EECS 489: Computer Networks

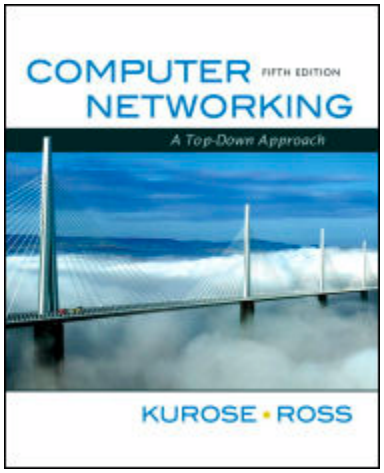
Lecture
- Time: MW 9:00-10:30
- Room: 1690 CSE

Discussion section:
- Time: Fri 9-10 (discussion starts this Friday)
- Room: 1690 CSE

Instructor: Z. Morley Mao
Office: 4629 CSE
Office hours: Mon 10:30-11:30, Wed 10:30-11:30, and by appt.
(but *never* right before lecture)
Tel: +1 734 763 5407

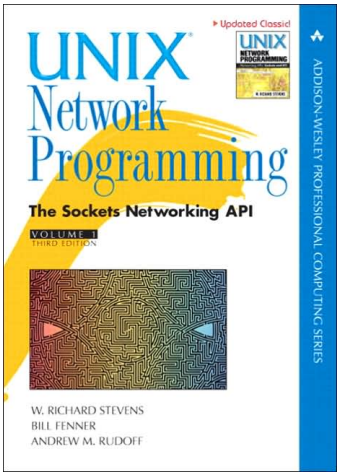
GSI: Zhiyun Qian (*zhiyunq*)
Office: 4917 CSE
Office hours: Tu 3:30-4:30PM, Fri 10-11AM, and by appt.

Required Textbook



Highly recommended Textbook

Source code at
http://www.unpbook.com/unpv13e.tar.gz



Web Site and Forum

Course Web site:
http://www.eecs.umich.edu/courses/eecs489/w10

- Course grade composition
- Policy on collaboration and cheating
- Regrade and late days

Lecture slides will be posted on web site *after* lecture

Web site and forum are "required readings"

Prerequisites:

- EECS 482
- C

Grading Policy

- 1 Final Exam: 30%
- 1 Midterm Exam: 20%
- 3 Homeworks: 15%
- 3 Programming Assignments: 30%
- Class Participation: 5%

Collaboration:

- All work must be done individually
- Cheating and plagiarizing are not tolerated

Regrade:

- Within 5 working days (except Final Exam, same day)
- Written request
- Whole work regraded

Late days:

- 4 free late days for the whole term
- 4% per 24 hours or fraction thereof thereafter

What this Course is NOT about

We do NOT cover:

- Homepage design, CSS, MySQL
- Photoshop, Flash, Silverlight, whatever
- Web site administration
- Web hosting and data center setup and maintenance
- DSL or cable modem setup
- LAN setup and administration
- How to connect to the Internet
- How to become an ISP
- How to run an ISP

What this Course Covers

Network Protocols and Architectures:

- Internet: a network of networks
- Application layer, naming
- Network layer: addressing and routing
- Link layer and wireless
- Transport layer and queue management
- Multimedia networking
- Security in networks

- Focus on the fundamental concepts, not merely the technology
- There will always be new protocols, but how do people design them?
- What are architectural principles?
- Provide high-level overview of computer networks
- Wired, wireless, cellular
- How they are interconnected

What is a Communication Network

Communication network offers one basic service: move information

- bird, fire, messenger, truck, telegraph, telephone, Internet …

Another example, transportation network: move objects

- horse, train, truck, airplane ...
- a car carrying a trunk load of tapes can also move information . . . .

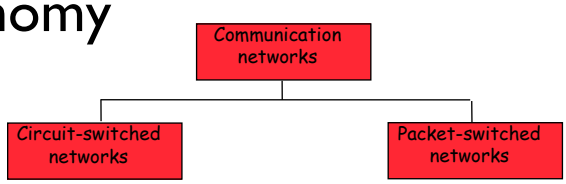
What distinguish different types of networks?

- the services they provide

What distinguish the services?

- Latency
- Bandwidth
  - a car carrying a trunk load of tapes has high bandwidth but low latency
- Loss rate
- Number of end systems supported
- Service interface (how to invoke the service?)
- Others
  - Reliability, unicast vs. multicast, real-time...

Communication Networks Taxonomy



POTS Network:

- parses number dialed
- sets up a circuit between caller and callee
- sends signal to ring callee's phone
- a circuit is set up between the two ends

Strengths:

- no end-point intelligence
- excellent voice performance

Weaknesses:

- difficult to add new services
- achieves performance and reliability by over-allocating resources (expensive)

The Internet:

- data parceled into packets
- each packet carries a destination address
- each packet is routed independently
- packets can arrive out of order
- packets may not arrive at all

Strengths:

- intelligence at end points
- decentralized control
- operates over heterogeneous access techs

Weaknesses:

- variable performance, no quality of service
- no trusted infrastructure

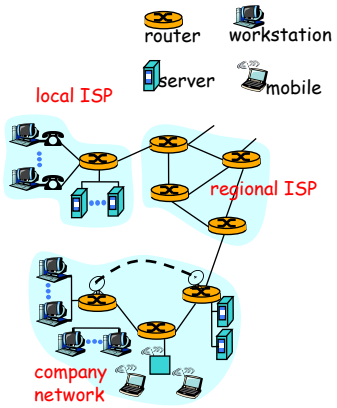
What's the Internet

Internet: "network of networks"

- loosely hierarchical
- public Internet versus private intranet

Network components:

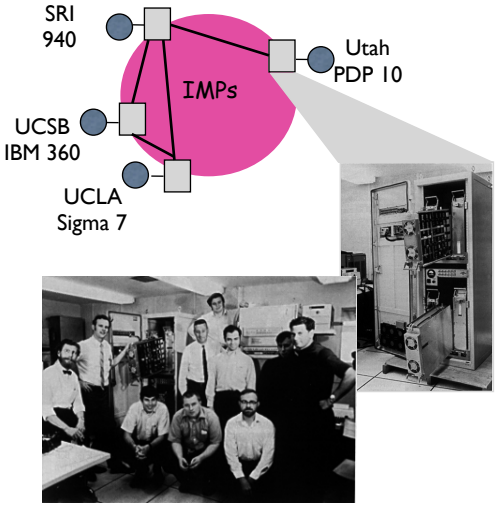
- hosts – communication endpoints: workstations, PDAs, cell phones, toasters, millions of them, running network applications
  - Applications: Web browser, Email clients, Chat clients, etc....
- links – carry bits from one place to another: fiber, copper, satellite, …
- routers/switches – interconnect links: store and forward packets



History of the Internet

- 68-70's: started as a research project, 56 kbps, initially 4 nodes (UCLA, UCSB, SRI, Utah) then < 100 computers
- 80-83: TCP/IP, DNS; ARPANET and MILNET split
- 85-86: NSF builds NSFNET as backbone, links 6 Supercomputer centers, 1.5 Mbps, 10,000 computers
- 87-90: link regional networks, NSI (NASA), ESNet (DOE), DARTnet, TWBNet (DARPA), 100,000 computers
- 90-92: NSFNET moves to 45 Mbps, 16 mid-level networks
- 94: NSF backbone dismantled, multiple private backbones; Introduction of Commercial Internet
- Today: backbones run at 10 Gbps, close to 200 millions computers in 150 countries

The ARPANet



Paul Baran

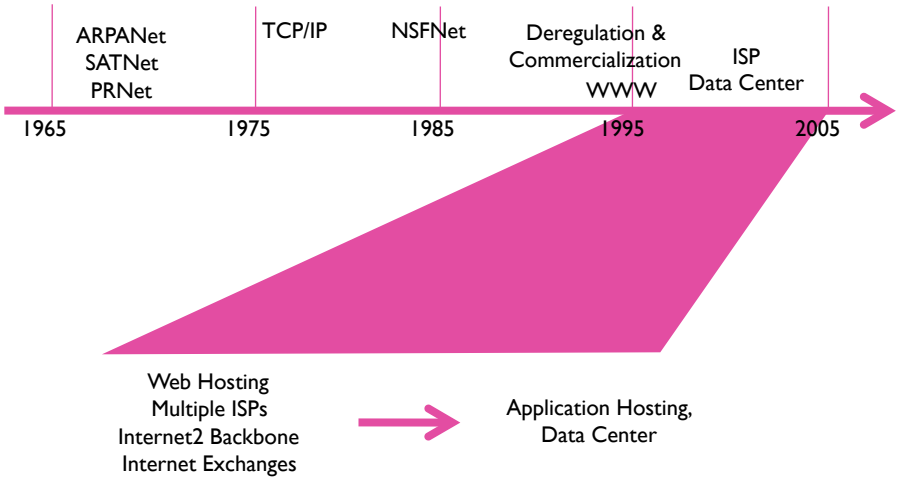
- RAND Corp, early 1960s
- Communications networks that would survive a major enemy attack

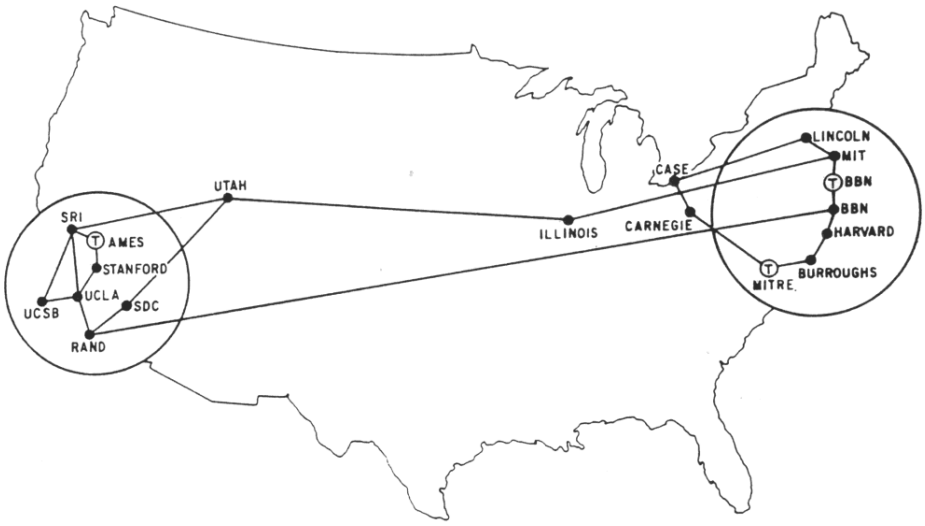
ARPANet: Research vehicle for "Resource Sharing Computer Networks"

- 2 September 1969: UCLA first node on the ARPANet
- December 1969: 4 nodes connected by phone lines

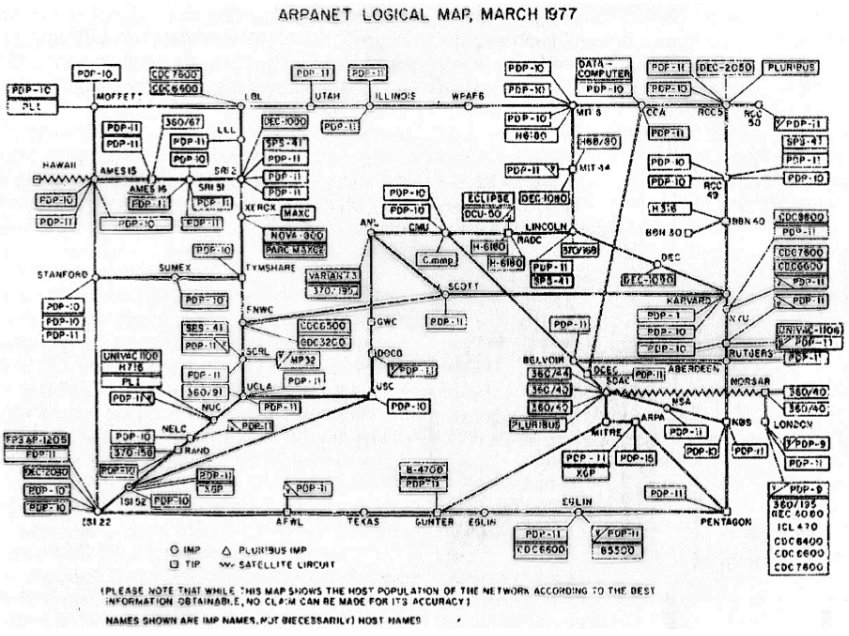
BBN team that implemented the interface message processor

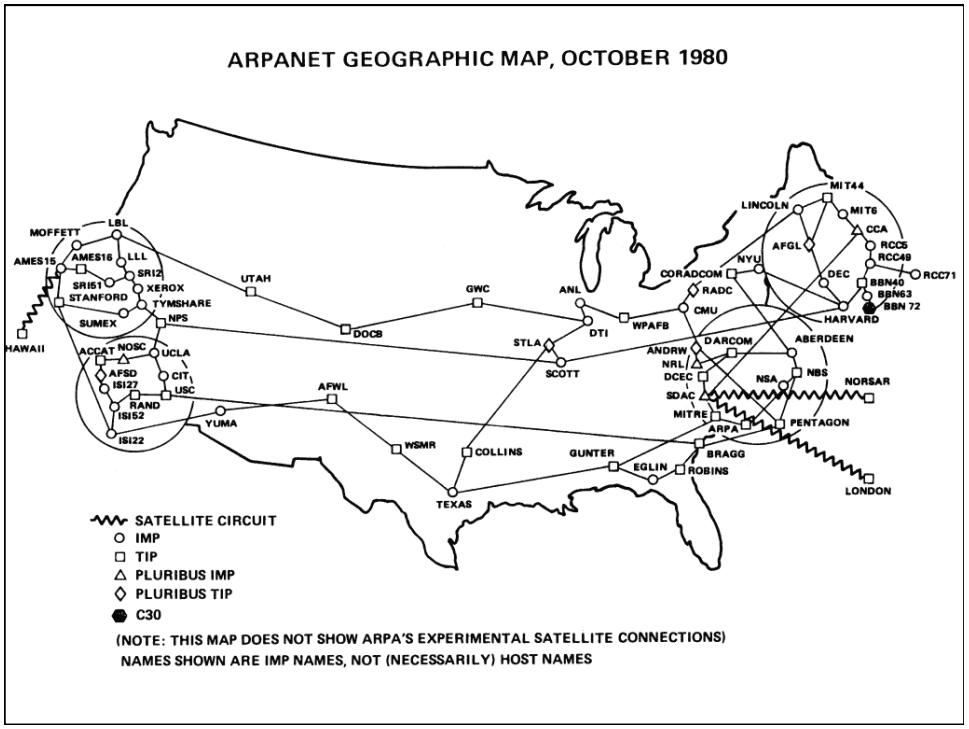
ARPANet Evolves into Internet

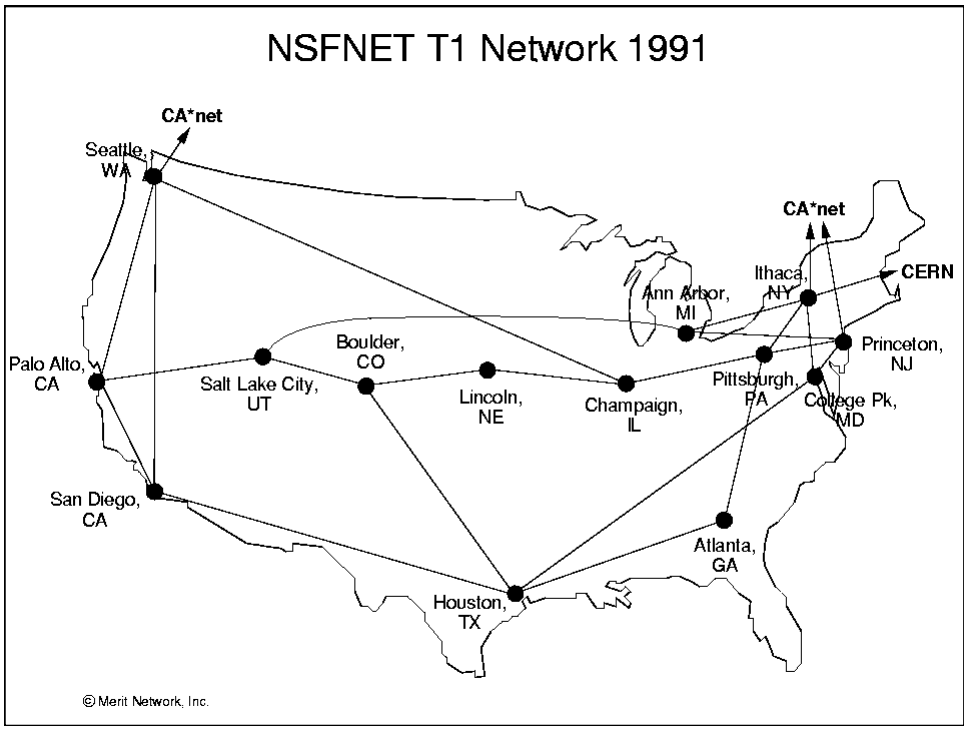


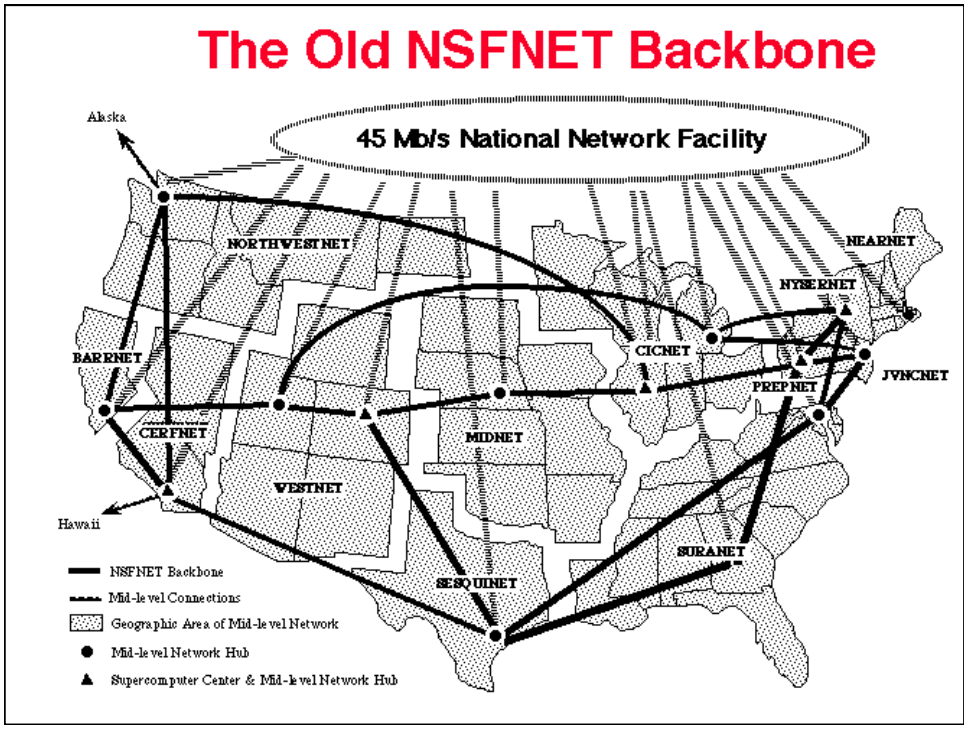


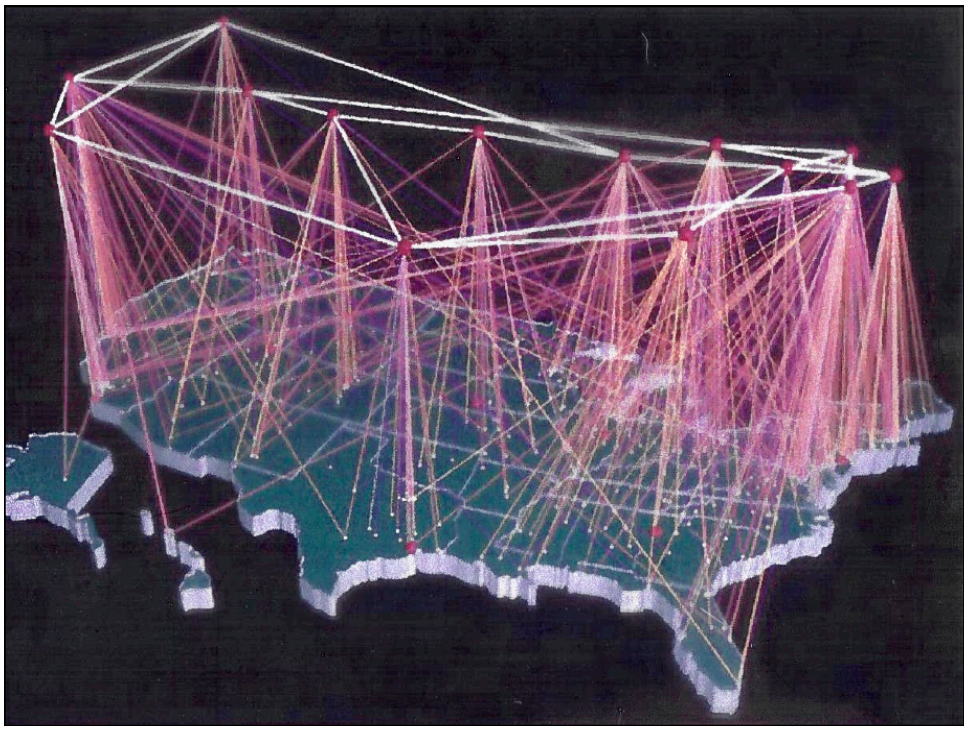
MAP 4 September 1971

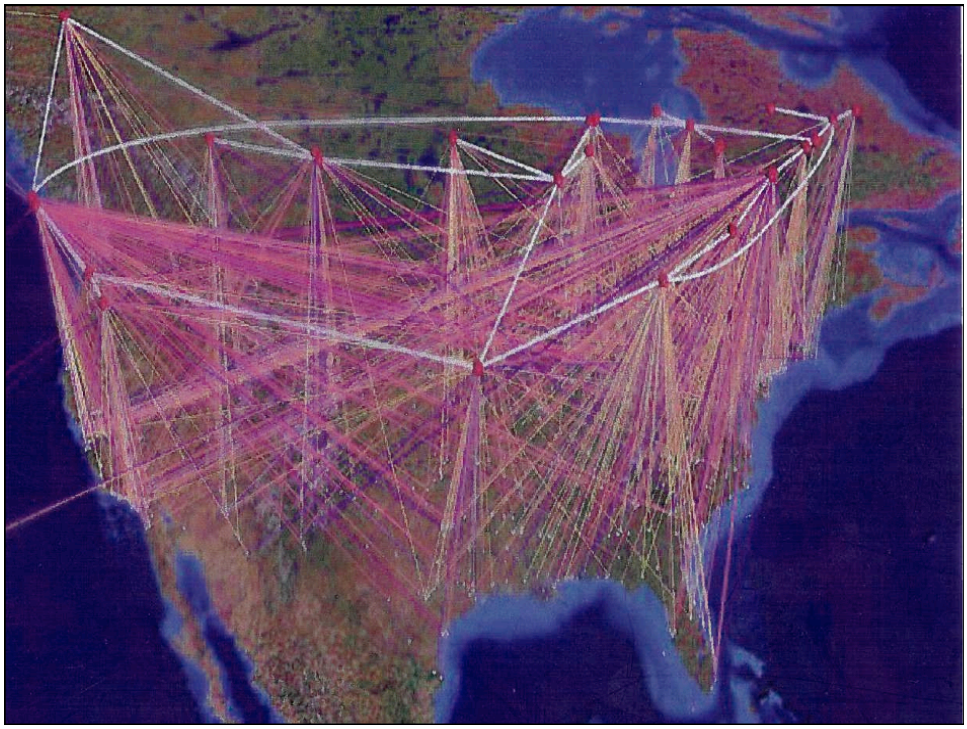


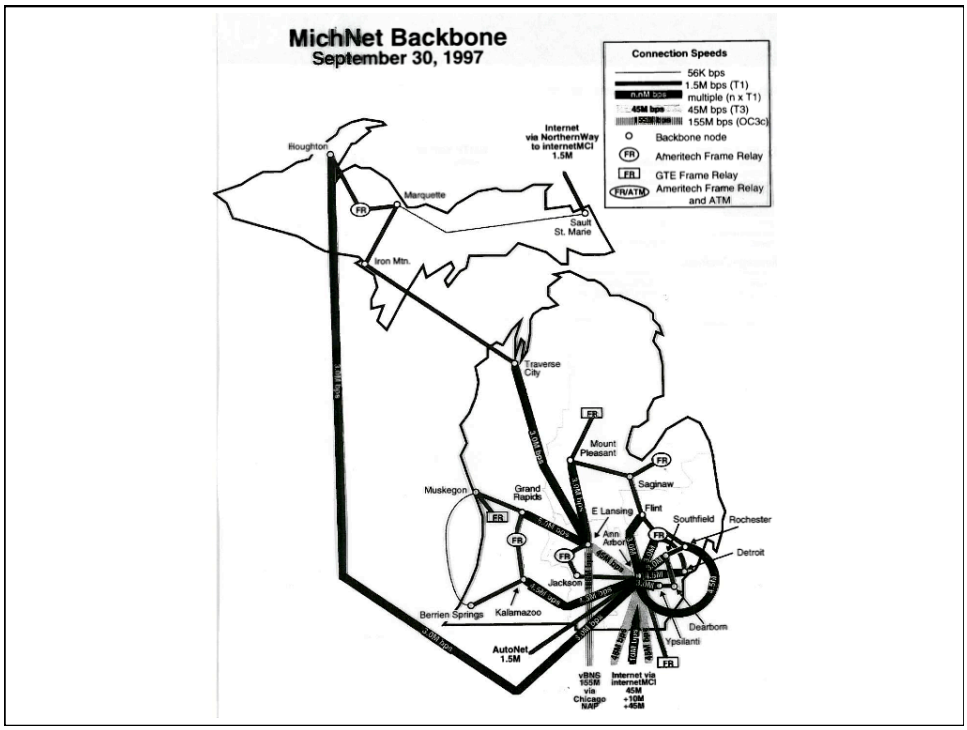

ARPANET GEOGRAPHIC MAP, OCTOBER 1980
LBL
MOFFETT
AMES15
AMES16
LLL
SRI2
SRI51
XEROX
STANFORD
TYMSHARE
SUMEX
NPS
HAWAII
ACCAT
NOSC
UCLA
AFSD
ISI27
CIT
USC
RAND
ISI52
ISI22
YUMA
AFWL
UTAH
DOCB
GWC
ANL
STLA
DTI
SCOTT
WPAFB
WSMR
COLLINS
TEXAS
GUNTER
EGLIN
ROBINS
BRAGG
CORADCOM
RADC
NYU
CMU
MIT44
LINCOLN
MIT6
CCA
AFGL
RCC5
RCC48
DEC
RCC71
BBN49
BBN63
BBN 72
HARVARD
ABERDEEN
DARCOM
ANDRW
NRL
DCEC
SDAC
MITRE
ARPA
NSA
NBS
NORSAR
PENTAGON
LONDON
SATELLITE CIRCUIT
IMP
TIP
PLURIBUS IMP
PLURIBUS TIP
C30
(NOTE: THIS MAP DOES NOT SHOW ARPA'S EXPERIMENTAL SATELLITE CONNECTIONS)
NAMES SHOWN ARE IMP NAMES, NOT (NECESSARILY) HOST NAMES

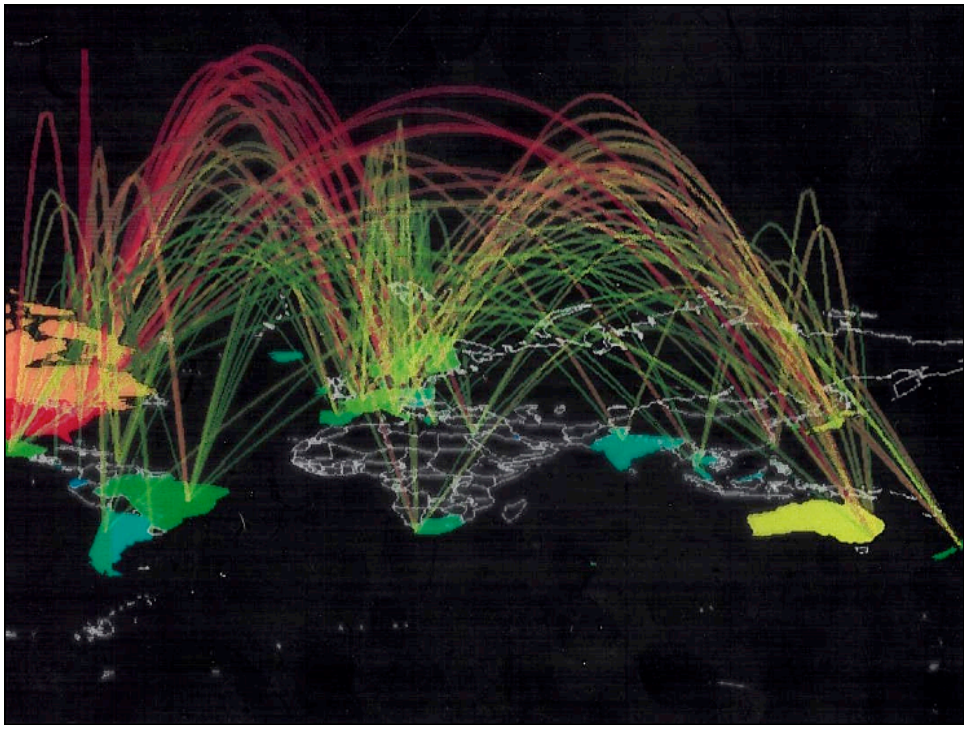

NSFNET T1 Network 1991
CA*net
Seattle, WA
CA*net
Ithaca, NY
CERN
Ann Arbor, MI
Boulder, CO
Princeton, NJ
Palo Alto, CA
Salt Lake City, UT
Lincoln, NE
Champaign, IL
Pittsburgh, PA
College Pk, MD
San Diego, CA
Atlanta, GA
Houston, TX
© Merit Network, Inc.


The Old NSFNET Backbone
45 Mb/s National Network Facility
Alaska
NORTHWESTNET
NEARNET
NYSERNET
CICNET
BARRNET
JVNCNET
PREPNET
CERFNET
MIDNET
VESTNET
Hawaii
SURANET
SESQUINET
NSFNET Backbone
Mid-level Connections
Geographic Area of Mid-level Network
Mid-level Network Hub
Supercomputer Center & Mid-level Network Hub

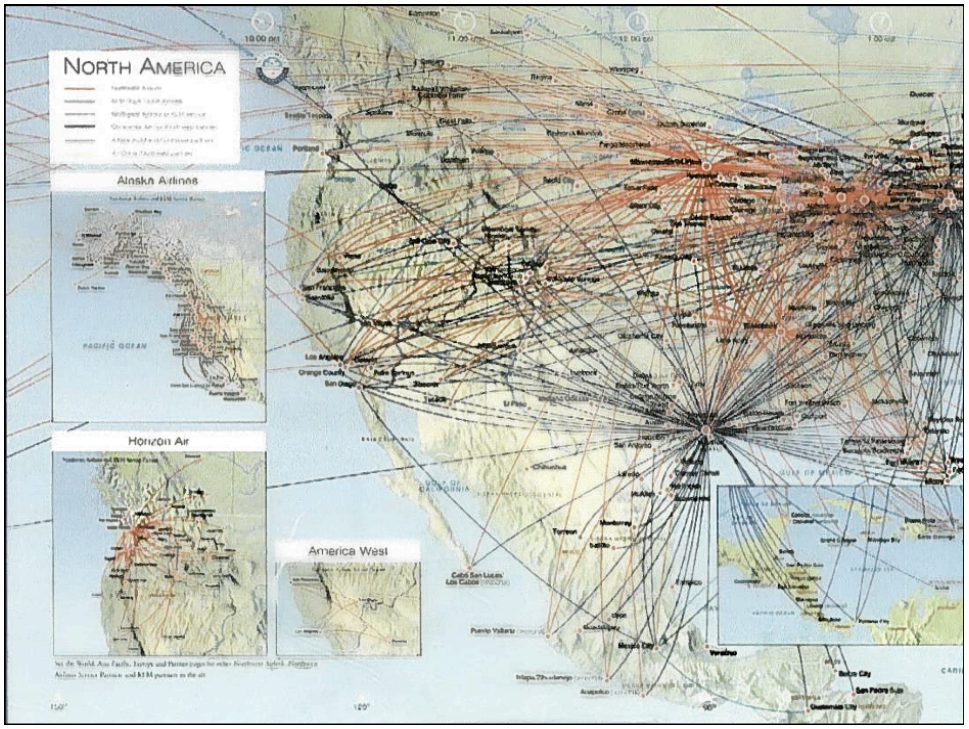


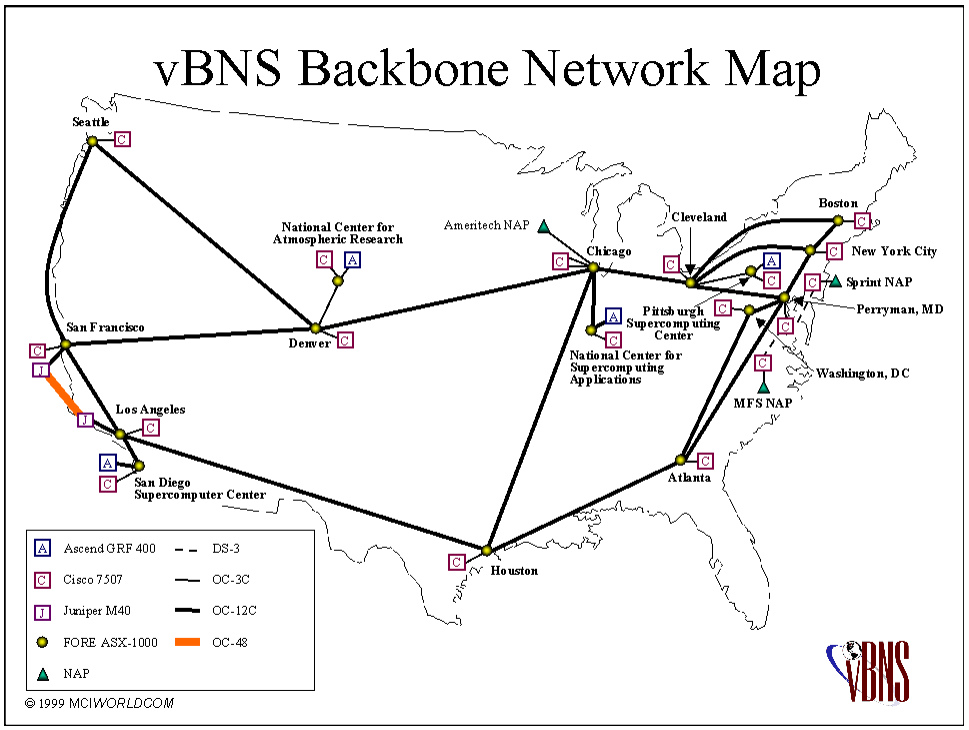


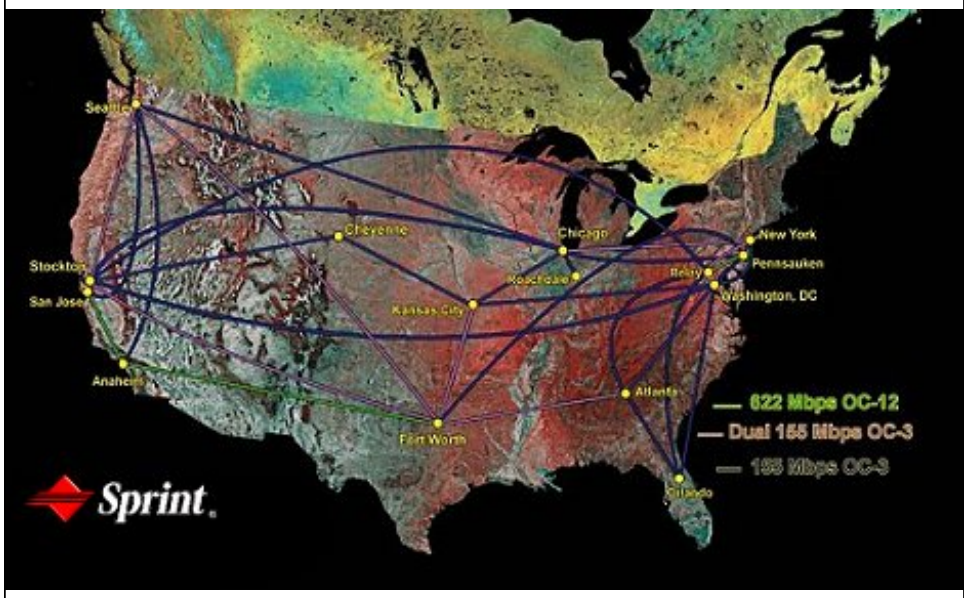

MichNet Backbone
September 30, 1997
Connection Speeds
56K bps
1.5M bps (T1)
multiple (n x T1)
45M bps (T3)
155M bps (OC3c)
Backbone node
Ameritech Frame Relay
GTE Frame Relay
Ameritech Frame Relay and ATM
Houghton
Internet via NorthernWay to internetMCI 1.5M
Marquette
Sault St. Marie
Iron Mtn.
Traverse City
Mount Pleasant
Saginaw
Muskegon
Grand Rapids
E Lansing
Flint
Ann Arbor
Southfield
Rochester
Detroit
Jackson
Kalamazoo
Berrien Springs
Dearborn
Ypsilanti
AutoNet 1.5M
vBNS 155M via Chicago NAP
Internet via internetMCI 45M +10M +45M



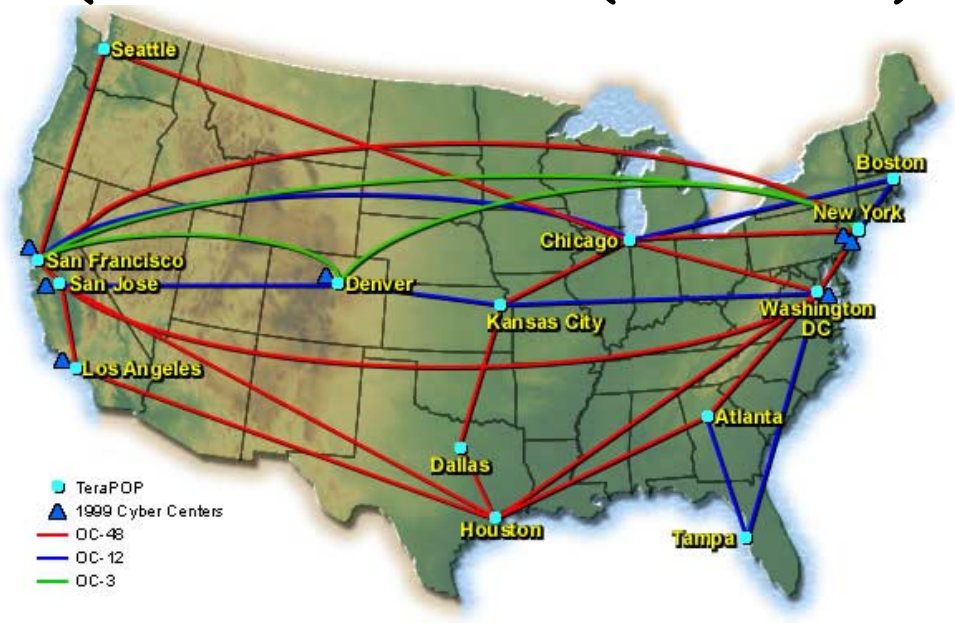
Parallel Backbones


NORTH AMERICA
Alaska Airlines
Horizon Air
America West

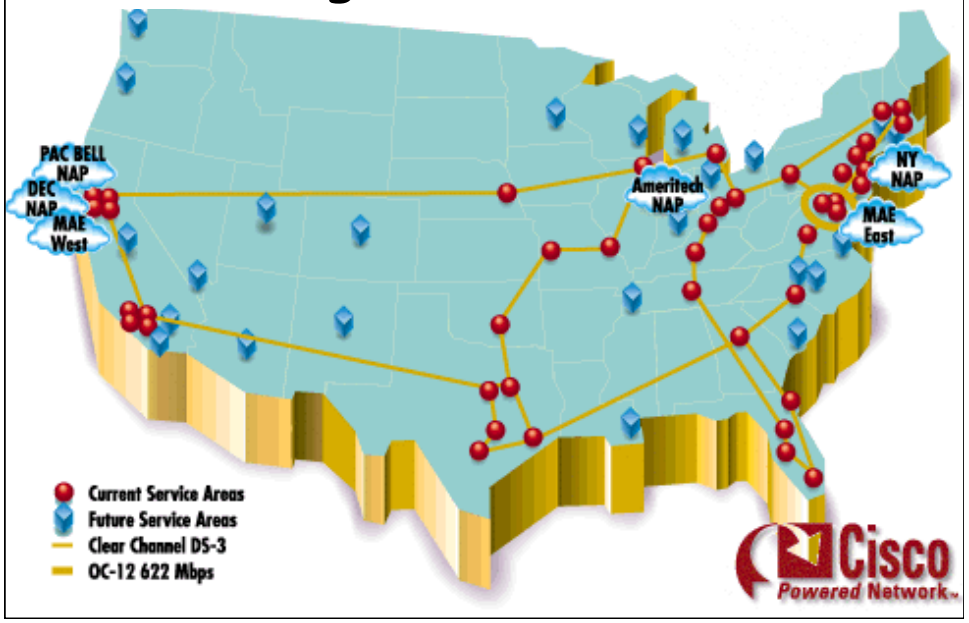

vBNS Backbone Network Map
Seattle
San Francisco
Los Angeles
San Diego
Supercomputer Center
Denver
National Center for
Atmospheric Research
Ameritech NAP
Chicago
Cleveland
Boston
New York City
Sprint NAP
Perrryman, MD
Pittsburgh
Supercomputing
Center
National Center for
Supercomputing
Applications
Washington, DC
MFS NAP
Atlanta
Houston
Ascend GRF 400
Cisco 7507
Juniper M40
FORE ASX-1000
NAP
DS-3
OC-3C
OC-12C
OC-48
© 1999 MCIWORLDCOM
vBNS



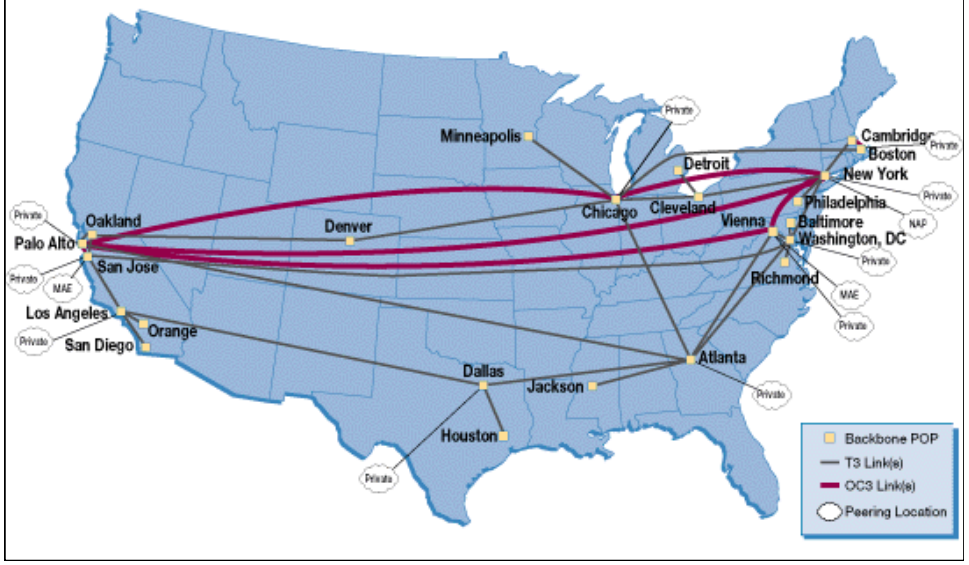
Qwest IP Backbone (Late 1999)

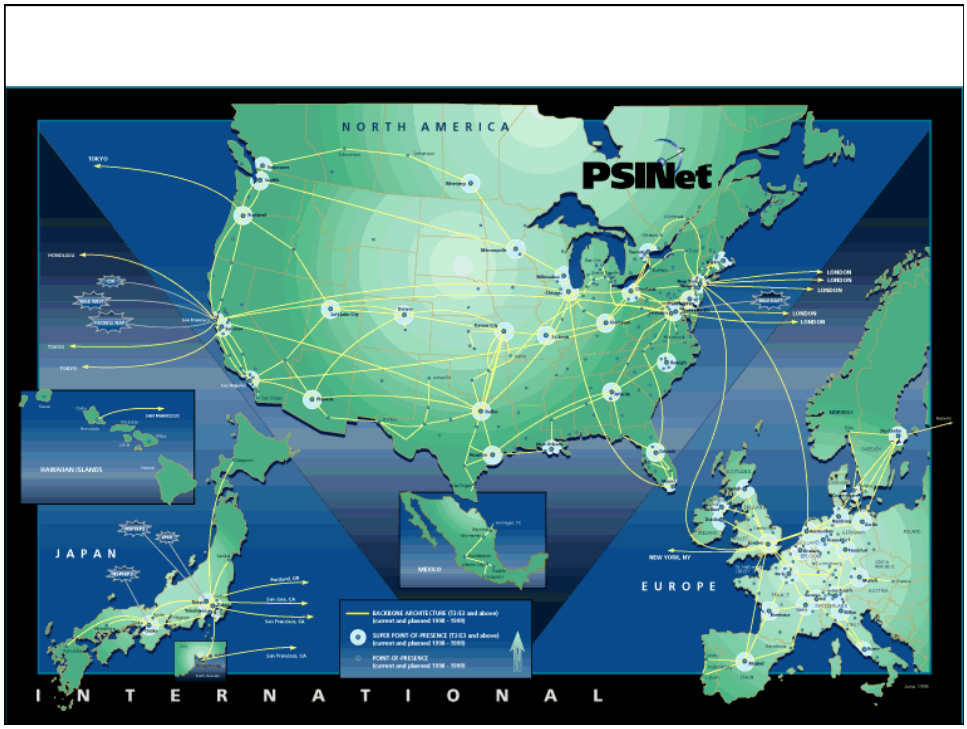


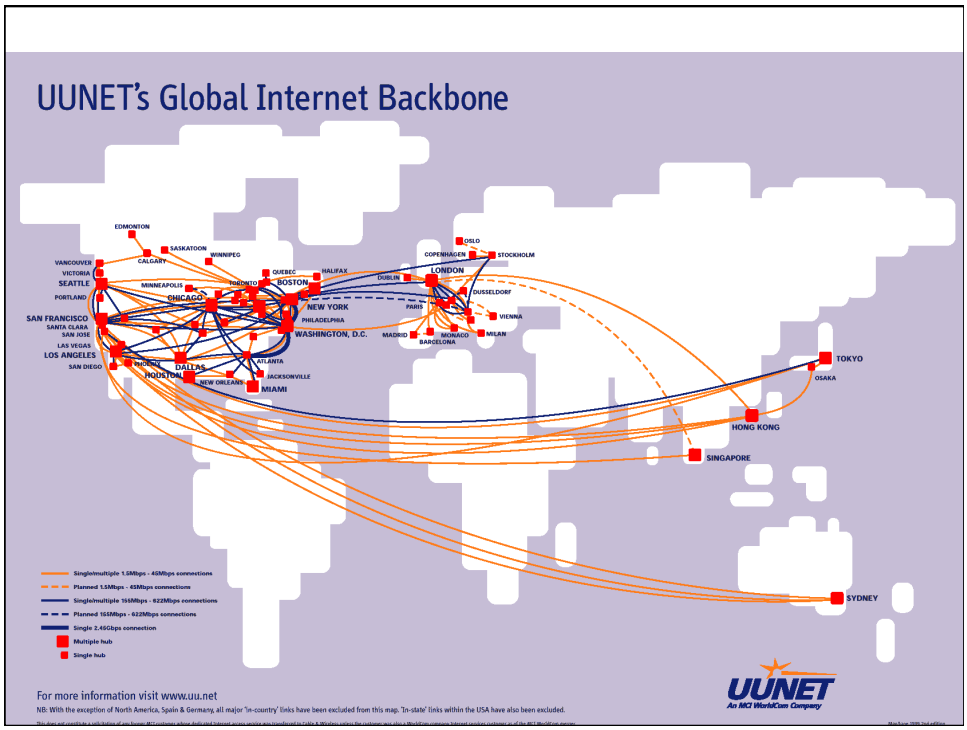
Digex Backbone

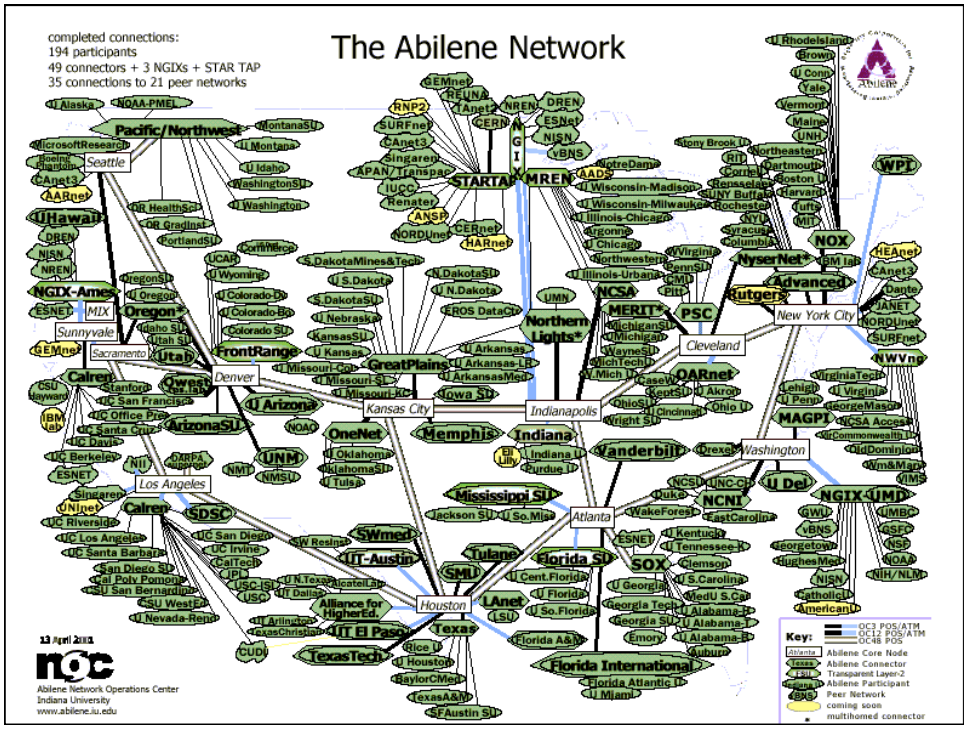


GTE Internetworking Backbone




NORTH AMERICA
PSINet
JAPAN
EUROPE
INTERNATIONAL


UUNET's Global Internet Backbone
EDMONTON
SASKATOON
WINNIPEG
CALGARY
VANCOUVER
VICTORIA
SEATTLE
PORTLAND
MINNEAPOLIS
CHICAGO
TORONTO
QUEBEC
BOSTON
HALIFAX
NEW YORK
PHILADELPHIA
WASHINGTON, D.C.
SAN FRANCISCO
SANTA CLARA
SAN JOSE
LAS VEGAS
LOS ANGELES
SAN DIEGO
PHOENIX
DALLAS
HOUSTON
ATLANTA
NEW ORLEANS
JACKSONVILLE
MIAMI
OSLO
COPENHAGEN
STOCKHOLM
LONDON
DUBLIN
PARIS
DUSSELDORF
VIENNA
MADRID
BARCELONA
MONACO
MILAN
TOKYO
OSAKA
HONG KONG
SINGAPORE
SYDNEY
Single/multiple 1.5Mbps - 45Mbps connections
Planned 1.5Mbps - 45Mbps connections
Single/multiple 155Mbps - 622Mbps connections
Planned 155Mbps - 622Mbps connections
Single 2.4Gbps connection
Multiple hub
Single hub
For more information visit www.uu.net
NB: With the exception of North America, Spain & Germany, all major 'in-country' links have been excluded from this map. 'In-state' links within the USA have also been excluded.
UUNET
An MCI WorldCom Company


The Abilene Network
completed connections:
194 participants
49 connectors + 3 NGIXs + STAR TAP
35 connections to 21 peer networks
Abilene Network Operations Center
Indiana University
www.abilene.iu.edu
Key:
Abilene Core Node
Abilene Connector
Transparent Layer-2
Abilene Participant
Peer Network
coming soon
multihomed connector
OC3 POS/ATM
OC12 POS/ATM
OC48 POS
Seattle
Sunnyvale
Los Angeles
Denver
Kansas City
Houston
Indianapolis
Atlanta
Cleveland
Washington
New York City
STARTAP
MREN
Pacific/Northwest
Northern Lights*
MERIT*
PSC
OARnet
NYSERNet*
Advanced
NOX
WPI
Rutgers
MAGPI
NCNI
NGIX
UMD
Vanderbilt
Indiana
Memphis
Mississippi St
Florida St
SOX
Florida International
Tulane
SMU
LAnet
Texas
TexasTech
IT El Paso
IT-Austin
SWmed
OneNet
GreatPlains
FrontRange
Utah
Oregon*
NGIX-Ames
Calren
SDSC
ArizonaSU
UNM
U Arizona
UHawaii
NOAA-PMEL
Alliance for HigherEd.
TexasA&M
Florida A&M
Florida Atlantic U
U Miami
Auburn
Emory
Georgia Tech
Georgia St
U Alabama
U Alabama-B
U Alabama-H
MedU S.Car
U S.Carolina
Clemson
U Kentucky
U Tennessee-K
WakeForest
Duke
UNC-CH
EastCarolin
U Del
Drexel
Lehigh
U Penn
U Virginia
VirginiaTech
GeorgeMason
NCSA Access
Commonwealth
OldDominion
Wm&Mary
VIMS
GWU
vBNS
Georgetown
HughesMed
NSF
NOAA
NIH/NLM
NISN
Catholic U
American U
U Rhodelsland
Brown
U Conn
Yale
Vermont
Maine
UNH
Stony Brook U
RIT
Cornell
Northeastern
Dartmouth
Boston U
Harvard
Tufts
MIT
Rensselaer
SUNY Buffalo
Rochester
NYU
Syracuse
Columbia
HEAnet
GEANT2
DANTE
JANET
NORDUnet
SURFnet
NWVng
IBM Yktl
Stanford
CSU Stanislaus
UC San Francisco
UC Office Prs
UC Santa Cruz
UC Davis
UC Berkeley
ESNET
NII
DARPA Supernet
NMI
NMSU
UC Riverside
UC Los Angeles
UC Santa Barbara
San Diego St
Cal Poly Pomona
CSU San Bernardino
CSU West Ed
U Nevada-Reno
UC San Diego
UC Irvine
CalTech
JPL
USC-ISI
USC
U Texas
U Dallas
U Arlington
TexasChristian
CUDI
AlcatelLab
W Reserve
Rice U
U Houston
BaylorCMed
SFAustin St
U Nebraska
KansasSU
U Kansas
Missouri-Co
Missouri-St
Missouri-Kc
Iowa St
U Arkansas
U ArkansasMed
U Arkansas-LR
Oklahoma St
U Tulsa
Indiana U
Purdue U
IU Lilly
Jackson St
U So.Miss
U Cent.Florida
U So.Florida
LSU
U Michigan
MichiganSt
WayneSt
MichTechU
U Mich Urn
CaseW
KentSt
U Akron
OhioSt
U Cincinnati
Ohio U
Wright St
U Illinois-Chicago
Argonne
U Chicago
Northwestern
U Illinois-Urbana
IUPUI
NCSA
CMU
Penn St
Pitt
U Virginia
NotreDame
AADS
U Wisconsin-Madison
U Wisconsin-Milwaukee
CERNet
HARnet
CANARIE
NORDUnet
ESnet
NISN
vBNS
DREN
CERN
GEMnet
RENATER
TAnet2
RNP2
SURFnet
CAnet3
Singaren
APAN/Transpac
IUCC
Renater
GEMnet
CAnet3
AARnet
MicrosoftResearch
Internet Chariotte
Alaska
MontanaSU
U Montana
U Idaho
WashingtonSU
U Washington
Dir.HealthSc
OR GradInst
PortlandSU
CornellTheo
UCAR
U Wyoming
OregonSU
U Oregon
U Colorado-D
U Colorado-Bo
Colorado St
Idaho St
Utah St
S.DakotaMines&Tech
S.Dakota
N.Dakota
S.DakotaSt
N.DakotaSt
EROS DataCtr
UMN
Northern Lights*
U Arkansas
U Arkansas-LR
U ArkansasMed
Iowa St
Missouri-Kc
Missouri-St
Missouri-Co
U Kansas
KansasSU
U Nebraska
FrontRange
Utah
Oregon*
Idaho St
Utah St
Colorado St
Colorado-Bo
U Colorado-D
U Oregon
OregonSU
U Wyoming
UCAR
CornellTheo
S.DakotaMines&Tech
S.Dakota
N.Dakota
S.DakotaSt
N.DakotaSt
EROS DataCtr
UMN
Northern Lights*
MERIT*
NCSA
CMU
Penn St
Pitt
PSC
Cleveland
OARnet
KentSt
U Akron
OhioSt
U Cincinnati
Ohio U
Wright St
NYSERNet*
Advanced
Rutgers
New York City
NOX
WPI
HEAnet
GEANT2
DANTE
JANET
NORDUnet
SURFnet
NWVng
MAGPI
NCSA Access
Commonwealth
OldDominion
Wm&Mary
VIMS
VirginiaTech
GeorgeMason
Lehigh
U Penn
U Virginia
U Del
Drexel
Washington
Vanderbilt
Indiana
Indiana U
Purdue U
IU Lilly
Memphis
OneNet
U Oklahoma
Oklahoma St
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UMD
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vBNS
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HughesMed
NSF
NOAA
NIH/NLM
NISN
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American U
SOX
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U Cent.Florida
U So.Florida
Florida A&M
Florida International
Florida Atlantic U
U Miami
Tulane
SMU
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Houston
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Rice U
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OR GradInst
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U Idaho
WashingtonSU
U Washington
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CAnet3
AARnet
Dir.HealthSc
OR GradInst
PortlandSU
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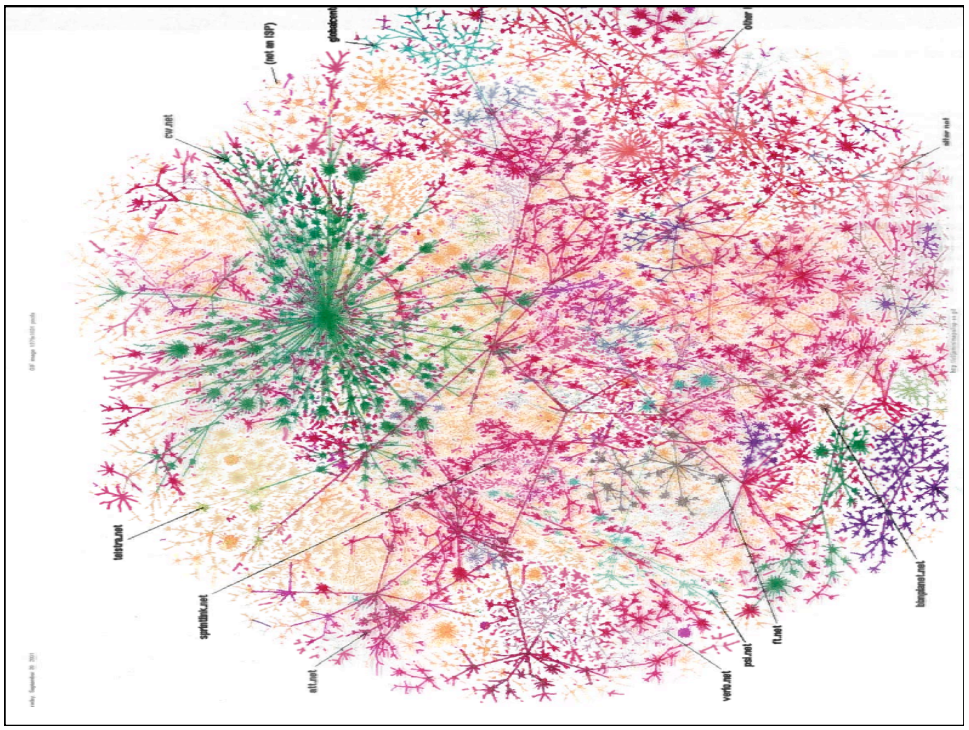
GEMnet
Sunnyvale
Los Angeles
Denver
Kansas City
Houston
Indianapolis
Atlanta
Cleveland
Washington
New York City



What's the Internet

Earlier we said . . . .

data parceled into packets

each packet carries a destination address

each packet is routed independently

packets can arrive out of order

packets may not arrive at all

However, the Internet provides two types of delivery services:

connectionless (datagram, UDP, e.g., streaming media app, games)

connection oriented (byte stream, TCP, e.g., web, email)

Connection oriented service provides:

end-to-end reliability (sender retransmit lost packets)

in-sequence delivery (receiver buffers incoming packets until it can deliver them in order)

How does a router know which router to forward a packet to?

How does a receiver know the correct ordering of packets?

How does a sender know which packet is lost and must be retransmitted?

Protocols – rules ("syntax" and "grammar") governing communication between nodes, e.g., TCP/IP

- a "node" is one of sender, router, or receiver

protocols define the format, order of msgs sent and received among network entities, and actions taken on msg transmission, receipt

Internet Protocol Stack

application: supporting network applications

- HTTP, SMTP, FTP, etc.

transport: endhost-endhost data transfer

- TCP, UDP

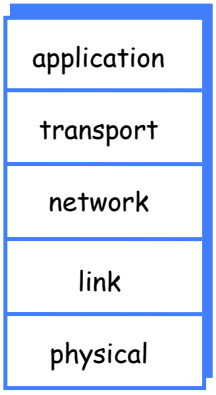
network: routing of datagrams from source to destination

- IP, routing protocols

link: data transfer between neighboring network elements

- Ethernet, WiFi

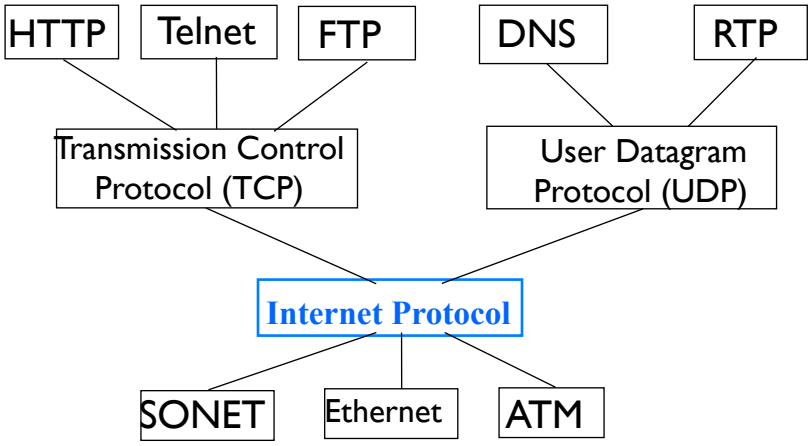
physical: bits "on the wire"



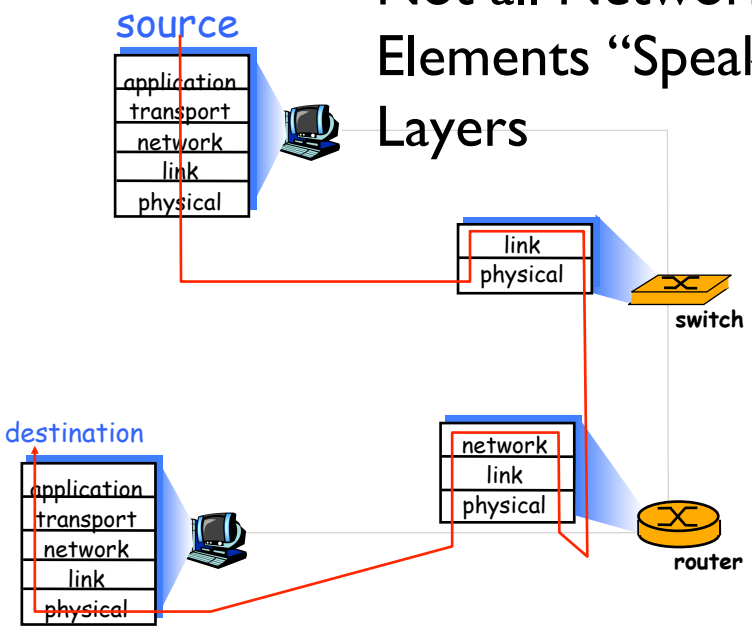
Some Network Apps (and Their Protocols)

- E-mail (SMTP)
- Web (HTTP)
- Instant messaging (IRC)
- Remote login (Telnet)
- P2P file sharing (Napster, Gnutella, KaZaa)
- Multi-user network games
- Streaming stored video clips (Adobe's RTMP)
- Internet telephone (Skype)
- Real-time video conference (RTP)
- Massively parallel computing

Layering in the IP Protocols



Not all Network Elements "Speak" All Layers



Why Layering?

Networks are complex! Many "pieces":

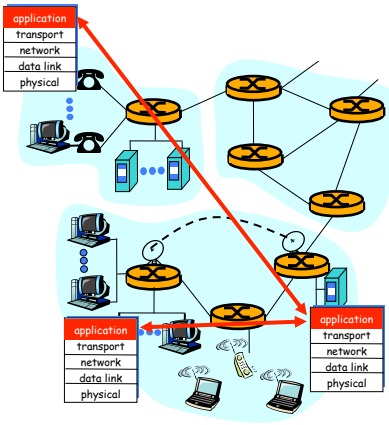
- applications
- hosts
- routers
- links of various media

Dealing with complex systems:

- explicit structure allows identification of well-defined, specific parts of a large and complex system
- modularization eases maintenance, updating of system
  - change of implementation of layer's service transparent to rest of system
    - note that change of implementation is different from change of service definition!

Creating a Network Application

- Write programs that
  - run on different end systems and
  - communicate over a network.
  - e.g., Web browser software communicates with browser server
- No app software written for devices in network core
  - Network core devices do not function at app layer
  - This design allows for rapid app development



Application Architecture: Client-Server Computing

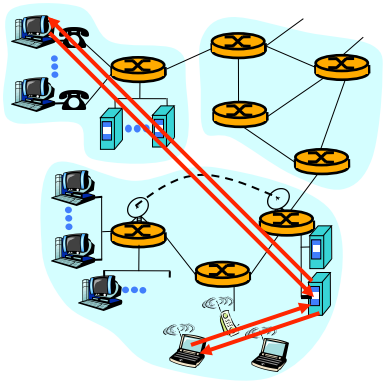
Email (SMTP) uses the client-server paradigm

server:

- a process that manages access to a resource
- usually has a permanent IP address
- waits for connection
- server farms for scaling
  - how do server farms maintain a single IP address externally?

client:

- a process that needs access to a resource
- initiates connection with server
- may be intermittently connected
- may have dynamic IP addresses
- do not communicate directly with each other

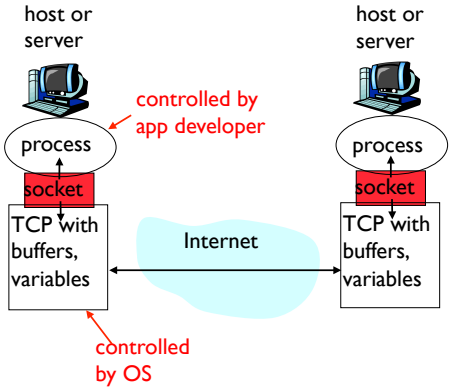


Process vs. machine

Alternative(s) to client-server?

Sockets

- process sends/receives messages to/from its socket
- socket analogous to door
  - sending process shoves message out of door
  - sending process relies on transport infrastructure on other side of door which brings message to socket at receiving process



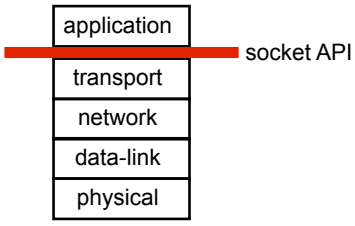
Sockets API Programming

What is a socket?

Review of sockets (assume familiarity from EECS 482)

(learn how to read `man` pages!)

Applications need Application Programming Interface (API) to use the network



API: set of function types, data structures, and constants

- allows programmer to learn once, write anywhere
- greatly simplifies job of application programmer

Addressing Socket

Server host may support many simultaneous application processes, each with one or more sockets

Web servers, for example, have different sockets for each connecting client

For a socket to receive messages, it must have an identifier

A host has a unique 32-bit IP address

Q: does the IP address of the host on which the process runs suffice for identifying the process?

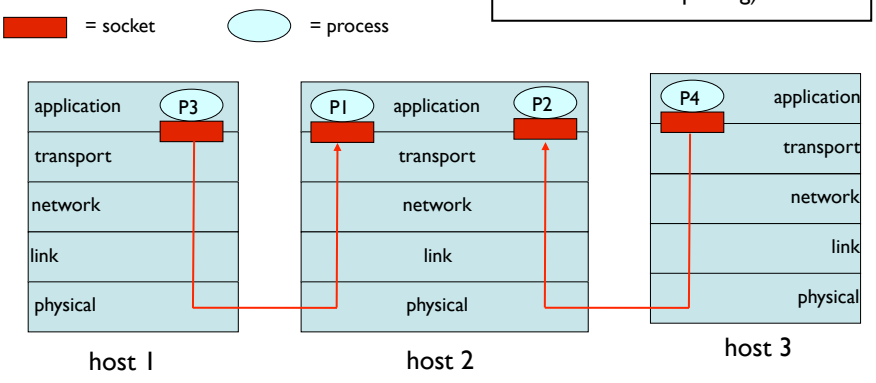
Multiplexing/demultiplexing

Demultiplexing at rcv host:

delivering received segments to correct socket

Multiplexing at send host:

gathering data from multiple sockets, enveloping data with header (later used for demultiplexing)

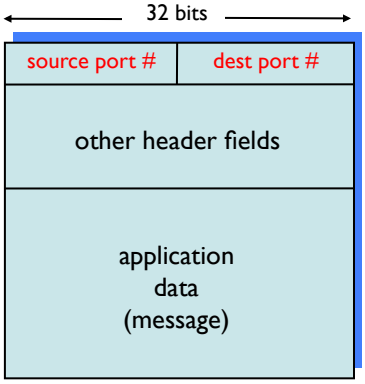


How Demultiplexing Works

Host receives IP packets

- each packet has source and destination IP addresses
- each packet carries one transport-layer segment
- each segment has source and destination port numbers

Host uses IP addresses & port numbers to direct segment to appropriate socket



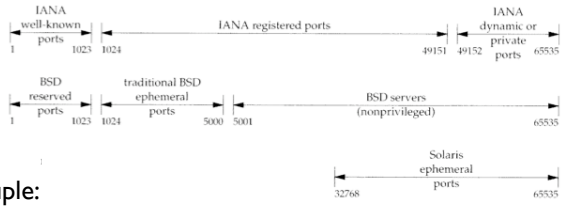
TCP/UDP segment format

Connection-oriented Demux

Socket identifier includes both the IP address and port numbers associated with the socket on the host

Example port numbers:

- HTTP server: 80
- Mail server: 25
- See `/etc/services`



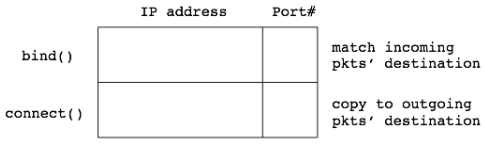
TCP socket identified by 4-tuple:

- source IP address
- source port number
- dest IP address
- dest port number

Receiver kernel uses all four values to direct packet to appropriate socket

Socket Addresses

Somewhere in the socket structure:



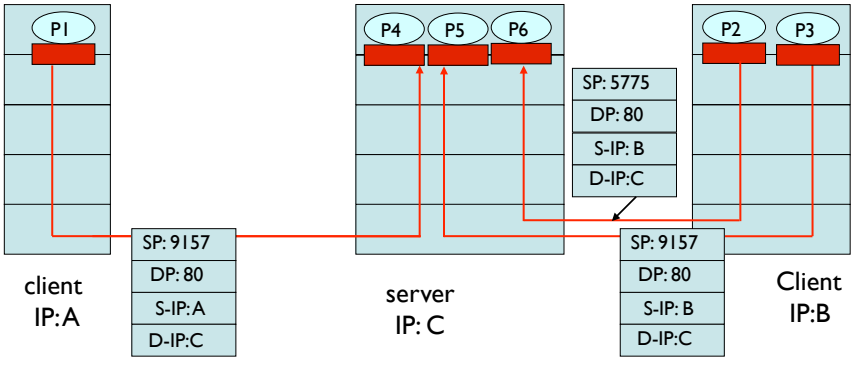
TCP Server:

IP address	Port#
INADDR_ANY	well-known
client's address	ephem-eral

TCP Client:

IP address	Port#
client's address	ephem-eral
server's address	well-known

Connection-oriented demux



Not so "recent" news

Taiwan earthquake on Dec. 26, 2006

Damaged several undersea cables, disrupting telecommunication services in various parts of Asia.

Is Internet not redundant enough?

Traceroute from Taiwan to China goes through U.S.!

```
[michigan_1@planetlab1 michigan_1]$ traceroute scut1.6planetlab.edu.cn
traceroute to scut1.6planetlab.edu.cn (219.243.200.25), 30 hops max, 38 byte packets
 1  140.112.107.254 (140.112.107.254)  0.459 ms  0.435 ms  0.371 ms
 2  140.112.0.21 (140.112.0.21)  0.506 ms  0.630 ms  0.468 ms
 3  140.112.0.1 (140.112.0.1)  0.621 ms  0.534 ms  0.478 ms
 4  203.160.226.233 (203.160.226.233)  0.953 ms  0.839 ms  0.806 ms
 5  tp_j160_1.twgate.net (203.160.227.176)  1.607 ms  1.431 ms  1.357 ms
    MPLS Label=580977 CoS=3 TTL=1 S=0
 6  la_c124_1.twgate.net (203.160.228.246)  139.122 ms  143.088 ms  138.635 ms
    MPLS Label=187 CoS=3 TTL=1 S=0
 7  ge41.ny_c76_2.twgate.net (203.160.228.190)  203.585 ms  203.288 ms  203.461 ms
 8  12.118.94.65 (12.118.94.65)  203.806 ms  203.779 ms  204.823 ms
 9  12.122.82.158 (12.122.82.158)  209.953 ms  210.320 ms  204.227 ms
    MPLS Label=31209 CoS=3 TTL=1 S=0
10  ggr2-p3120.n54ny.ip.att.net (12.123.3.109)  203.499 ms  203.746 ms  205.360 ms
11  att-gw.nyc.dtag.de (192.205.32.58)  205.137 ms  206.690 ms  205.350 ms
12  * 217.239.41.10 (217.239.41.10)  450.638 ms *
13  * * *
14  * 202.112.61.17 (202.112.61.17)  532.956 ms *
15  202.112.61.193 (202.112.61.193)  509.868 ms  528.050 ms *
16  202.112.53.181 (202.112.53.181)  529.697 ms  531.163 ms  526.445 ms
17  202.127.216.22 (202.127.216.22)  559.867 ms *  562.172 ms
18  * 202.112.53.150 (202.112.53.150)  552.522 ms  552.684 ms
19  * * *
20  * * *
21  * *
```