Information Theory and Networks

Lecture 27: A Brief History of Networks

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September 20, 2013

Processing delay

Section 1

Computer Networks

Computer networks are a recent invention (in human history), but they have been around for longer than some of you may think. In this lecture we consider the underlying drivers in computer networks, and how this subject fits with the ongoing development of those networks.

Computer pre-history

- The original "computers" were people
  - numerical algorithms performed with pencil and paper
  - later with mechanical adding machines
- Algorithms were often parallelized
  - multiple computers worked on same problem to speed up or check calculations
  - a "computer network" was result of passing bits of paper

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20th century

Computer networks:

- First generation of electrical digital computers 1940s
- Second generation – late 1950s and early 1960s
  - transistor invented in 1947 (at AT&T)
  - direct networks: peripherals such as printers directly attached to computers
- Third generation, post-1964
  - integrated circuits
  - real computer networks start
- 1965, Moore's law discovered
  - computers get better and better ...

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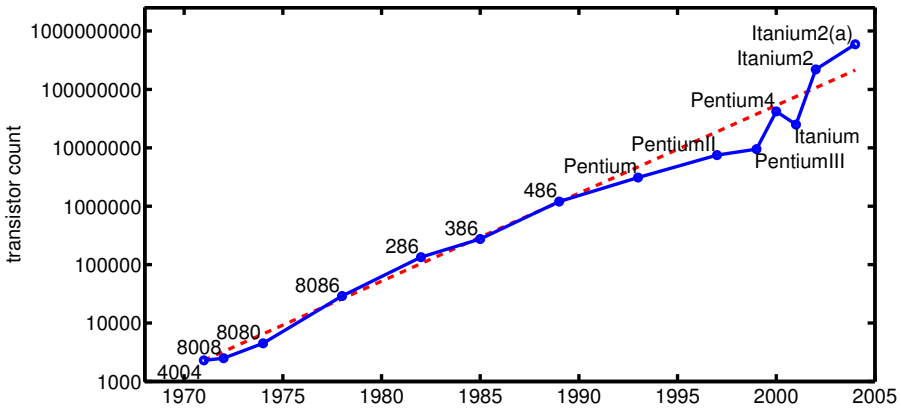
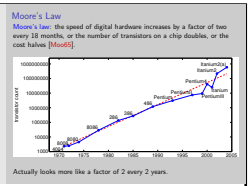
- 1965, Moore's law discovered
  - computers get better and better ...

Moore's Law

Moore's law: the speed of digital hardware increases by a factor of two every 18 months, or the number of transistors on a chip doubles, or the cost halves [Moo65].



Actually looks more like a factor of 2 every 2 years.



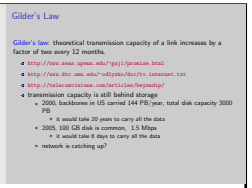
Intel's pages on Moore's law:
http://www.intel.com/technology/mooreslaw/index.htm
ftp://download.intel.com/research/silicon/moorespaper.pdf

Other links to Moore's law:
http://en.wikipedia.org/wiki/Moore's_law
http://www.thocp.net/biographies/papers/moores_law.htm
http://www.firstmonday.org/issues/issue7_11/tuomi/
http://www.hyperdictionary.com/computing/moore's+law
http://www.physics.udel.edu/wwwusers/watson/scen103/intel.html
http://www.ziplink.net/~lroberts/Forecast69.htm

Gilder's Law

Gilder's law: theoretical transmission capacity of a link increases by a factor of two every 12 months.

- http://www.seas.upenn.edu/~gaj1/promise.html
- http://www.dtc.umn.edu/~odlyzko/doc/tv.internet.txt
- http://telecomvisions.com/articles/beyondip/
- transmission capacity is still behind storage
  - 2000, backbones in US carried 144 PB/year, total disk capacity 3000 PB
    - it would take 20 years to carry all the data
  - 2005, 100 GB disk is common, 1.5 Mbps
    - it would take 6 days to carry all the data
  - network is catching up?



"I returned, and saw under the sun, that the race is not to the swift, nor the battle to the strong, neither yet bread to the wise, nor yet riches to men of understanding, nor yet favor to men of skill; but time and chance happeneth to them all."

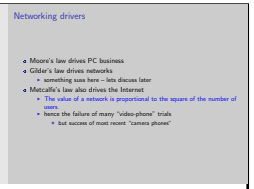
Ecclesiastes 9:11

The race is not always to the swift, nor the battle to the strong, but that's the way to bet.

Anon

Networking drivers

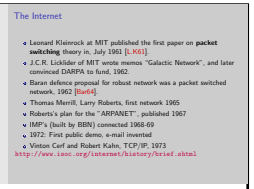
- Moore's law drives PC business
- Gilder's law drives networks
  - something suss here – lets discuss later
- Metcalfe's law also drives the Internet
  - The value of a network is proportional to the square of the number of users.
  - hence the failure of many "video-phone" trials
    - but success of most recent "camera phones"



The Internet

- Leonard Kleinrock at MIT published the first paper on **packet switching** theory in, July 1961 [L.K61].
- J.C.R. Licklider of MIT wrote memos "Galactic Network", and later convinced DARPA to fund, 1962.
- Baran defence proposal for robust network was a packet switched network, 1962 [Bar64].
- Thomas Merrill, Larry Roberts, first network 1965
- Roberts's plan for the "ARPANET", published 1967
- IMP's (built by BBN) connected 1968-69
- 1972: First public demo, e-mail invented
- Vinton Cerf and Robert Kahn, TCP/IP, 1973

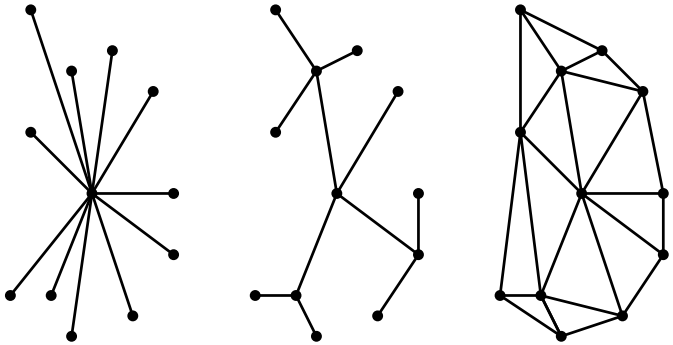
http://www.isoc.org/internet/history/brief.shtml



FEBRUARY, 2005: The Association for Computing Machinery (ACM) awarded Internet pioneers Vinton Cerf and Robert Kahn the Turing Award (often considered the Nobel Prize of Computing) for "pioneering work on internetworking, including the design and implementation of the Internet's basic communications protocols, TCP/IP, and for inspired leadership in networking."
http://www.acm.org/awards/turing_citations/cerf_kahn.html

The Early Internet

Paul Baran, 1960s, envisioned a comm.s network that would survive a major enemy attack. The sketch shows three network topologies described in [Bar64].



Original available at
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centralized decentralized distributed
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The centralized network is highly vulnerable to damage to it central node, and other nodes will be detached from the network by link failures

The distributed network structure has best survivability.

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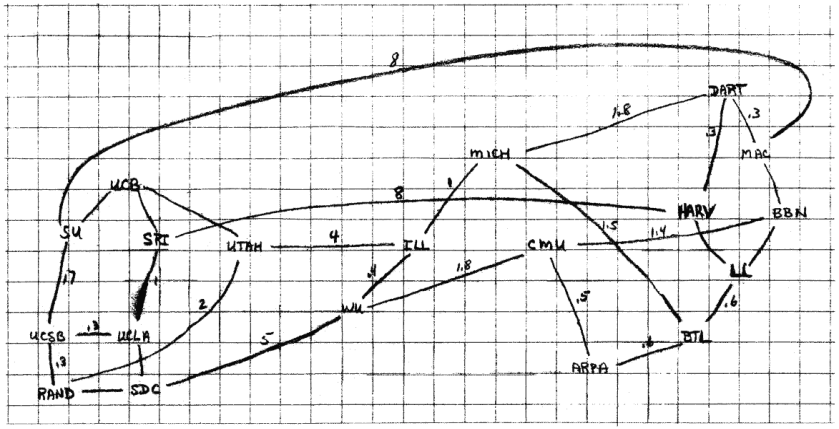
A rough sketch map of the possible topology of ARPANET by Larry Roberts. Drawn in the late 1960s as part of the planning for the network [HL96, p.50].



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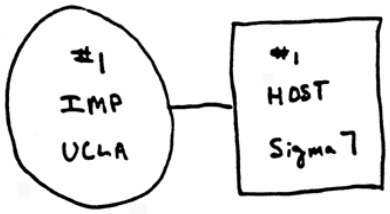
Early on, the ARPANET was small enough to design on the back of an envelope. This is rarely possible for todays networks.

The Early Internet

The first node on ARPANET at University California Los Angeles (UCLA) on the 2nd of September 1969 [CK90].



IMP = Interface Message Processor
what we would call a router
TIP = Terminal IMP
IMP to which terminals can directly connect
Host = computer (which provides services)

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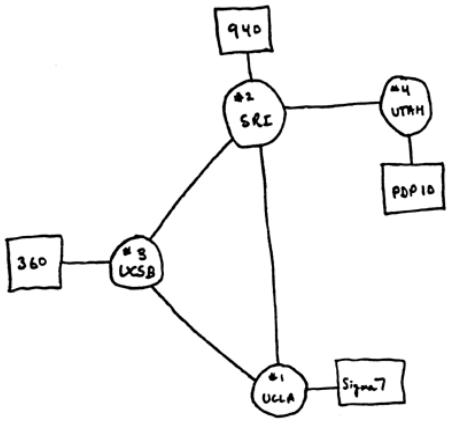

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The first letters transmitted on the Internet were "lo", transmitted between SRI and UCLA on October 29, 1969. The letters were the beginning of "login" of which only the first two letters were sent before the system crashed.

http://www.lk.cs.ucla.edu/first_words.html

The Internet: the 80's

- new developments
  - Personal Computers (PCs)
    $\Rightarrow$ lots more computers to network
  - Ethernet (1973, Robert Metcalfe) creates LANs
- the Internet
  - TCP/IP provides a way to hook up the LANs and PC over wide areas (standard in 1980)
  - scale gets bigger
    - ★ numbers increase
    - ★ becomes international
  - partitioning
    - ★ ARPANET splits into MILNET and ARPANET in early 80's, followed by further additions

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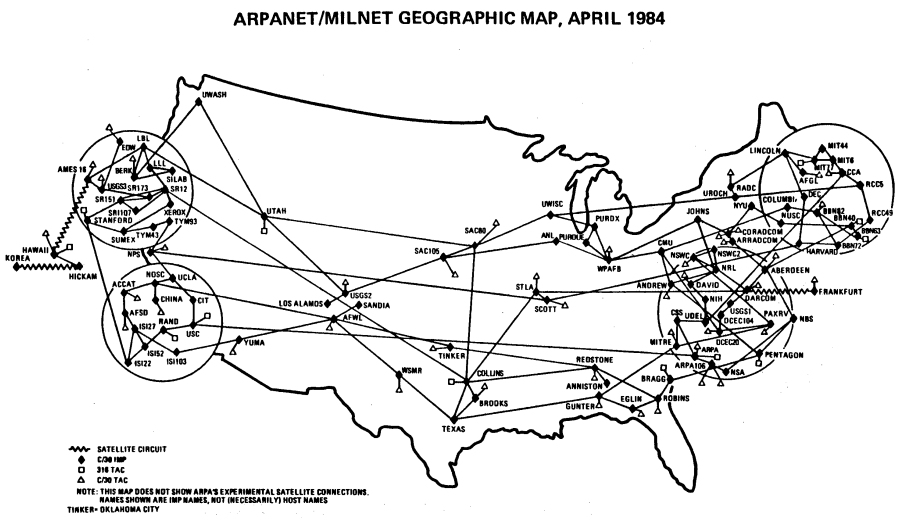

The Internet: the 80's
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The Internet: the 90's

- ARPANET decommissioned 1990
  - NSF Backbone connects many other networks
    - ★ Australia connected in 1990 [Abb99]

```
It was the first, and being first, was best,
but now we lay it down to rest.
Now pause with me a moment, shed some tears.
For auld lange syne, for love, for years and years
of faithful service, duty done, I weep.
Lay down thy packet, now, O friend, and sleep.
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Vinton Cerf, 1989

- commercial Internet services evolve
  - 1995 NSFNET terminated (replaced by vBNS)
  - effectively fully privatised Internet
  - links through exchange points

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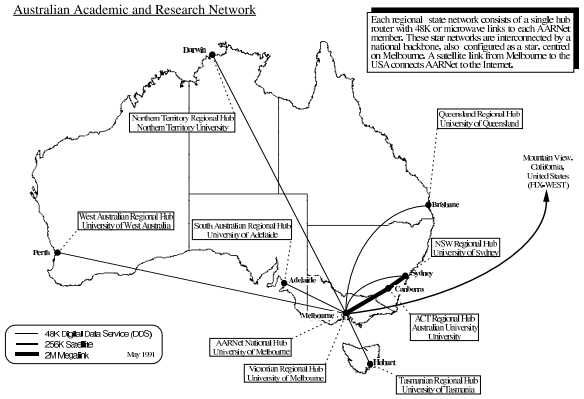

http://www.ucs.ed.ac.uk/fmd/unix/edftp/pub/maps/

New network
http://www.aarnet.edu.au/engineering/aarnet3/

The Internet: the 90's
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The Internet: the 90's

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- 1990: World Wide Web
  Tim Berners-Lee created HyperText Markup Language, or HTML. Along with URL (Uniform Resource Locators), and HTTP (HyperText Transfer Protocol), created the web. Based on earlier work at CERN (1980).
- 1993: Mosaic (Marc Andreesen, NCSA)
  Mosaic became the first popular web browser. It was not only easy to use to access the World Wide Web, but it was also extremely easy to download and install!
- Killer app =¿ the Internet takes off in a big way

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Early Internet Bandwidth Growth

All the time **backbone** link speeds have been growing

- 1969: 50kbps
- 1988: NSFNET backbone upgraded to T1 (1.544Mbps)
- 1991: NSFNET backbone upgraded to T3 (44.736Mbps)
- 1996: MCI upgrades Internet backbone 622Mbps
- 1999: MCI/Worldcom begins upgrading the US backbone to 2.5 Gbps (OC48)
- circa 2003: 10 Gbps (OC192)

Backbone speeds are behind limits of transmission tech.
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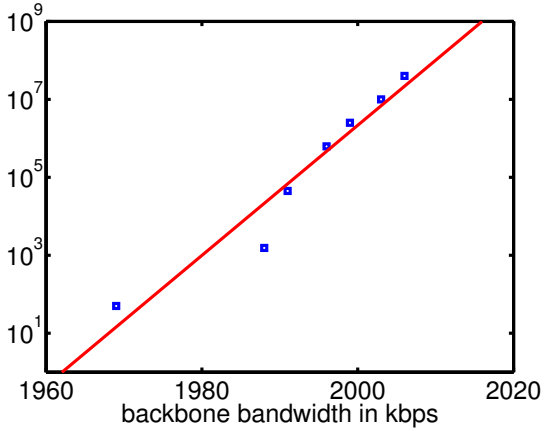
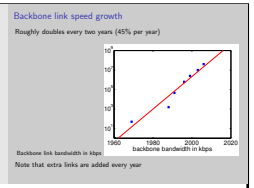
Backbone link speed growth

Roughly doubles every two years (45% per year)



Backbone link bandwidth in kbps

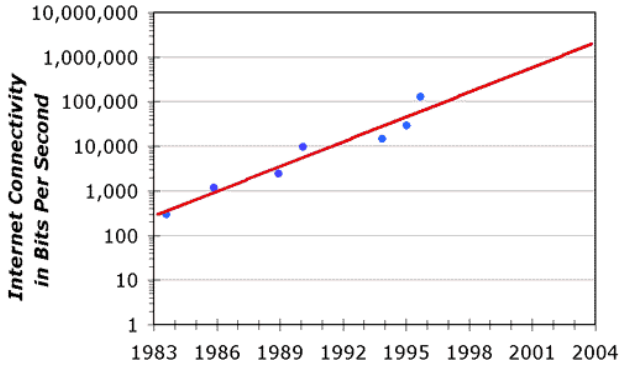
Note that extra links are added every year

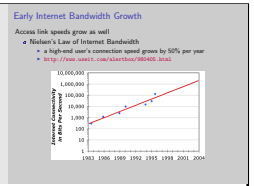


Early Internet Bandwidth Growth

Access link speeds grow as well

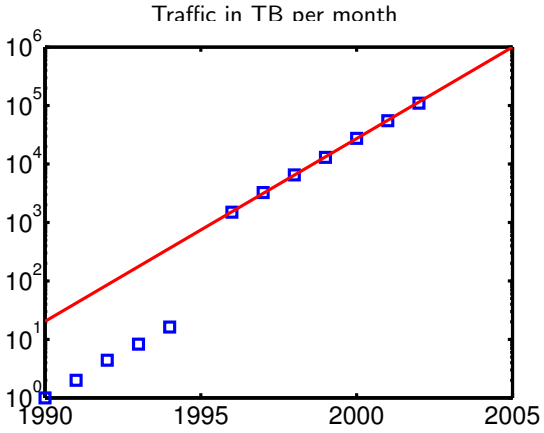
- Nielsen's Law of Internet Bandwidth
  - a high-end user's connection speed grows by 50% per year
  - http://www.useit.com/alertbox/980405.html



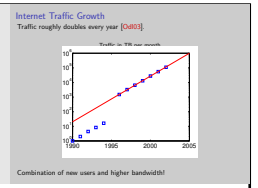


Internet Traffic Growth

Traffic roughly doubles every year [Odl03].



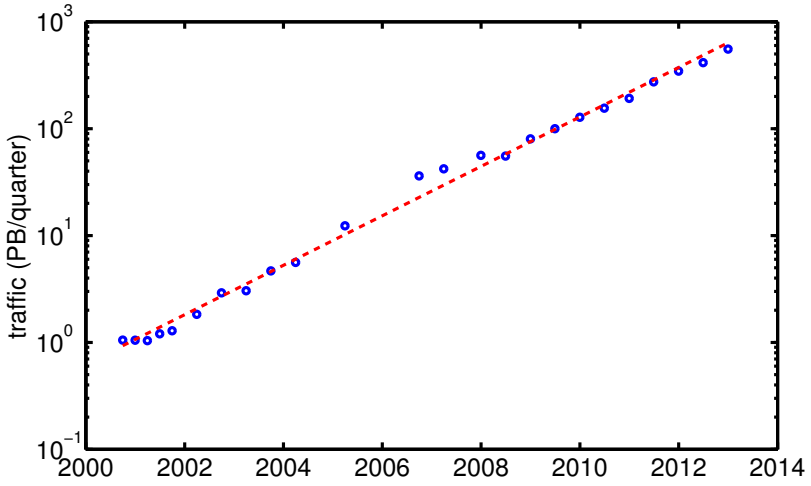
Combination of new users and higher bandwidth!



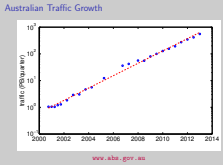
Internet traffic was believed to overtake telephone traffic around 2002.

Extrapolated Internet growth from 90's data.
http://www.cc.gatech.edu/gvu/stats/NSF/Extrap.GIF

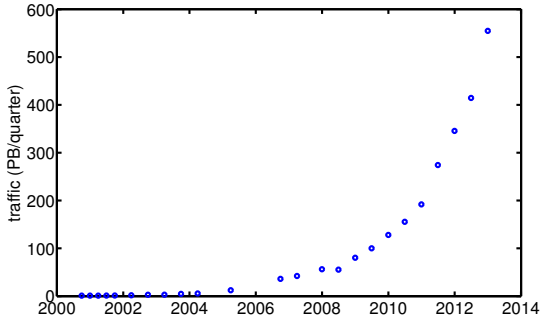
Australian Traffic Growth



www.abs.gov.au



Measurements taken from the Australian Bureau of Statistics: see
http://www.abs.gov.au/ausstats/abs@.nsf/mf/8153.0/



Part I

A Brief History of Communications Networks

> You know what they say. Those of us who fail history, are doomed to repeat it in summer school.
>
> *Buffy (the Vampire Slayer), "After Life" (Season 6, Ep. 3), 2001*

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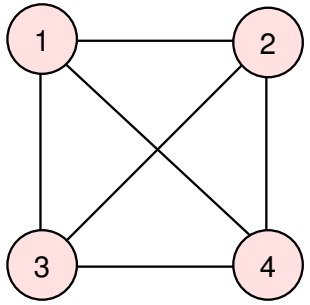
Why bother?

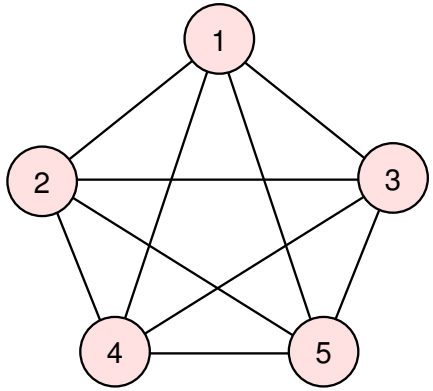
- ideas have their time
  - most things are invented for a need
  - this gives insight into network design
- most things in networking are reinvented again and again
  - can save a lot of time if you already know the answer
- gentle introduction to some concepts

Dumb network design

One link between every pair who wish to speak

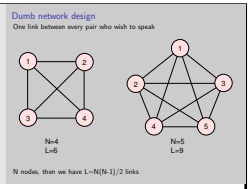


N=4
L=6



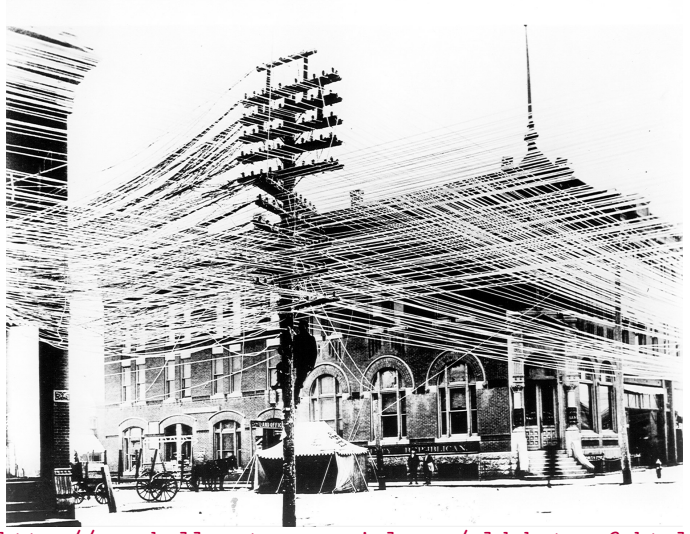
N=5
L=9

N nodes, then we have L=N(N-1)/2 links

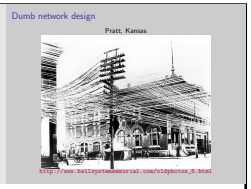


Dumb network design

Pratt, Kansas



http://www.bellsystemmemorial.com/oldphotos_6.html



PUT BACK PARTS ON SWITCHING

Towards modern telephony

- switching
  - electronic switch (instead of electromechanical)
  - 4ESS (like a building)
    http://www.att.com/history/nethistory/switching.html
- networks become hierachical
  - long distance versus local
- reliability and redundancy become important
  - alternate routing
- billing systems
  - harder than you think!

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Some additional links

More detailed telephony timelines can be found at
http://www.telephonetribute.com/timeline.html
http://www2.fht-esslingen.de/telehistory/
http://www.webbconsult.com/hist-time.html
http://www.ieee.org/organizations/history_center/comsoc/timelines.html
http://williamstallings.com/Extras/Telecom.html
http://aronsson.se/hist.html

Histories of computing and computer networks
http://en.wikipedia.org/wiki/Computing_timeline
http://www.isoc.org/internet/history/
http://www.isoc.org/internet/history/brief.shtml
http://www.dei.isep.ipp.pt/docs/arpa.html
http://www.zakon.org/robert/internet/timeline/
http://en.wikipedia.org/wiki/History_of_the_Internet
http://goldenink.com/computersandnetworks.shtml
http://www.davesite.com/webstation/net-history.shtml
http://www.computerhistory.org/exhibits/internet_history/
http://www.tranquileye.com/cyber/
http://www.caslon.com.au/timeline.htm

Section 2

Computer Networks

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  - real computer networks start
- 1965, Moore's law discovered
  - computers get better and better ...

20th century

Computer networks:

- First concept of idea of digital computer 1940s
- Second generation – late 1950s and early 1960s
  - transistor invented in 1947 (at AT&T)
  - direct networks: peripherals such as printers directly attached to computers
- Third generation, post-1964
  - integrated circuits
  - real computer networks start
- 1965, Moore's law discovered
  - computers get better and better ...

Networking drivers

- Moore's law drives PC business
- Gilder's law drives networks
  - something suss here – lets discuss later
- Metcalfe's law also drives the Internet
  - The value of a network is proportional to the square of the number of users.
  - hence the failure of many "video-phone" trials
    - but success of most recent "camera phones"

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- J.C.R. Licklider of MIT wrote memos "Galactic Network", and later convinced DARPA to fund, 1962.
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FEBRUARY, 2005: The Association for Computing Machinery (ACM) awarded Internet pioneers Vinton Cerf and Robert Kahn the Turing Award (often considered the Nobel Prize of Computing) for "pioneering work on internetworking, including the design and implementation of the Internet's basic communications protocols, TCP/IP, and for inspired leadership in networking."
http://www.acm.org/awards/turing_citations/cerf_kahn.html

The Early Internet

Kleinrock's insight [L.K61]

- computer traffic is bursty (it comes in spurts)
- more efficient to transmit packets of data on-demand than to reserve circuits between computers
  - setting up a circuit takes time (high latency)
  - keeping up a circuit set up is inefficient
    - not used most of the time
  - all you want to do is send one little chunk of data
    - example: typing – one character at a time
    - even a whole email is quite small
  - alternative: send data as packets

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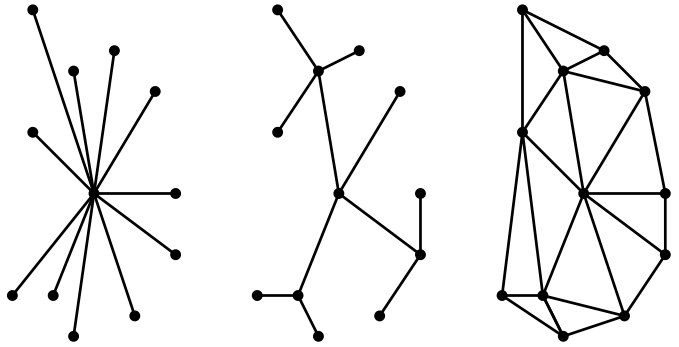
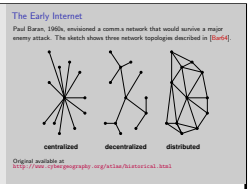
The Early Internet

Paul Baran, 1960s, envisioned a comm.s network that would survive a major enemy attack. The sketch shows three network topologies described in [Bar64].



centralized **decentralized** **distributed**

Original available at
http://www.cybergeography.org/atlas/historical.html

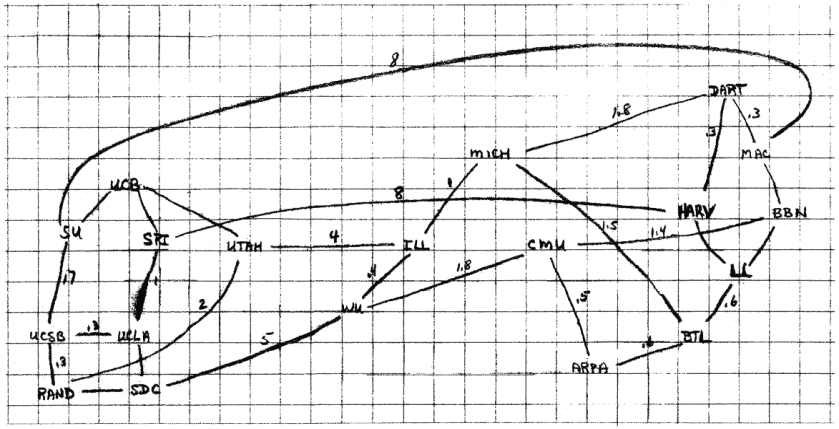


The centralized network is highly vulnerable to damage to it central node, and other nodes will be detached from the network by link failures

The distributed network structure has best survivability.

The Early Internet

A rough sketch map of the possible topology of ARPANET by Larry Roberts. Drawn in the late 1960s as part of the planning for the network [HL96, p.50].



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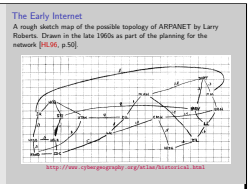
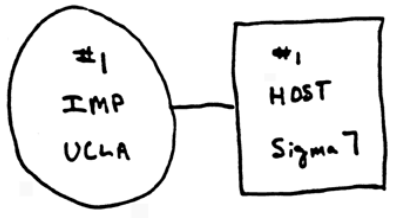


Early on, the ARPANET was small enough to design on the back of an envelope. This is rarely possible for todays networks.

The Early Internet

The first node on ARPANET at University California Los Angeles (UCLA) on the 2nd of September 1969 [CK90].



IMP = Interface Message Processor
what we would call a router
TIP = Terminal IMP
IMP to which terminals can directly connect
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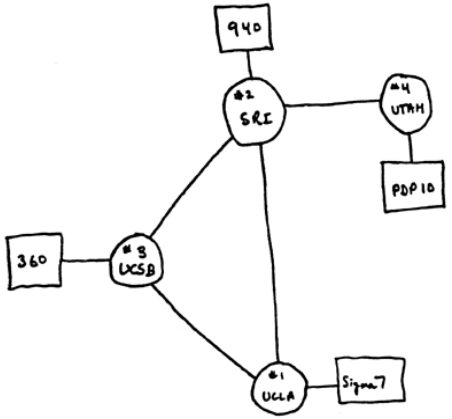

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The first letters transmitted on the Internet were "lo", transmitted between SRI and UCLA on October 29, 1969. The letters were the beginning of "login" of which only the first two letters were sent before the system crashed.

http://www.lk.cs.ucla.edu/first_words.html

The Early Internet

- a lot of effort went into design of the protocols, and architecture
- the actual network was designed more by constraints: geographic, cost, political, (i.e. who had funding to participate)
  - some formal optimization (Howard Frank in particular)
- you can design a network on the back of an envelope when it has 4 nodes.
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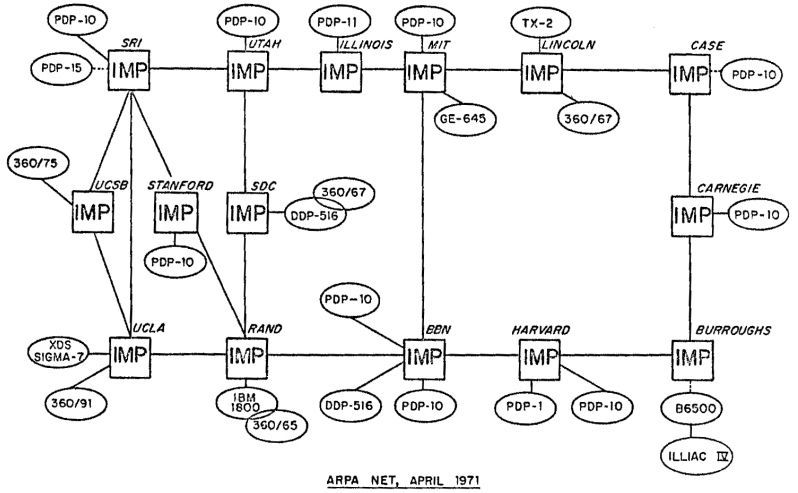
Formal optimization of computer networks reputedly first appeared in "Optimal Design of Centralized Computer Networks", H.Frank, I.T.Frisch, R.Van Slyke, and W.S.Chou, Networks, Vol.1, No.1, pp.43–58, 1971, but I haven't been able to obtain a copy as yet.

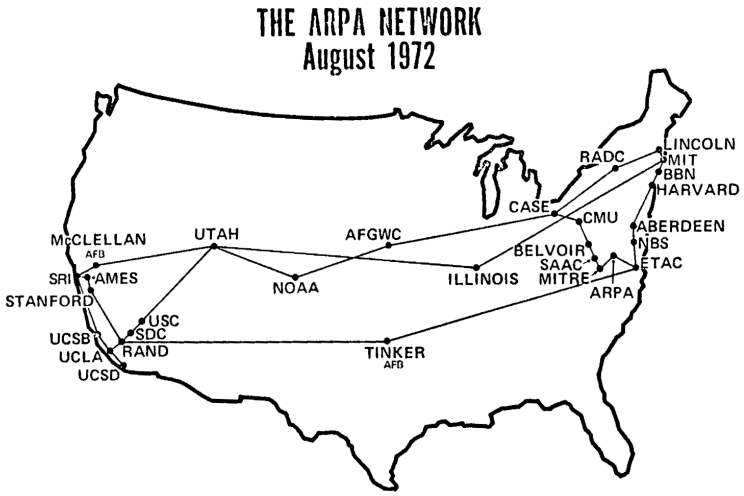
The Early Internet

The map above shows the logical topology of ARPANET in April 1971. (computers connect direct to IMPs) [CK90].



The Early Internet

ARPANET grew rapidly as more sites are connected [CK90].



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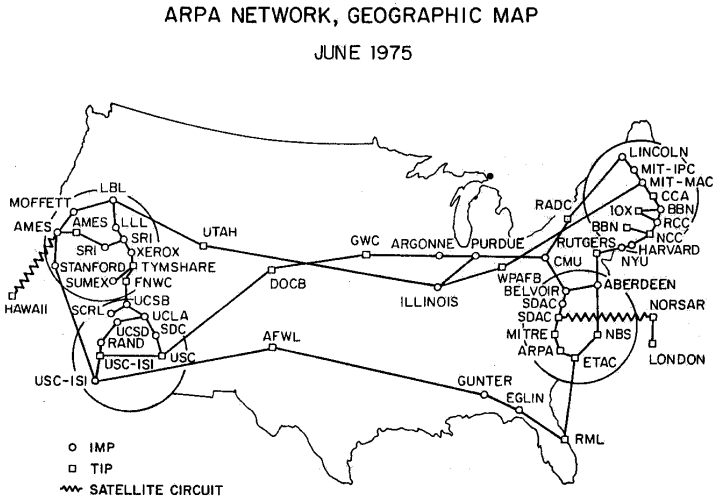

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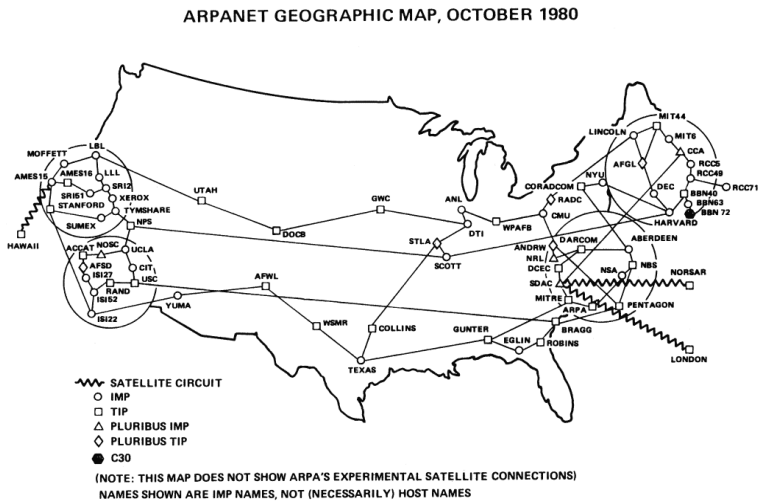

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The Internet: the 80's

- new developments
  - Personal Computers (PCs)
    $\Rightarrow$ lots more computers to network
  - Ethernet (1973, Robert Metcalfe) creates LANs
- the Internet
  - TCP/IP provides a way to hook up the LANs and PC over wide areas (standard in 1980)
  - scale gets bigger
    - ★ numbers increase
    - ★ becomes international
  - partitioning
    - ★ ARPANET splits into MILNET and ARPANET in early 80's, followed by further additions

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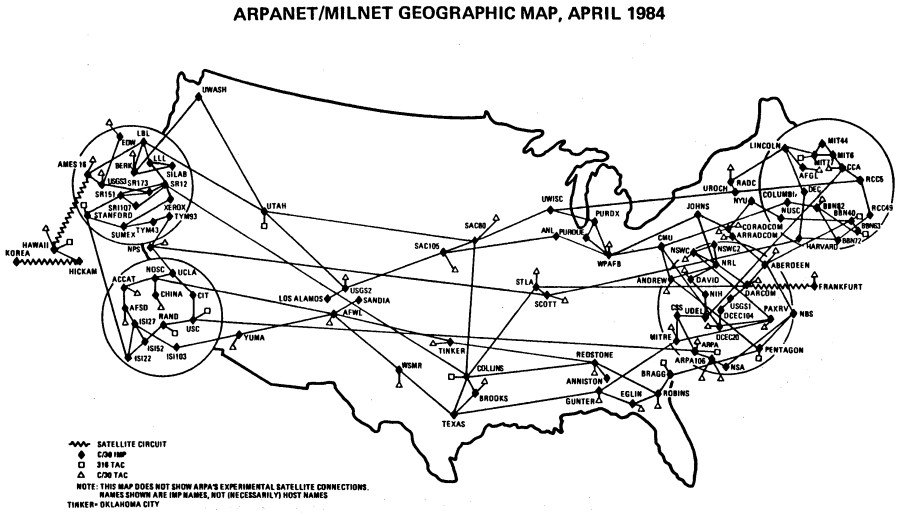
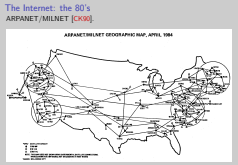
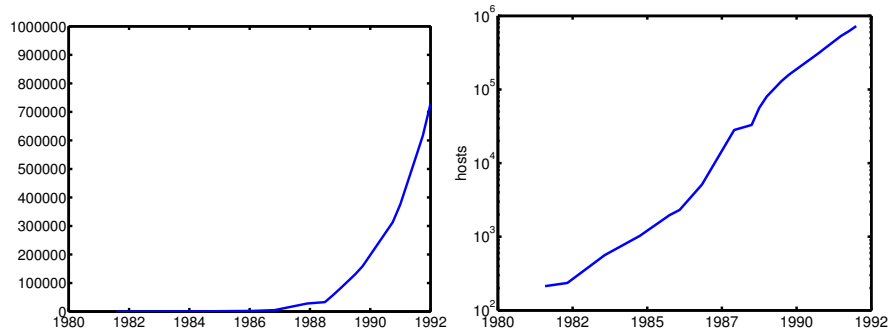


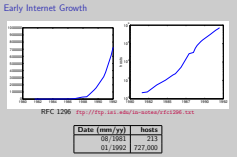


Early Internet Growth



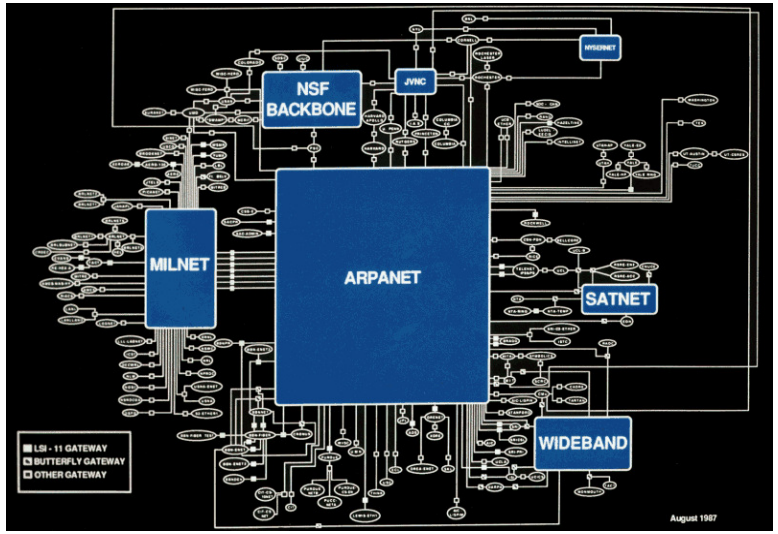
RFC 1296 ftp://ftp.isi.edu/in-notes/rfc1296.txt

Date (mm/yy)	hosts
08/1981	213
01/1992	727,000



The Early Internet

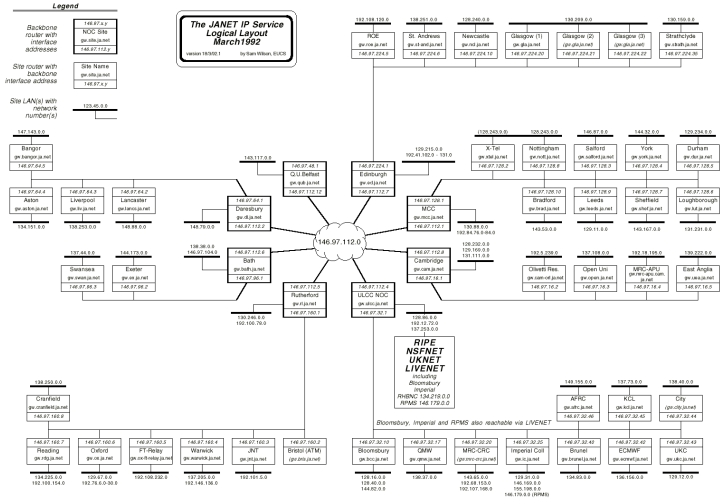
State of the core of the Internet in August 1987.



http://www.cybergeography.org/atlas/historical.html

Networks of networks

These maps show the structure of JANET, the UK's academic and research network, in 1992.



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- ARPANET decommissioned 1990
  - NSF Backbone connects many other networks
    - ★ Australia connected in 1990 [Abb99]

```
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but now we lay it down to rest.
Now pause with me a moment, shed some tears.
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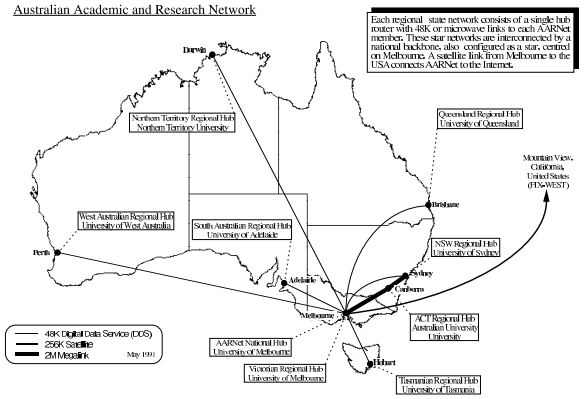
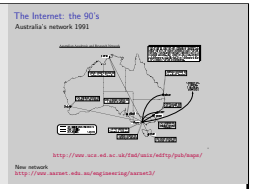


http://www.ucs.ed.ac.uk/fmd/unix/edftp/pub/maps/

New network
http://www.aarnet.edu.au/engineering/aarnet3/



The Internet: the 90's

http://www.w3.org/History.html

- 1990: World Wide Web
  Tim Berners-Lee created HyperText Markup Language, or HTML. Along with URL (Uniform Resource Locators), and HTTP (HyperText Transfer Protocol), created the web. Based on earlier work at CERN (1980).
- 1993: Mosaic (Marc Andreesen, NCSA)
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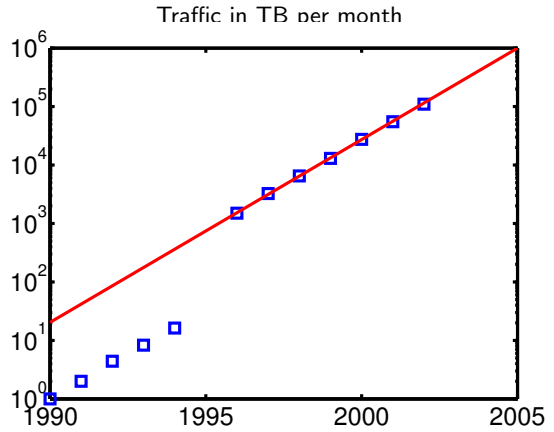
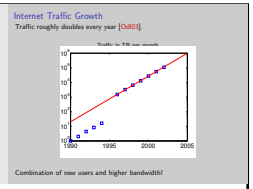
Internet Traffic Growth

Traffic roughly doubles every year [Odl03].



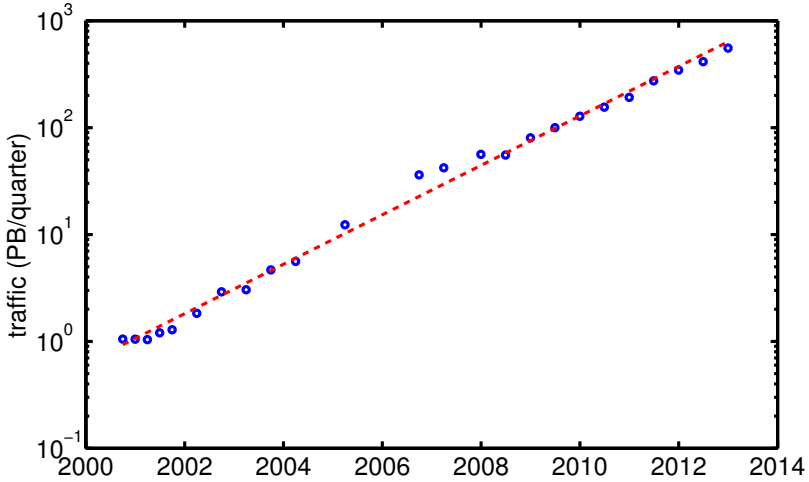
Combination of new users and higher bandwidth!



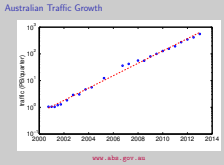
Internet traffic was believed to overtake telephone traffic around 2002.

Extrapolated Internet growth from 90's data.
http://www.cc.gatech.edu/gvu/stats/NSF/Extrap.GIF

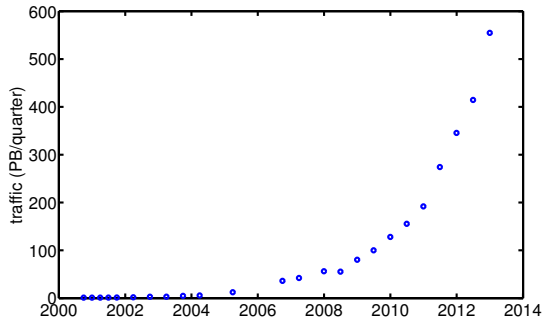
Australian Traffic Growth



www.abs.gov.au



Measurements taken from the Australian Bureau of Statistics: see
http://www.abs.gov.au/ausstats/abs@.nsf/mf/8153.0/



Other computer networks

The history of computer communications is not just about the Internet

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- other countries, e.g.
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BIT MORE ON HOW PACKET NETWORKS WORK

Further reading I

- Janet Abbate, *Inventing the internet*, MIT Press, 1999.
- Paul Baran, *On distributed communications: 1. introduction to distributed communications network*, RAND Memorandum, August 1964.
- V. Cerf and B. Kahn, *Selected ARPANET maps*, Computer Communications Review (CCR) **20** (1990), 81–110.
- Katie Hafner and Matthew Lyon, *Where wizards stay up late: The origins of the internet*, Touchstone, 1996.
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Further reading II

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