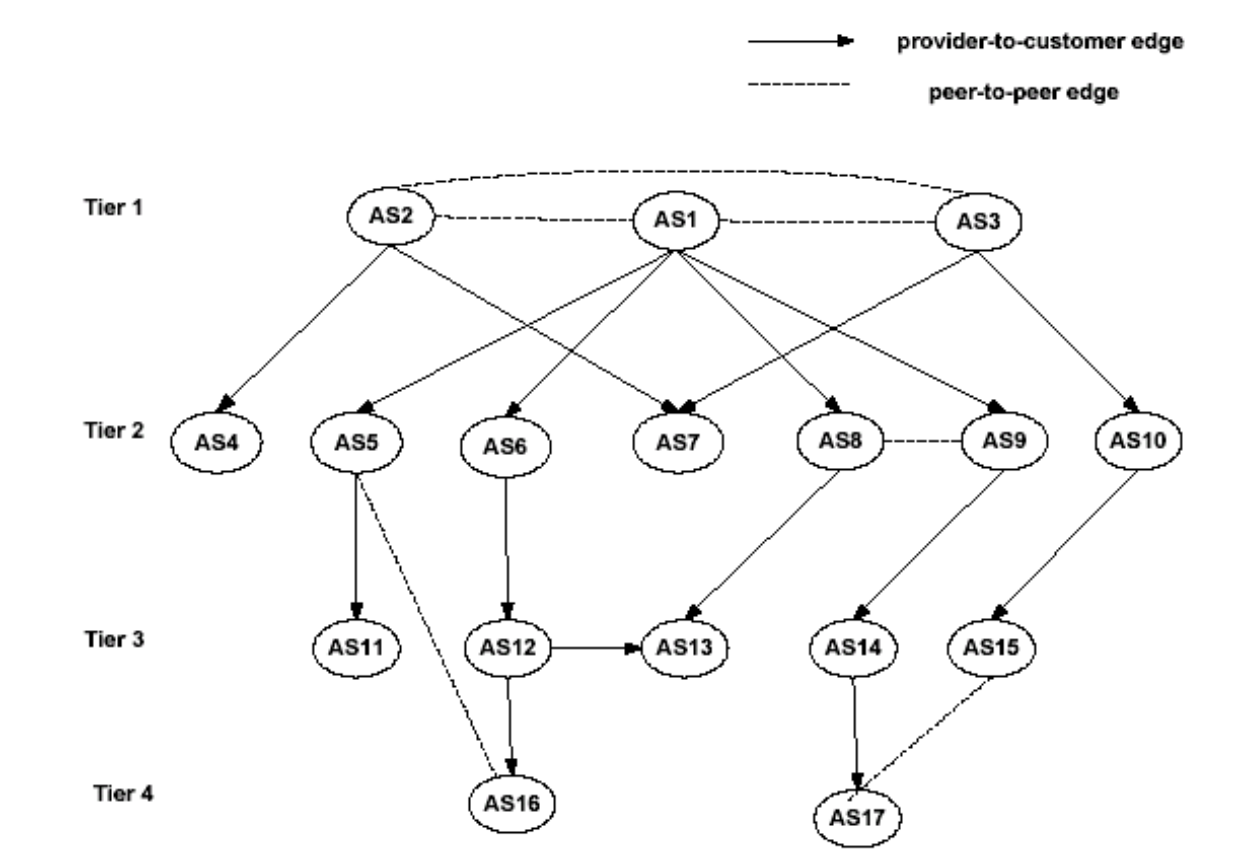
AS-level Internet on 3 December 1998 (generated by Skitter)

Internet Hierarchical Structures

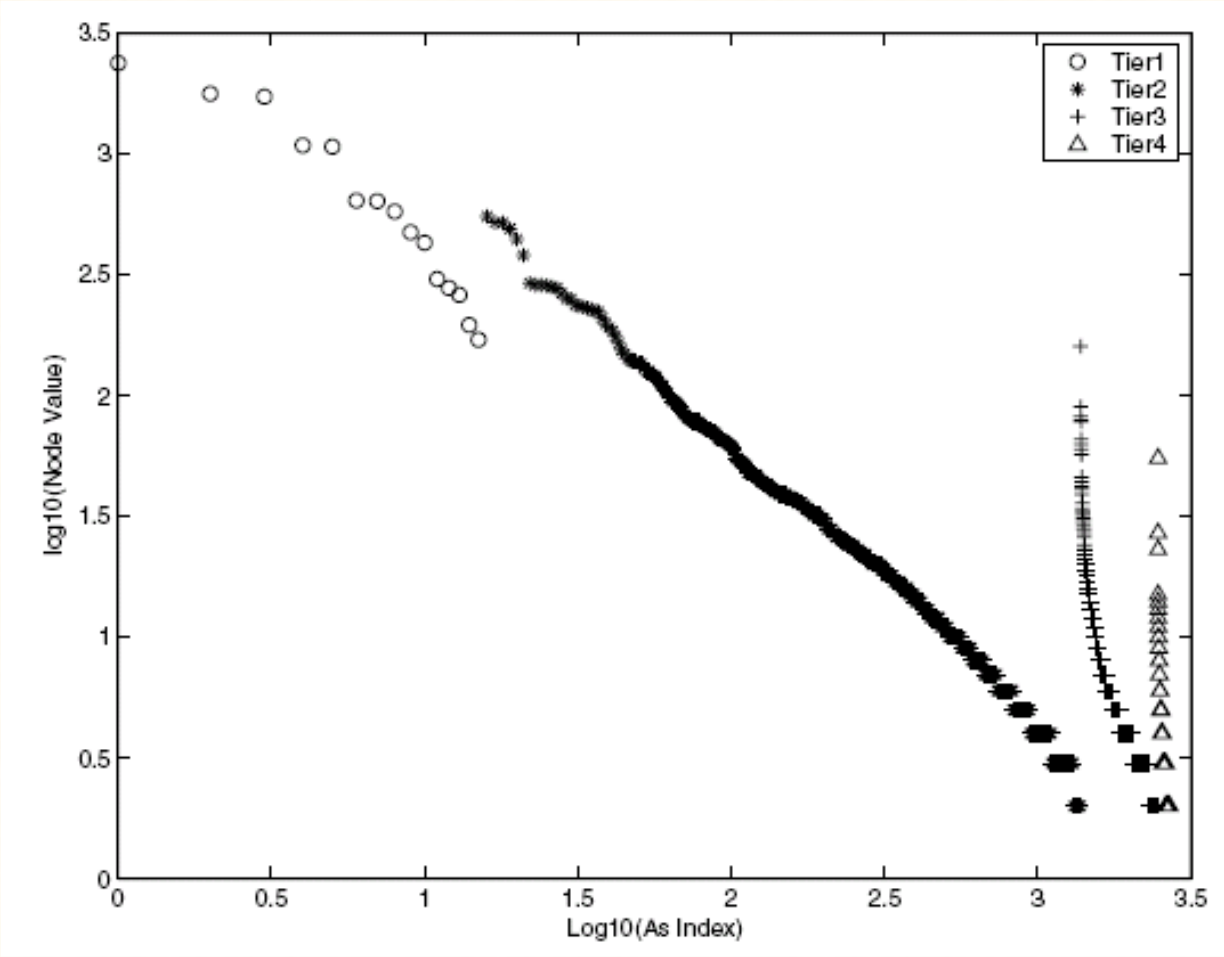
- AS on the Internet can be considered as some kind of *Tier*
- An AS at the highest Tier belongs to the Transit domain, called *Tier-1* provider

- Those Transit and Stub domains at a *lower Tier* depend on the Transit nodes at a *higher Tier* to communicate with the other domains at their same level

(Cai et al., 2004)



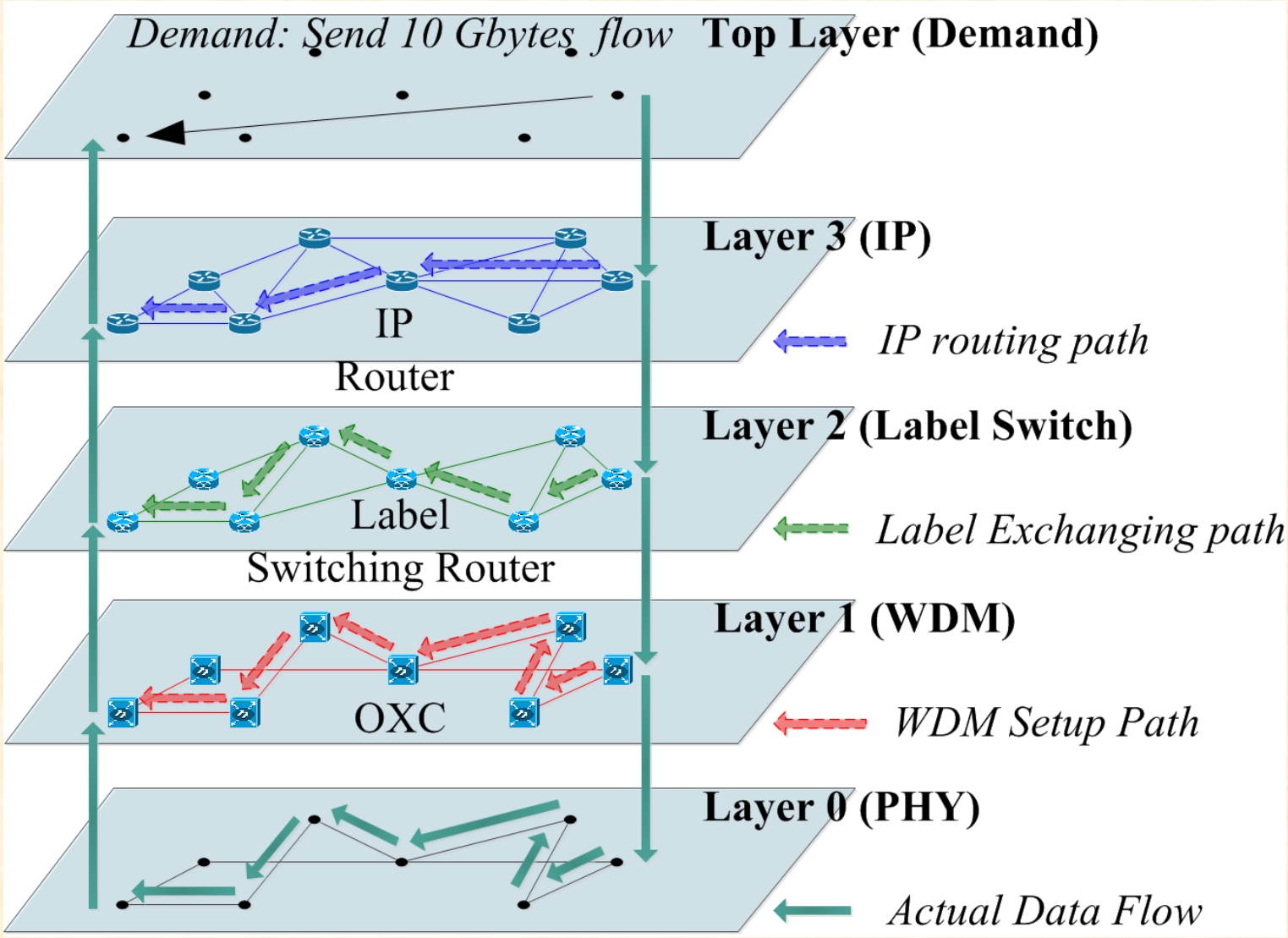
Internet Hierarchical Structures



Degree distribution of the AS-level Internet at different tiers

(Jaiswal et al., 2004)

Multi-Layered Network Structure

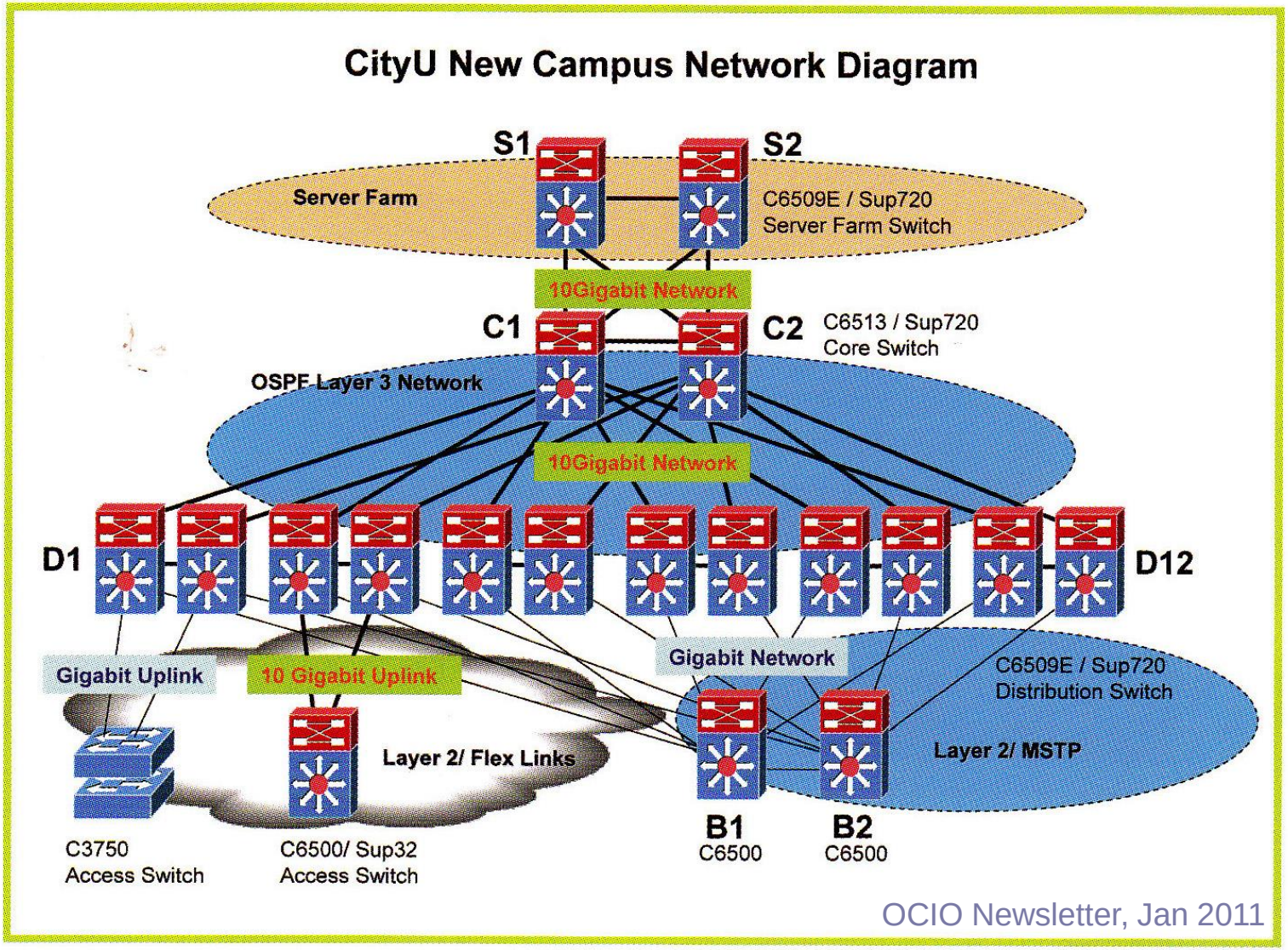


3-Tier Structure of the CTNET (HK CityU Campus Network, 1985 -)

Core layer

Distribution layer

Access layer

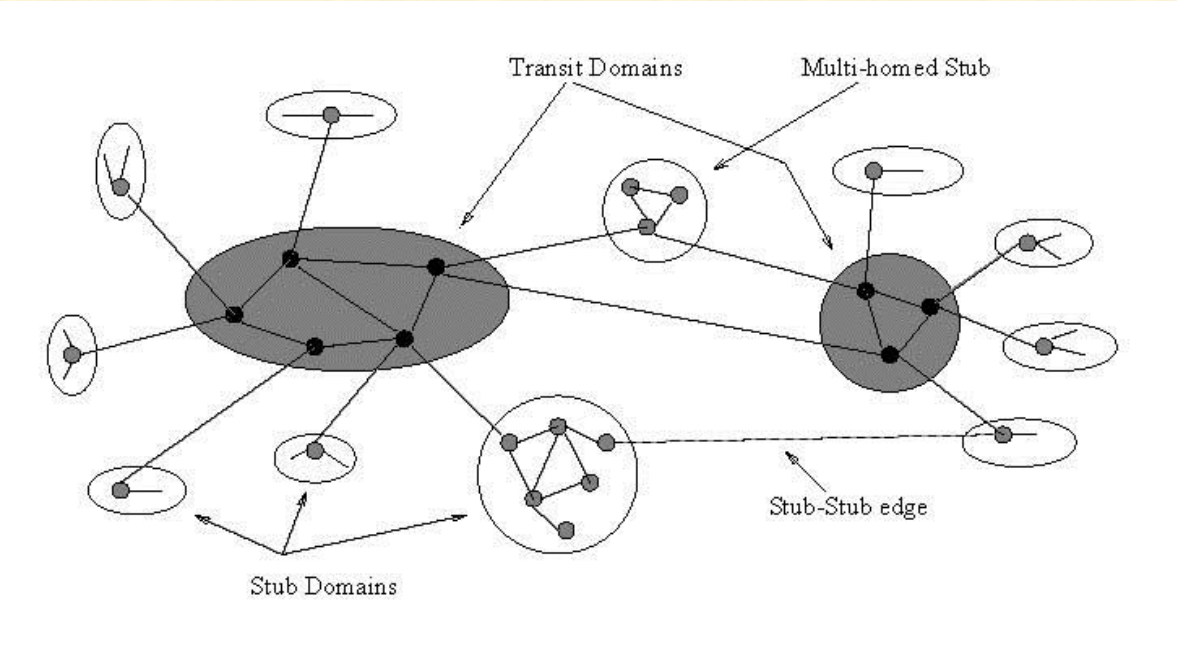


OCIO Newsletter, Jan 2011

Internet: Some Basic Properties

Rich-Club Phenomenon

In the Internet, a few nodes have a large number of edges, called ***hubs***, and they tend to connect to each other – Rich-club phenomenon – Assortativity



Rich-club phenomenon (Zegura et al., 1997)

Rich-Club Phenomenon

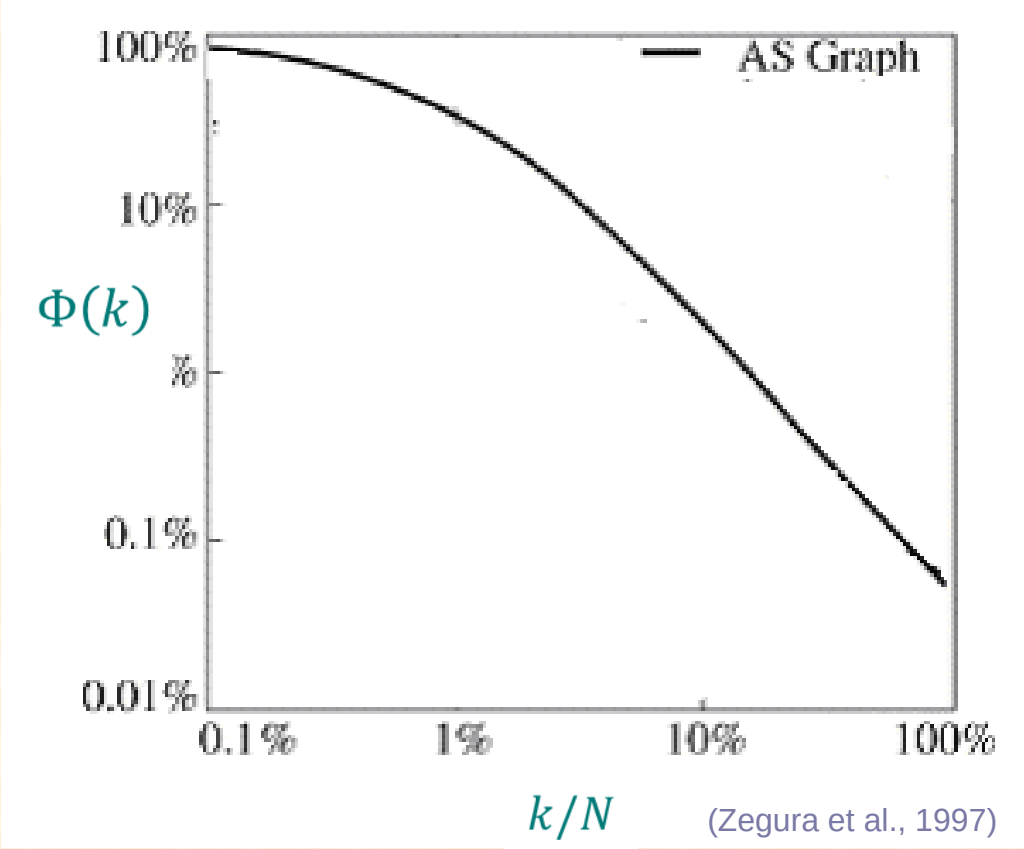
- The rich-club phenomenon in an AS is defined by

$$\Phi(k) = \frac{E_{>k}}{N_{>k}(N_{>k} - 1)/2}$$

where $N_{>k}$ is the number of nodes with degree $> k$, and $E_{>k}$ is the number of edges between such nodes

- If $\Phi(k) = 1$, then the first k biggest nodes compose a fully-connected sub-network (assortative)
- If $\Phi(k) = 0$, then the first k biggest nodes are not connected to each other (dis-assortative)

Rich-Club Phenomenon



(Zegura et al., 1997)

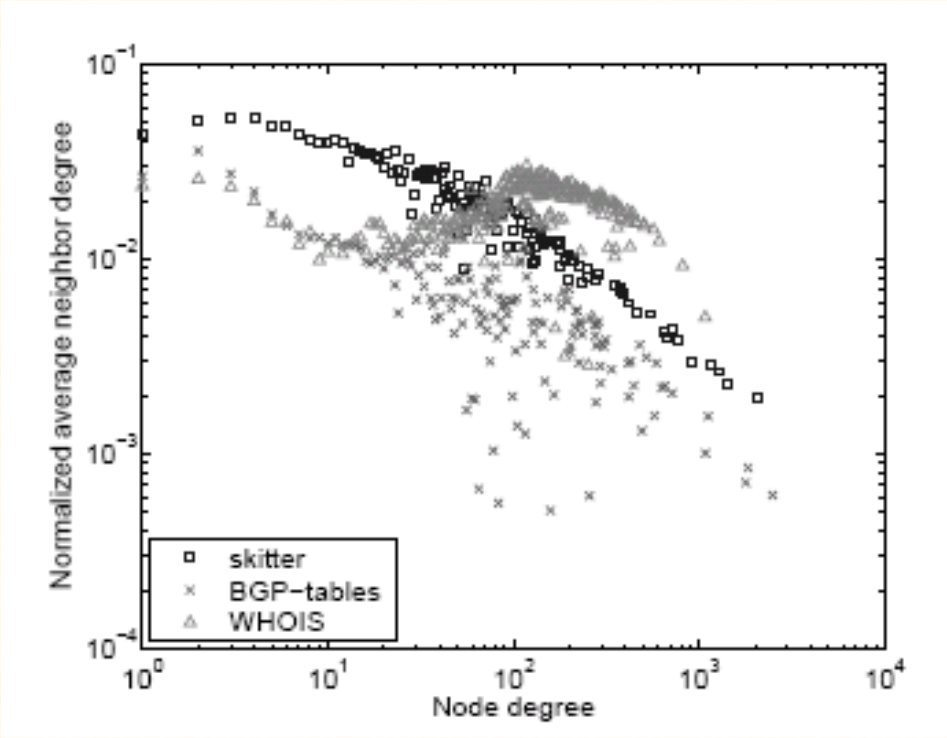
Real data have verified that the rich-club index follows nearly a power-law form

Most nodes in the Internet are small

- In the Internet, hubs are well interconnected (rich clubs)
- Most neighbors of a hub typically have small degrees (star-shaped structure)

- Analysis on the Internet data of April 2002 shows that nodes with degrees of 1, 2, and 3 were 26%, 38% and 14%, respectively, which sums up to about 80% of the whole network

(Zhou and Mondragon, 2004)



(Mahadevan et al., 2005)

Internet is dis-assortative

Assortativity Coefficient of a network is defined by

$$r = \frac{M^{-1}\sum_i j_i k_i - \left[M^{-1}\sum_i \frac{1}{2}(j_i + k_i)\right]^2}{M^{-1}\sum_i \frac{1}{2}(j_i^2 + k_i^2) - \left[M^{-1}\sum_i \frac{1}{2}(j_i + k_i)\right]^2}$$

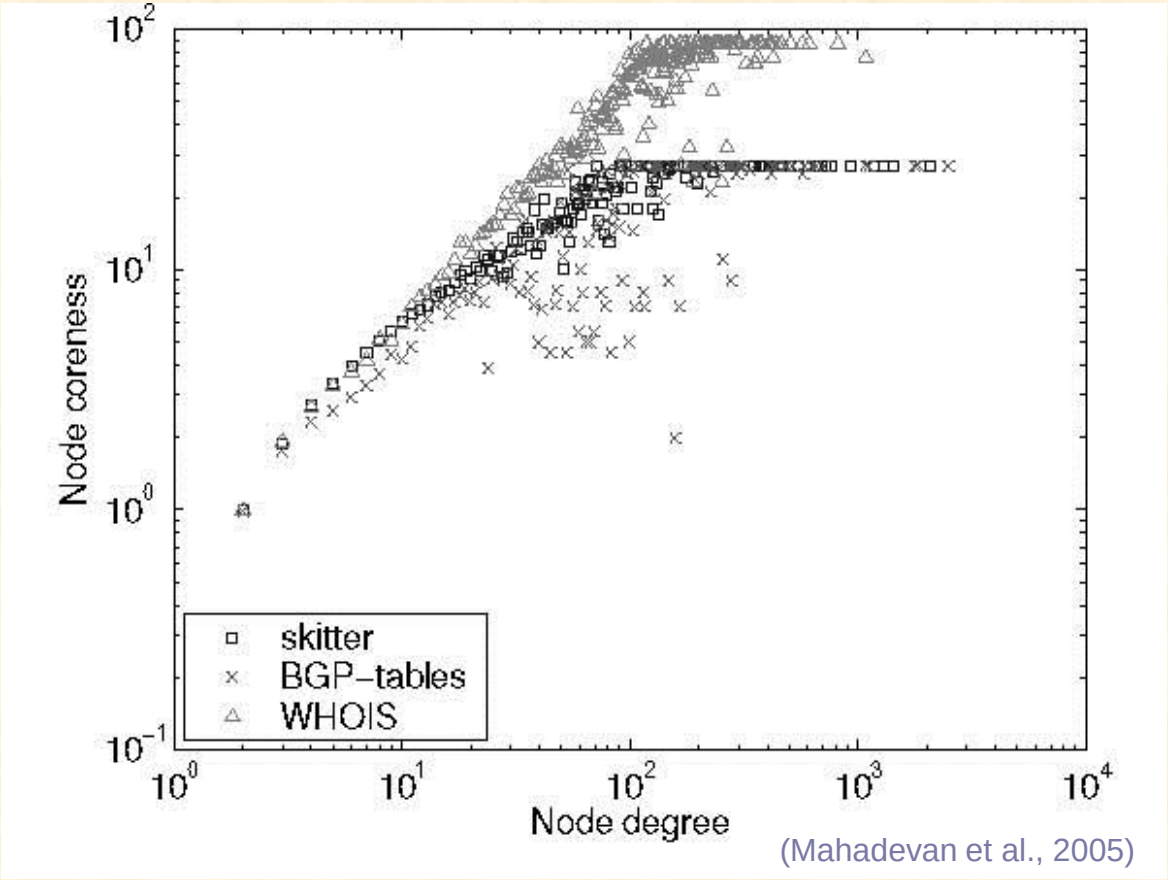
where k_i and j_i are the degrees of the end nodes of edge i, and M is the total number of edges in the network

If $r > 0$ then the network is *assortative* (big-big nodes)

if $r < 0$ then the network is *dis-assortative* (big-small nodes)

Analysis on real data using Skitter, BGP and Whois about the Internet at some AS levels shows that their assortativity coefficients of the Internet are – 0.24, – 0.19 and – 0.04, respectively, implying that Internet is overall dis-assortative

Coreness



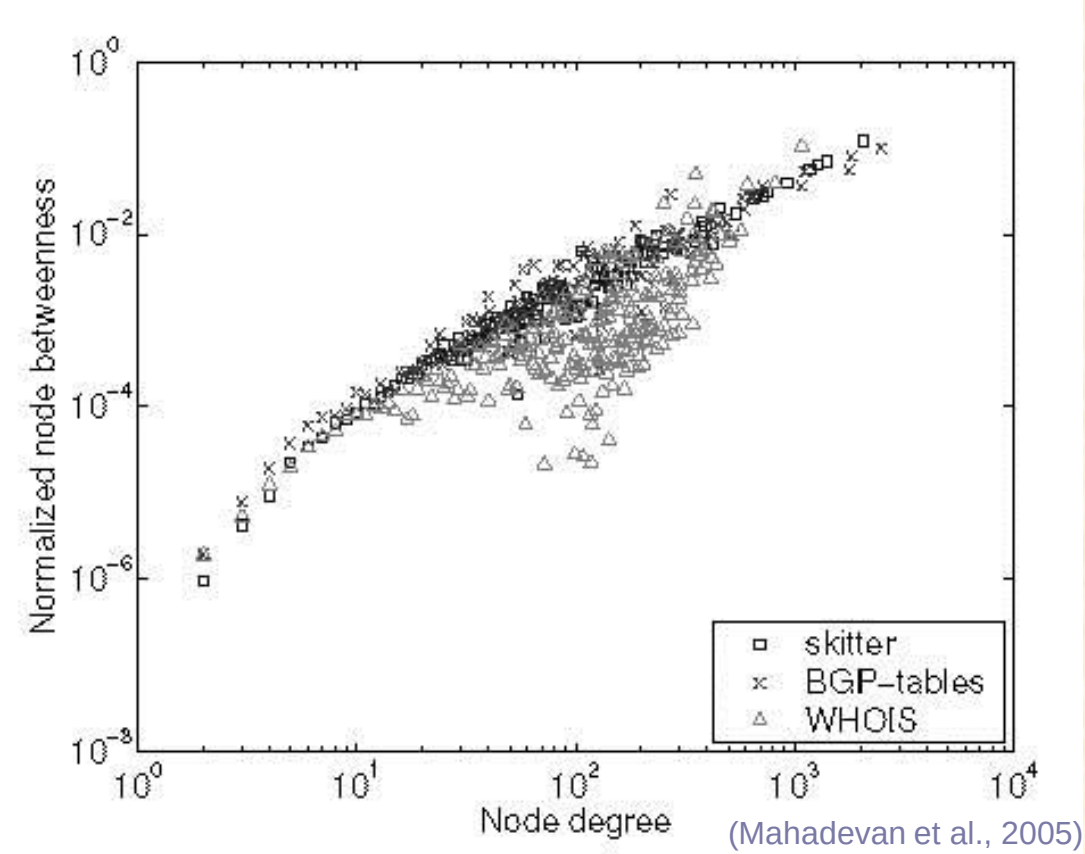
(Mahadevan et al., 2005)

Internet data from Skitter, BGP and Whois:

when the node degree is relatively small, they have a power-law relation, with exponents **0.58**, **0.68** and **1.07**, respectively;

when the node-degree > 100, their coreness values become saturated.

Betweenness



(Mahadevan et al., 2005)

Internet data from Skitter, BGP and Whois:

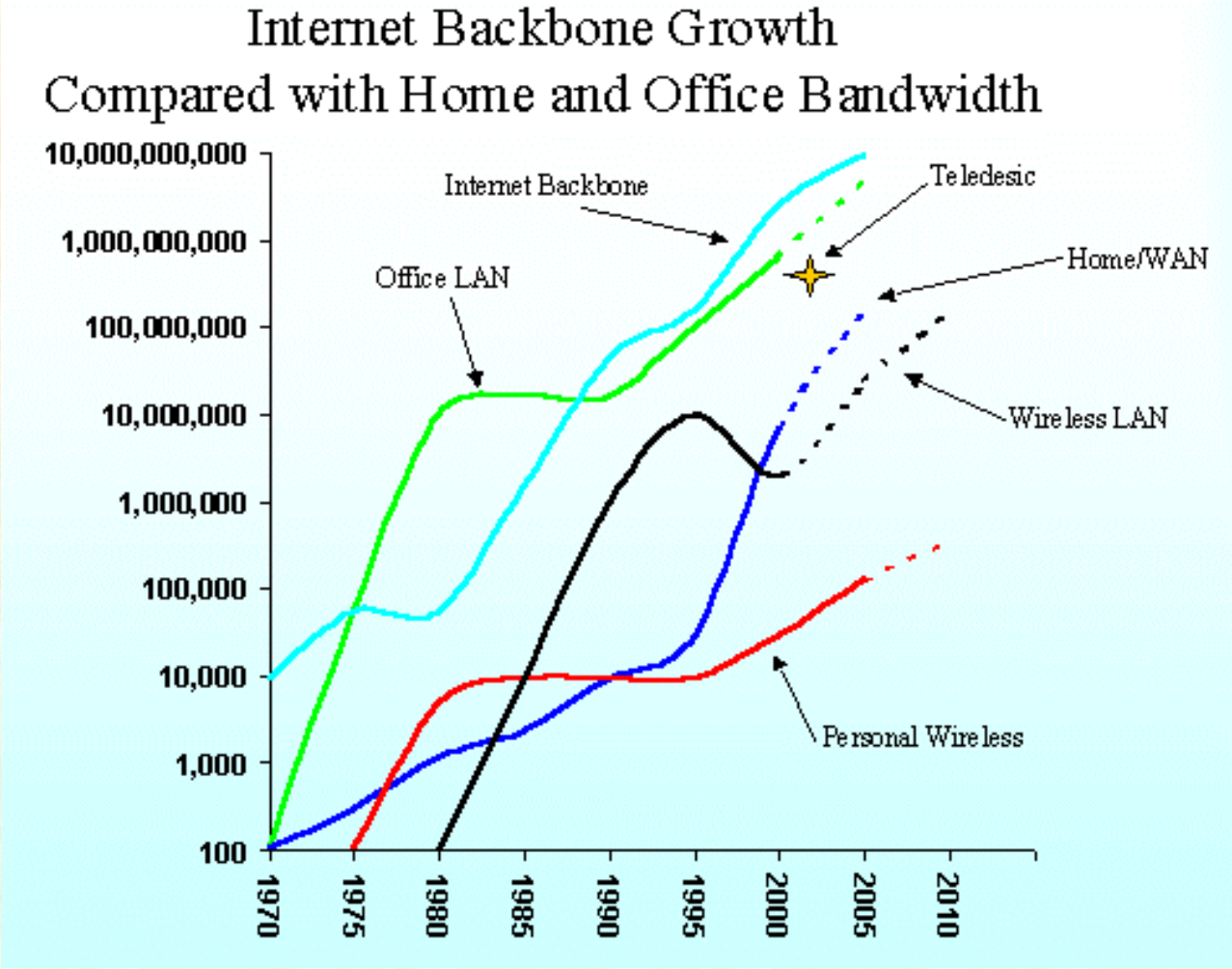
For those from Skitter and BGP, their relations follow prominent power-law distributions with components **1.35** and **1.17**, respectively

Growth of the Internet

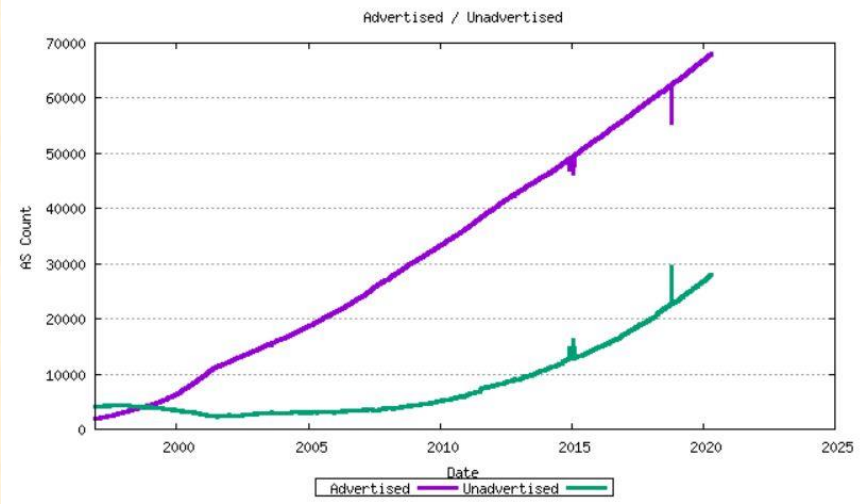
- Internet is a dynamically evolving complex network, which is rapidly and continuously growing and restructuring

- Some historical data of the Internet are examined below, which were provided by
  - SCAN Project with the software named Mercator
  - Oregon router services (at the AS level)
  - Topology Project of the Computer Science Department of the Michigan University (at the Extended AS level)

Growth of the Internet



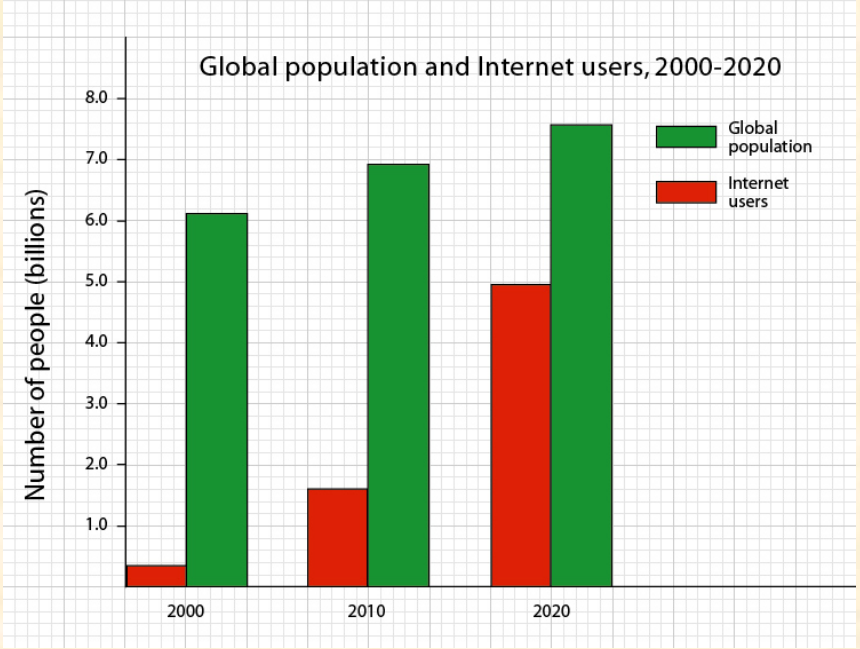
Growth of the Internet



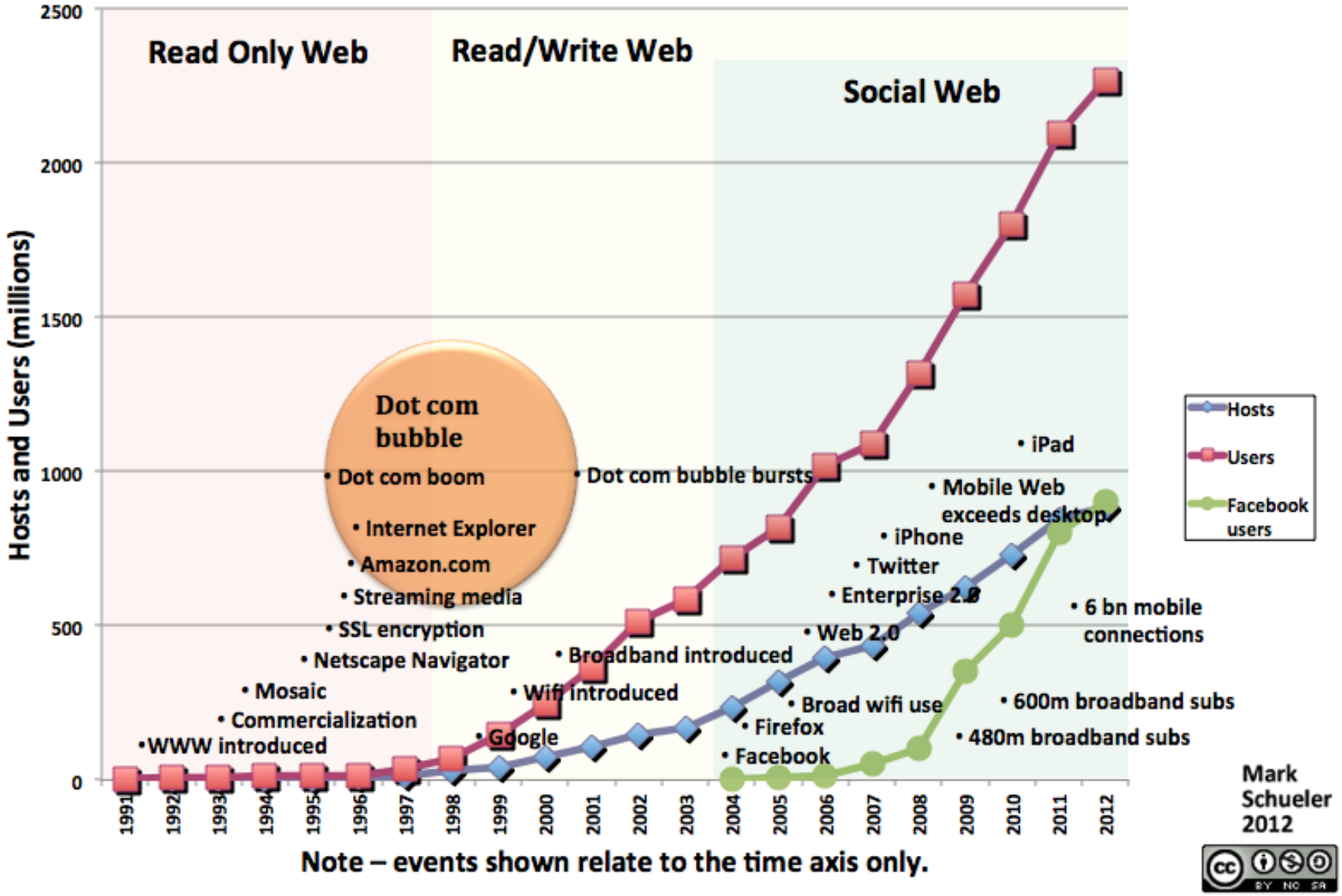
AS Numbers

(Data Source)

Comparison →



Internet Growth - Usage Phases - Tech Events



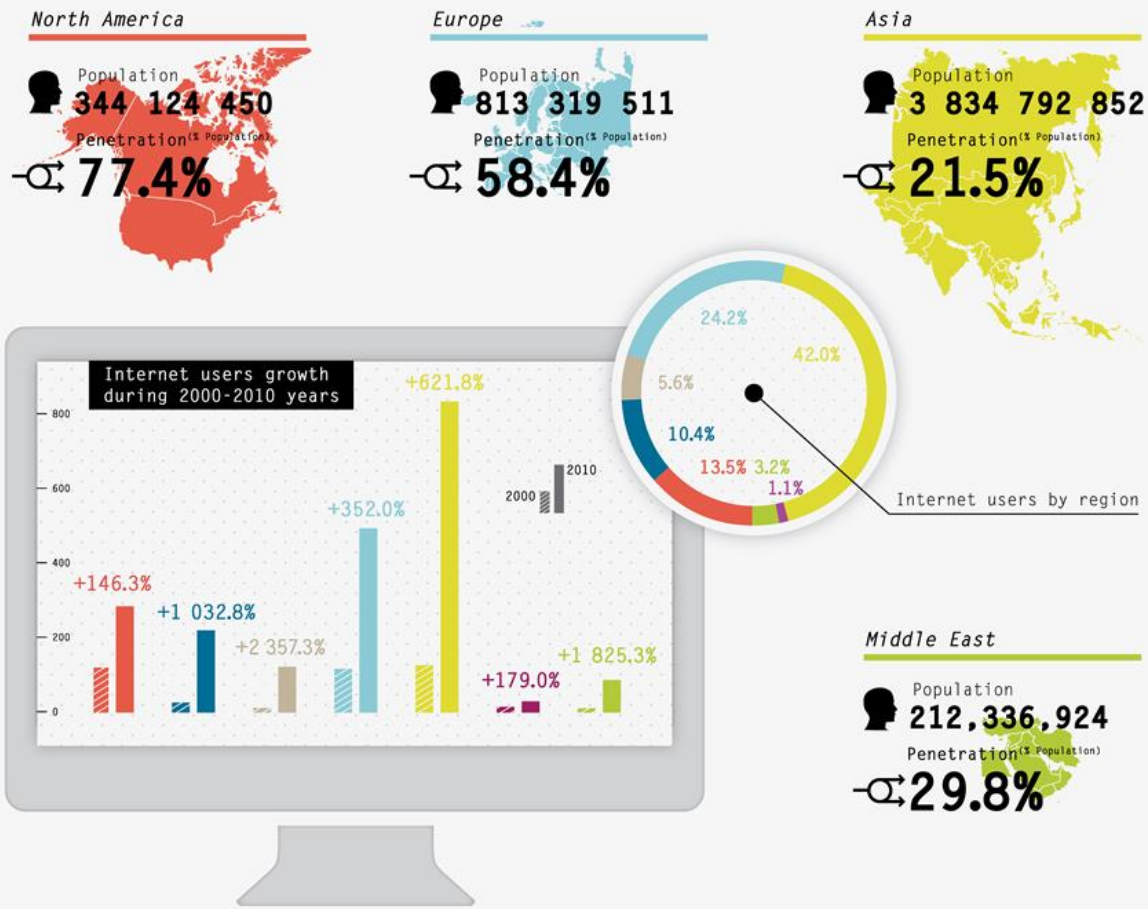
← THE INTERNET GROWTH →

North America

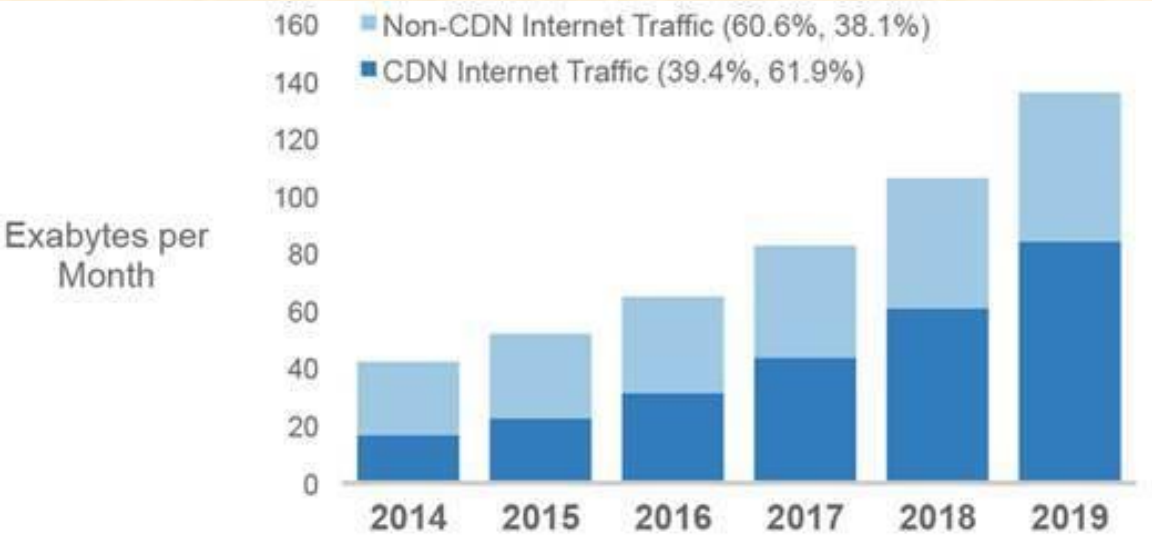
Asia

South America

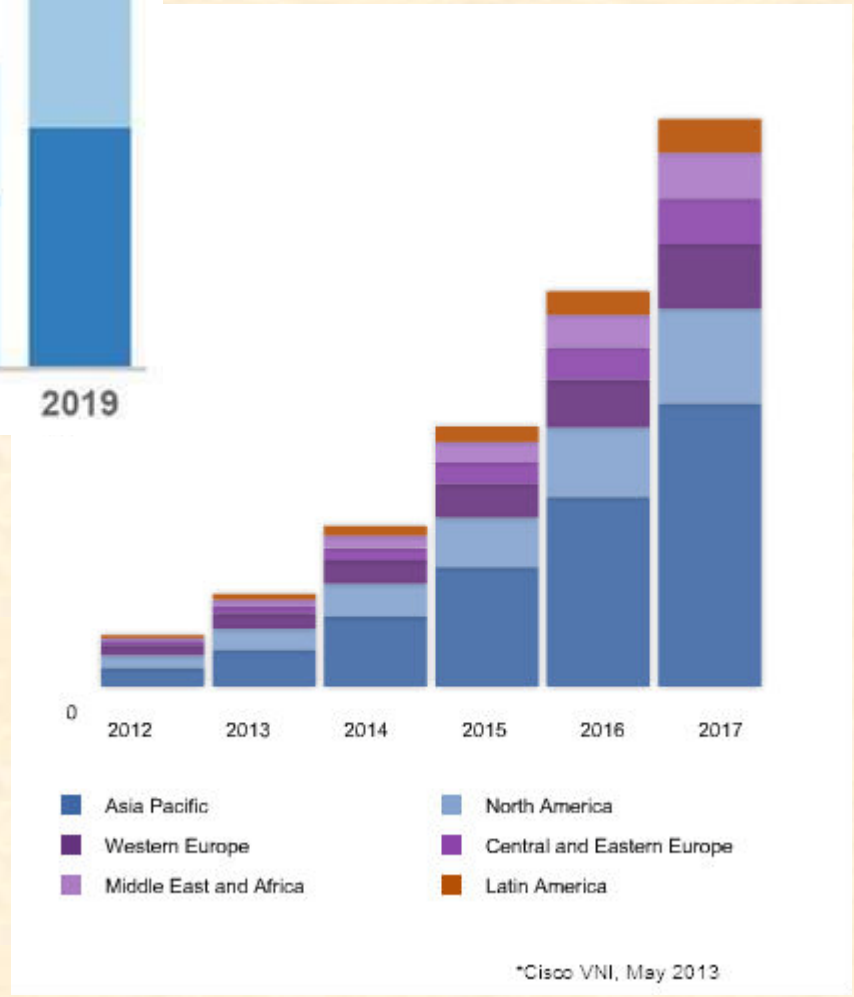
Australia



Internet Traffic Growth



CDN = Content Delivery Network



Features of the Internet

Table 4-1 Some average measures of the Internet at the IR, AS, and EAS levels

Level	N	E	$\langle k \rangle$	C	L	B
IR	228,263	320,149	2.8	0.03	9.5	5.3
AS	11,174	23,409	4.2	0.30	3.6	2.3
EAS	11,461	32,730	5.7	0.35	3.6	2.3

IR -- Internet Router
AS -- Autonomous System
EAS -- Extended Autonomous System

N -- number of nodes
E -- number of edges
$\langle k \rangle$ -- average node degree
C -- average clustering coefficient
L -- average shortest path lengths
B -- average node-betweenness

(Pastor-Satorras and Vespignani, 2004)

Features of the Internet

Reproducing the IPv6 Internet AS topology

	AS by Dolphin	BA Model	EBA Model
Number of nodes	419	419	419
Number of edges	1812	1661	1694
Avg degree	8.64	7.92	8.09
Exponent of $P(k)$	1.27	2.82	2.13
Max degree	119	55	57
Avg distance	2.78	3.00	3.12
Nomalized avg node betweenness	4.2E-3	4.7E-3	5.0E-3
Nomalized avg edge betweenness	1.5E-3	1.8E-3	1.5E-3
Avg clustering	0.692	0.041	0.293
Exponent of rich club	-1.26	-1.10	-1.19

B. Xiao, et al., Physica A (2009)

Node Evolution of the Internet

Table 4-2 Total numbers of additions and deletions of the Internet at the AS level

Degree	Number of Additions	Number of Deletions
1	5,591	1,184
2	816	204
3	23	22
4	4	6
5	1	4
6	1	1
7	1	1
9	0	1
10	1	0
11	1	0
12	0	1
14	1	0
48	0	1

(Qin et al., 2002)

Edge Evolution of the Internet

Table 4-3 Monthly rate of new edges connecting old nodes to new and old ones

Year	1998	1999
$E_{n,o}$	170	231
$E_{o,o}$	350	450
$E_{n,o} / E_{o,o}$	0.48	0.53

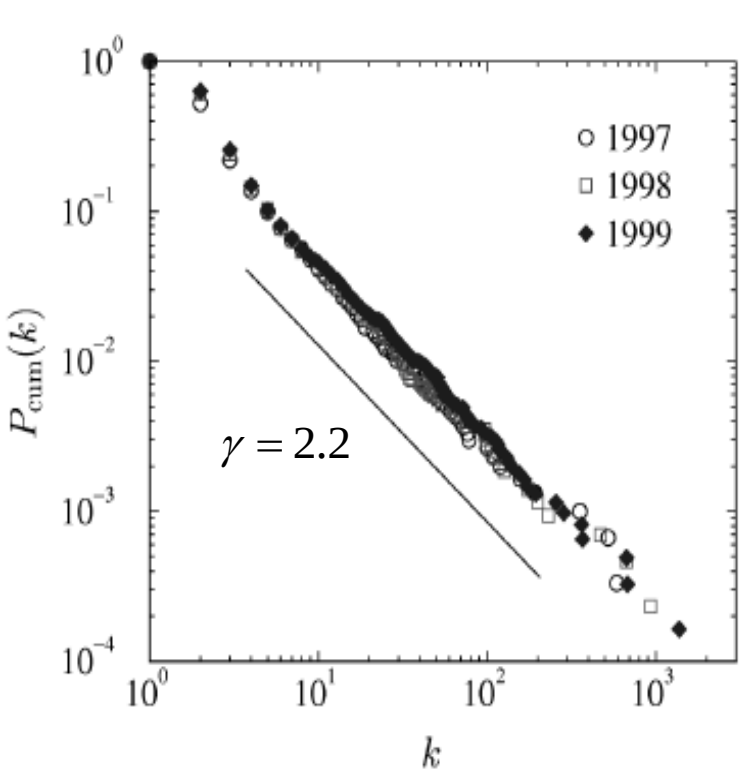
$E_{n,o}$ -- numbers of new edge additions between incoming nodes and existing nodes

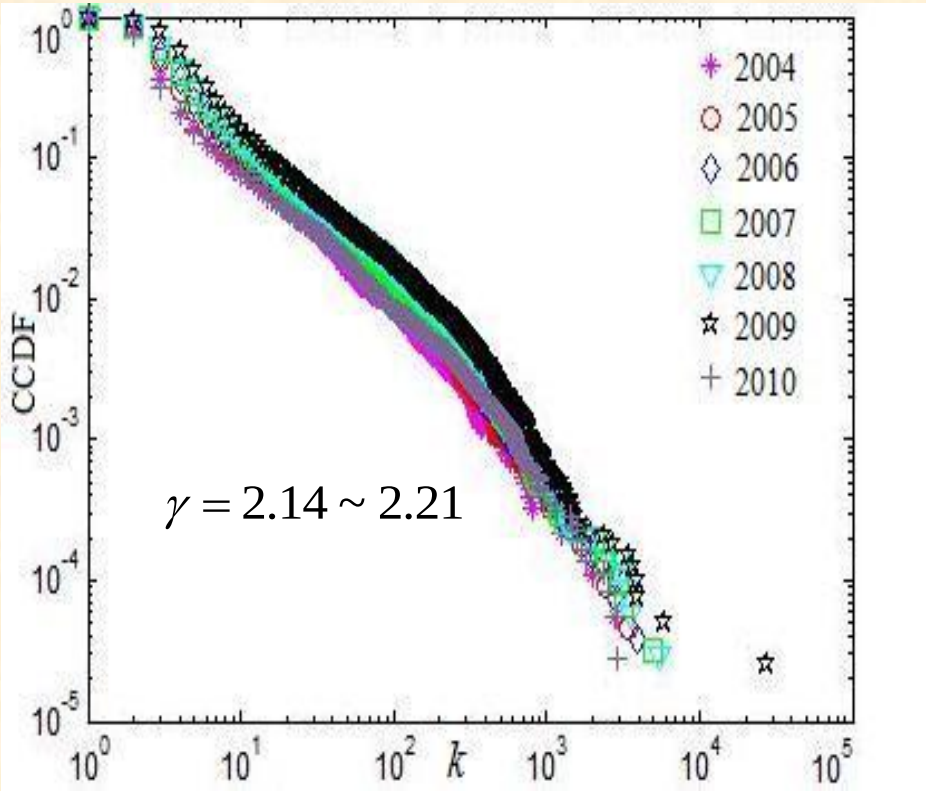
$E_{o,o}$ -- numbers of new edge additions between two existing nodes

(Vazquez et al., 2002)

Scale-Free Internet

$$P(k) \sim k^{-\gamma}$$



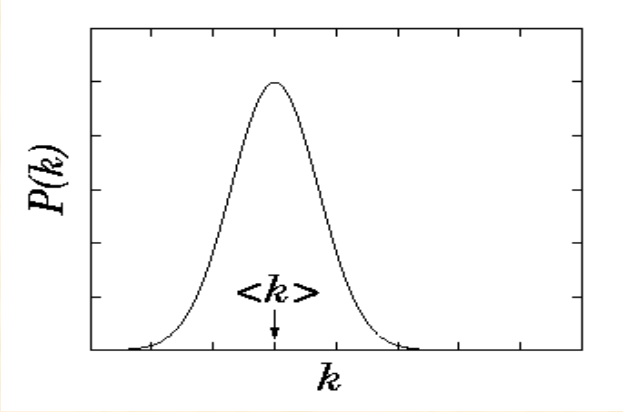


(Autonomous Systems level)

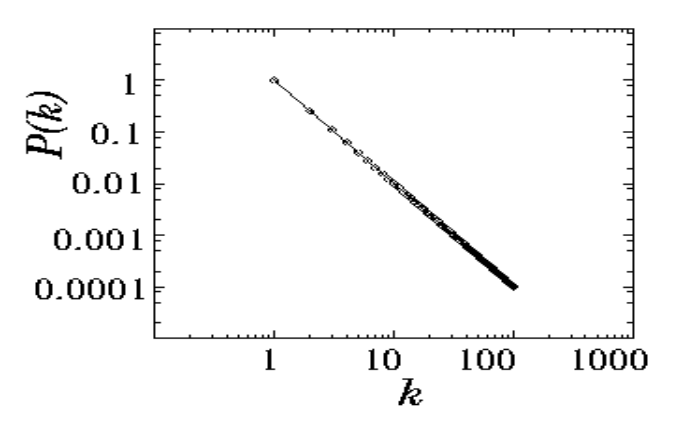
Z. P. Fan and G. R. Chen (2005, 2010)

Road Map vs Airline Routing Map

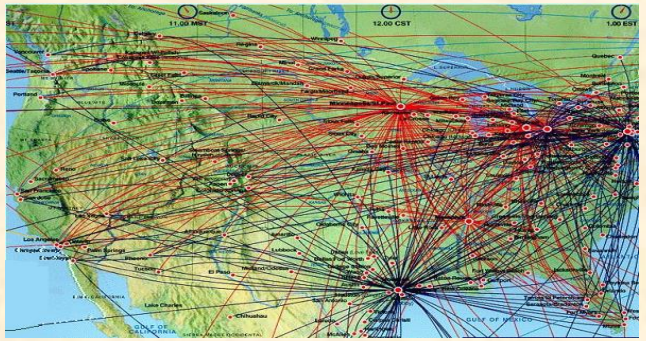
Poisson distribution



Power-law distribution $p(k) \sim k^{-\gamma}$



Small-world Network



Scale-free Network

(nodes: cities edges: highways)

(nodes: airports edges: flights)

Robustness and Fragility of Scale-Free Networks

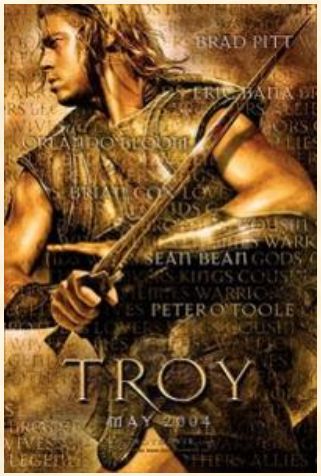
"Achilles' heel"

R. Albert, H. Jeong, A. L. Barabasi, Nature, 406, 387-482 (2000)

In Greek mythology, when Achilles was a baby, his mother Thetis took him to the River Styx, which was supposed to offer powers of invulnerability, and dipped his body into the water. But as mother held Achilles by the heel, his heel was not washed over by the water of the magical river. Achilles grew up to be a man of war who survived many great battles. On one day, a poisonous arrow shot at him was lodged in his heel, killing him shortly after.

“Achilles' heel”

Corfu, Greece



2004 film: TROY

特洛伊

Trojan Hours

Robustness versus Fragility

Illustration:

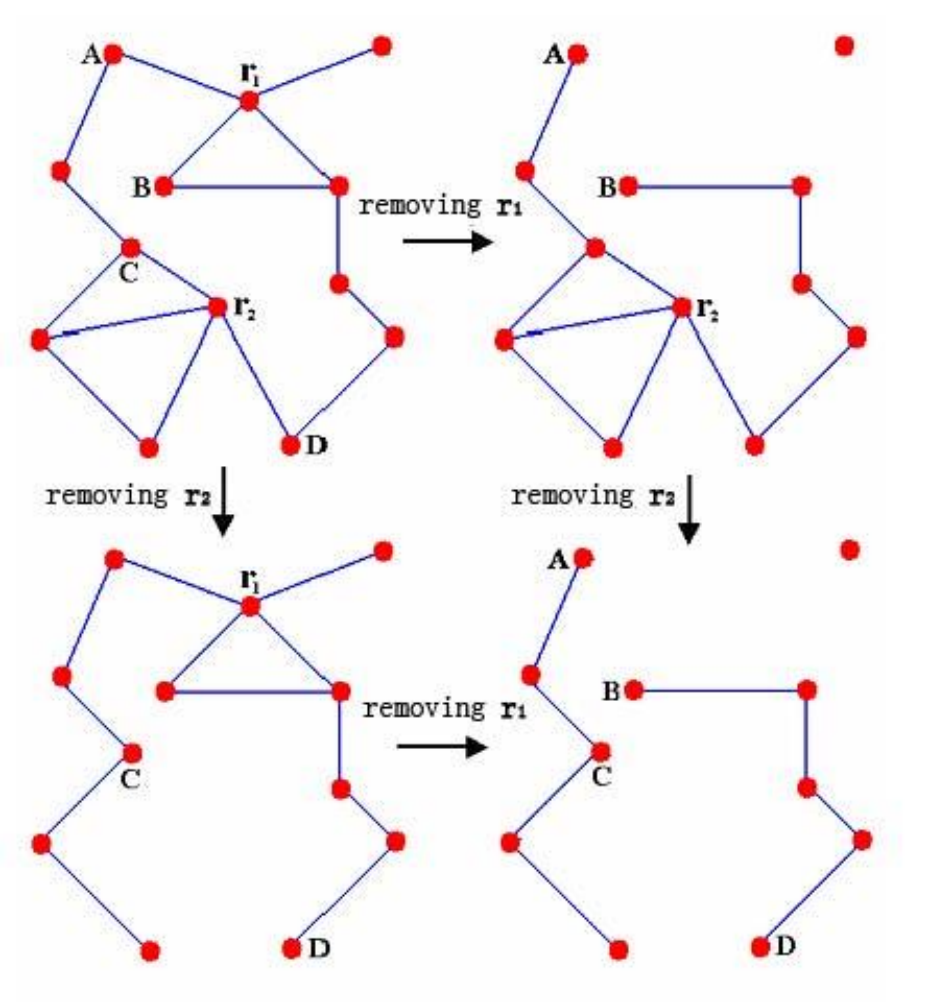
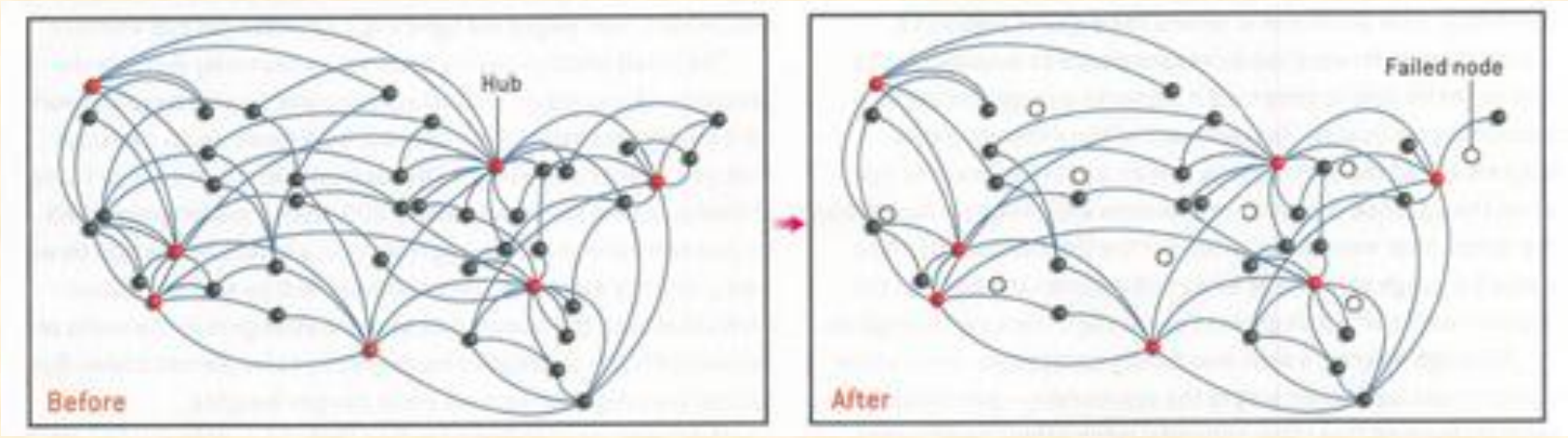
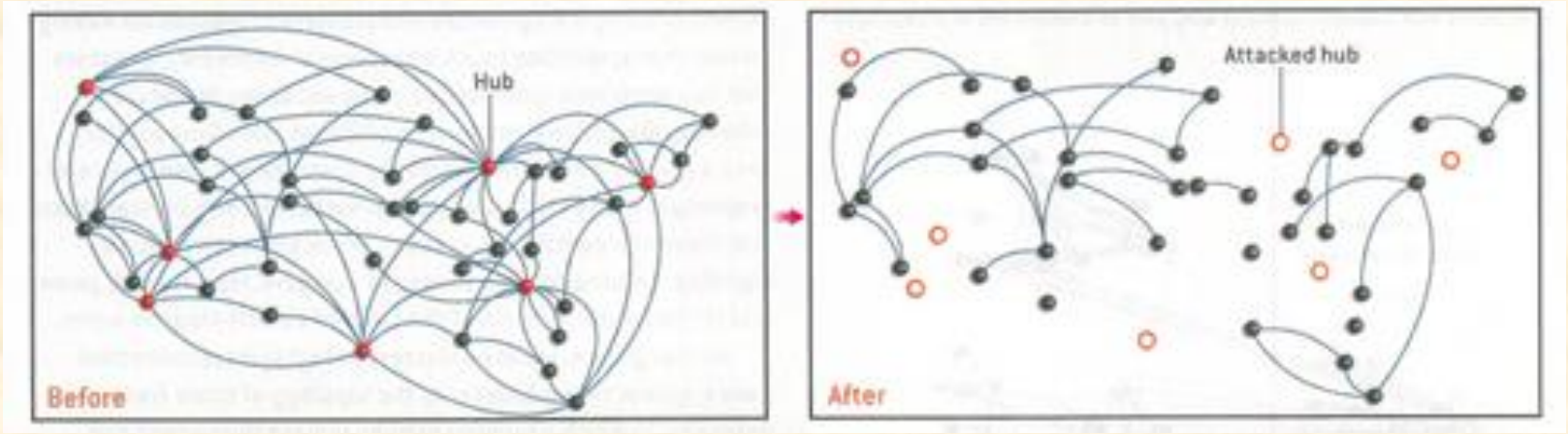


Illustration Example:

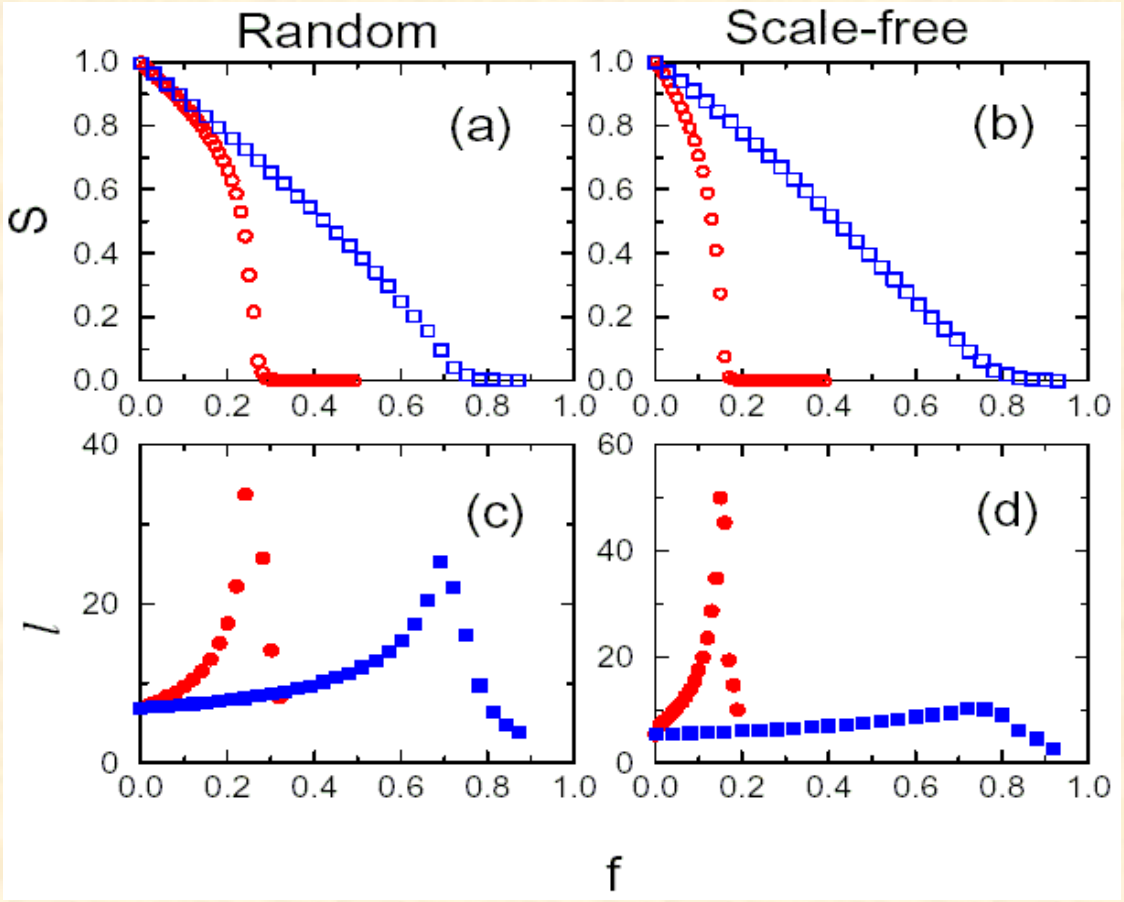


(a) Random failures



(b) Intentional attacks

Simulation Example:



S – size of largest subgraph

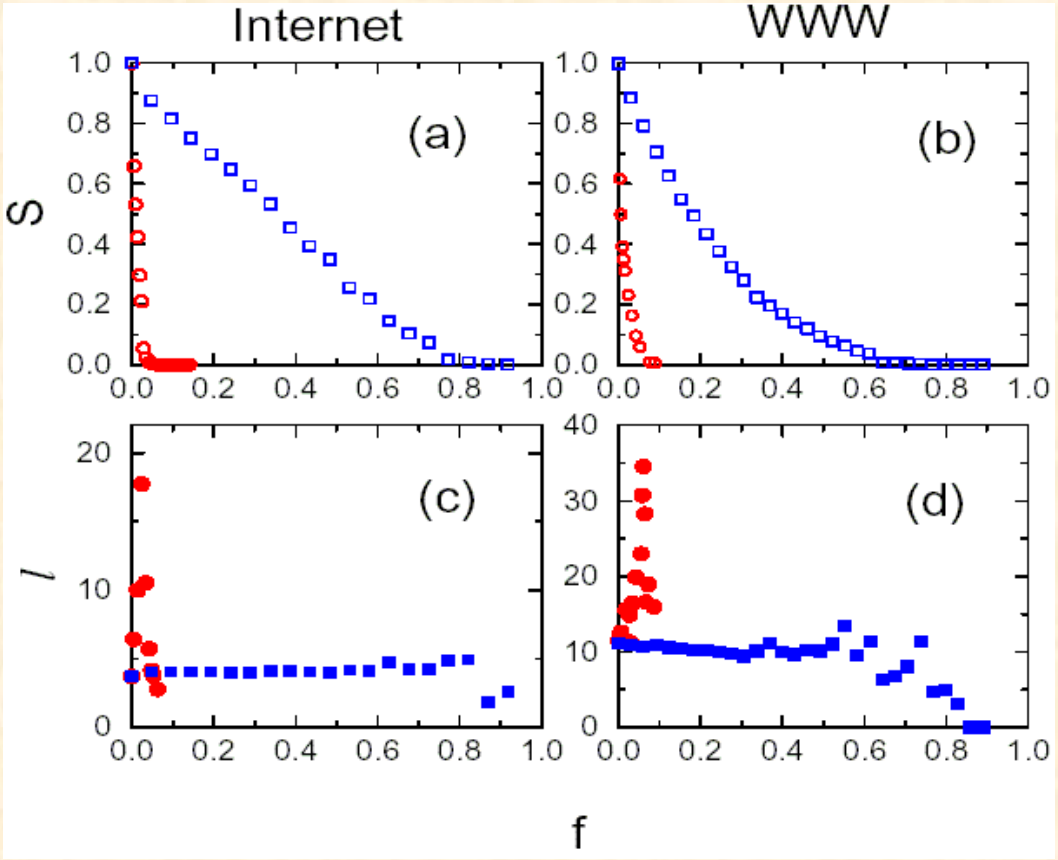
l – average path length

f – fraction of attacks

R. Albert, H. Jeong, A. L. Barabasi, Nature, 406, 387-482 (2000)

Robustness and fragility of ER random-graph and BA scale-free networks: (a) and (c): ER random-graph networks; (b) and (d): BA scale-free networks; squares—random removal of nodes; circles—intentional removal of nodes

Internet and WWW: Simulation Results



S – size of largest subgraph

l – average path length

f – fraction of attacks

R. Albert, H. Jeong, A. L. Barabasi, Nature, 406, 387-482 (2000)

Robustness and fragility of the Internet and WWW against intentional attacks:
(a) and (c): Internet; (b) and (d): WWW
squares—random failures, circles—intentional attacks

End