eScience as a Lens on the World

Ed Lazowska

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University of Washington

Chair
Computing Community Consortium

CENIC Annual Conference

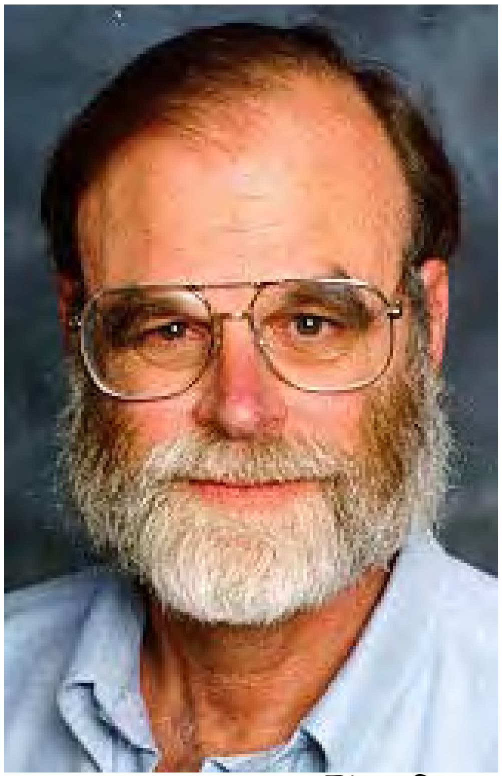
March 2010

http://lazowska.cs.washington.edu/cenic.pdf

This morning

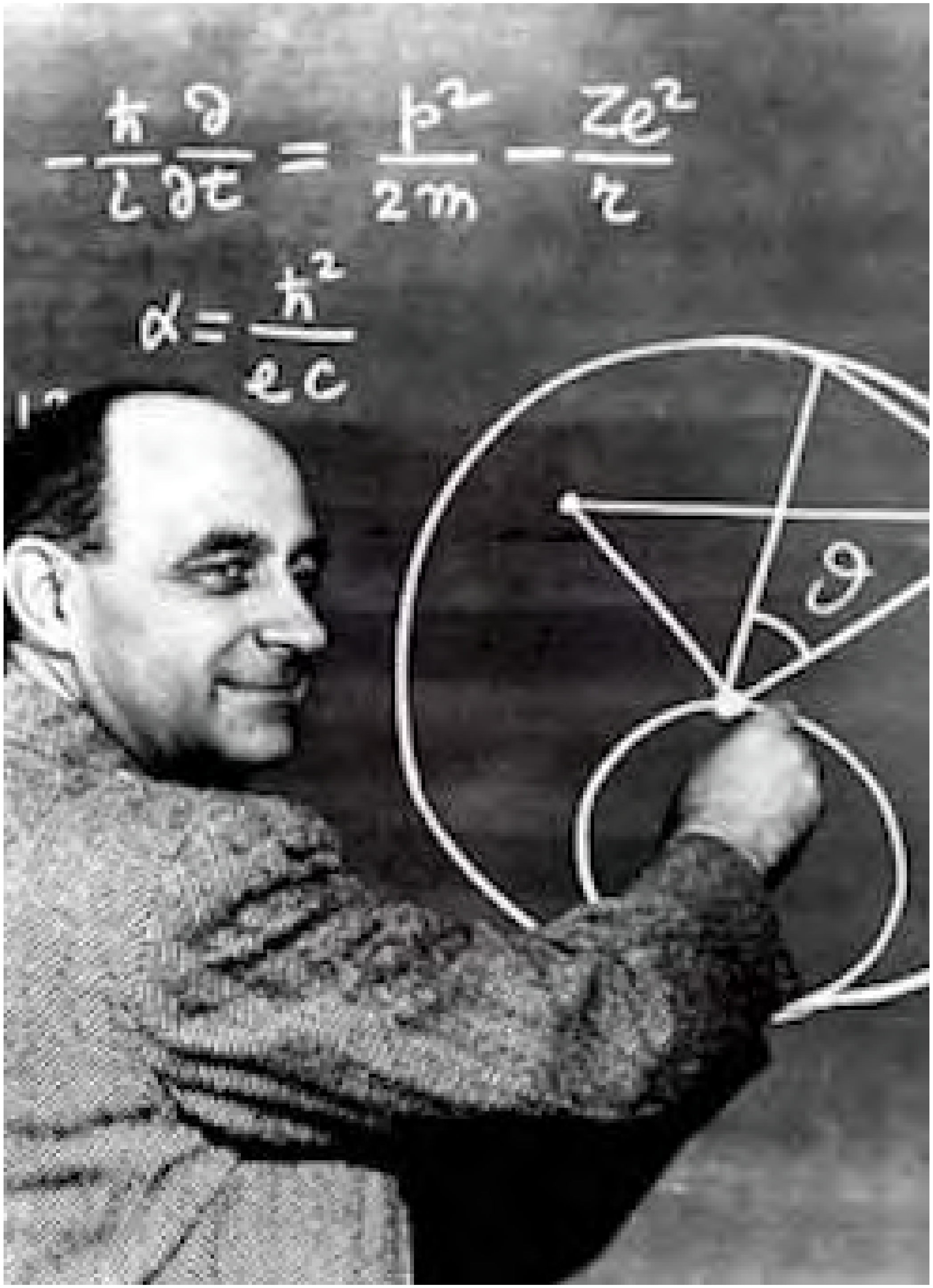
- The nature of eScience
- The University of Washington eScience Institute
- The advances that enable eScience
- Scalable computing for everyone
- Broadband, and the role of higher education
- Computer science: Changing the world

eScience: Sensor-driven (data-driven) science and engineering



Jim Gray

Transforming science (again!)



Theory

Experiment

Observation

Theory

Experiment

Observation

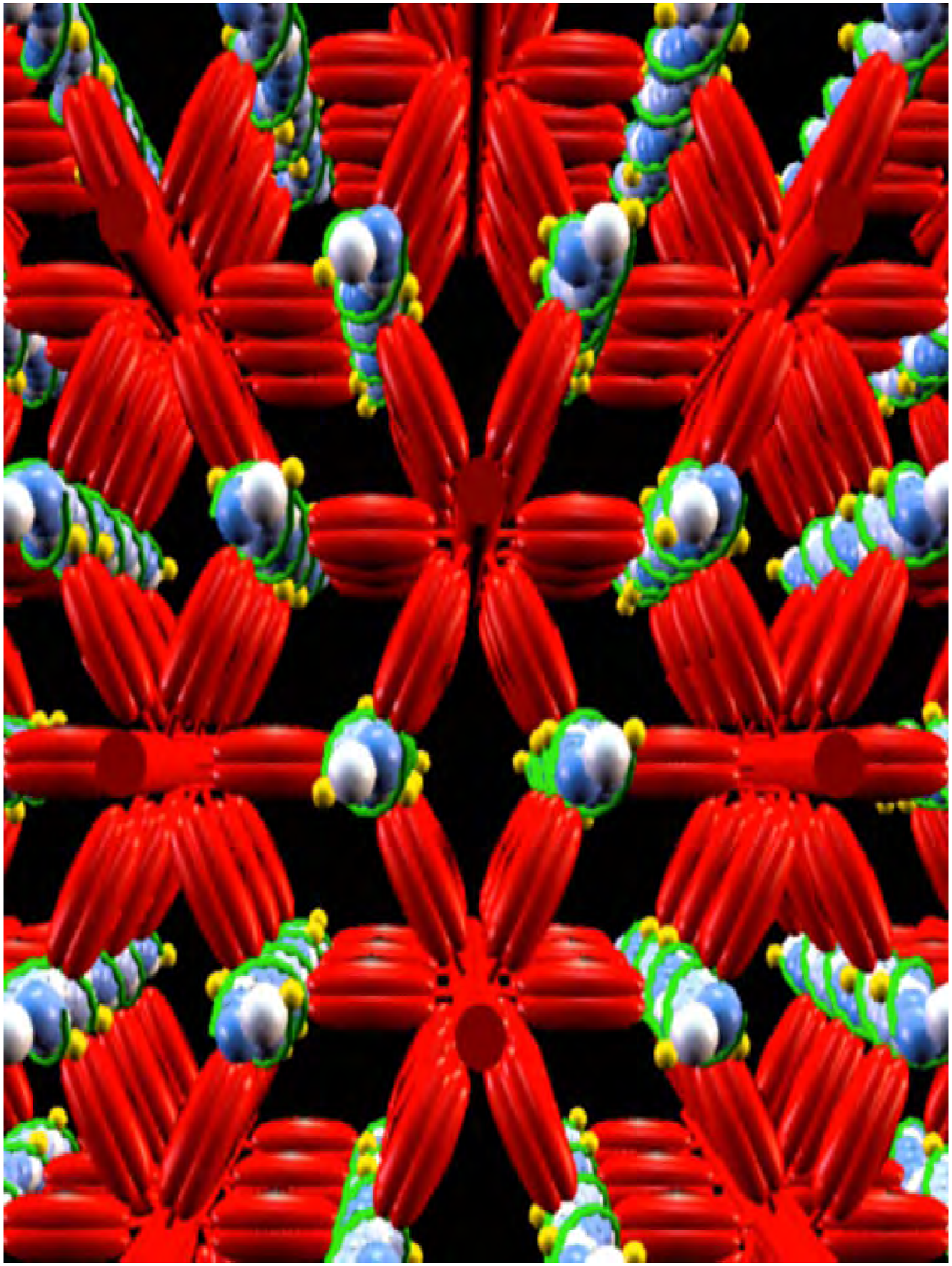

Theory
Experiment
Observation
[John Delaney, University of Washington]

Theory

Experiment

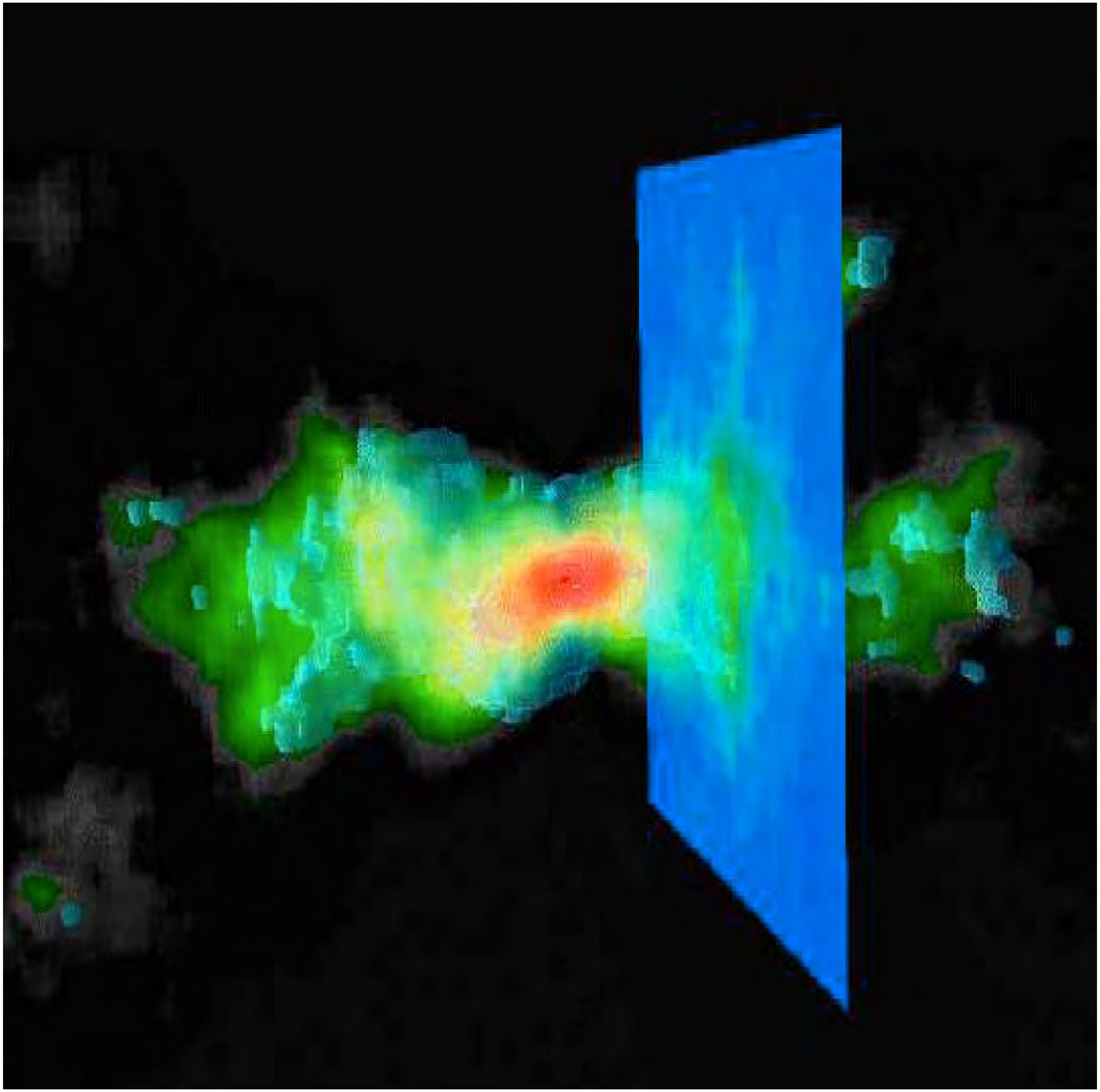
Observation

Computational Science



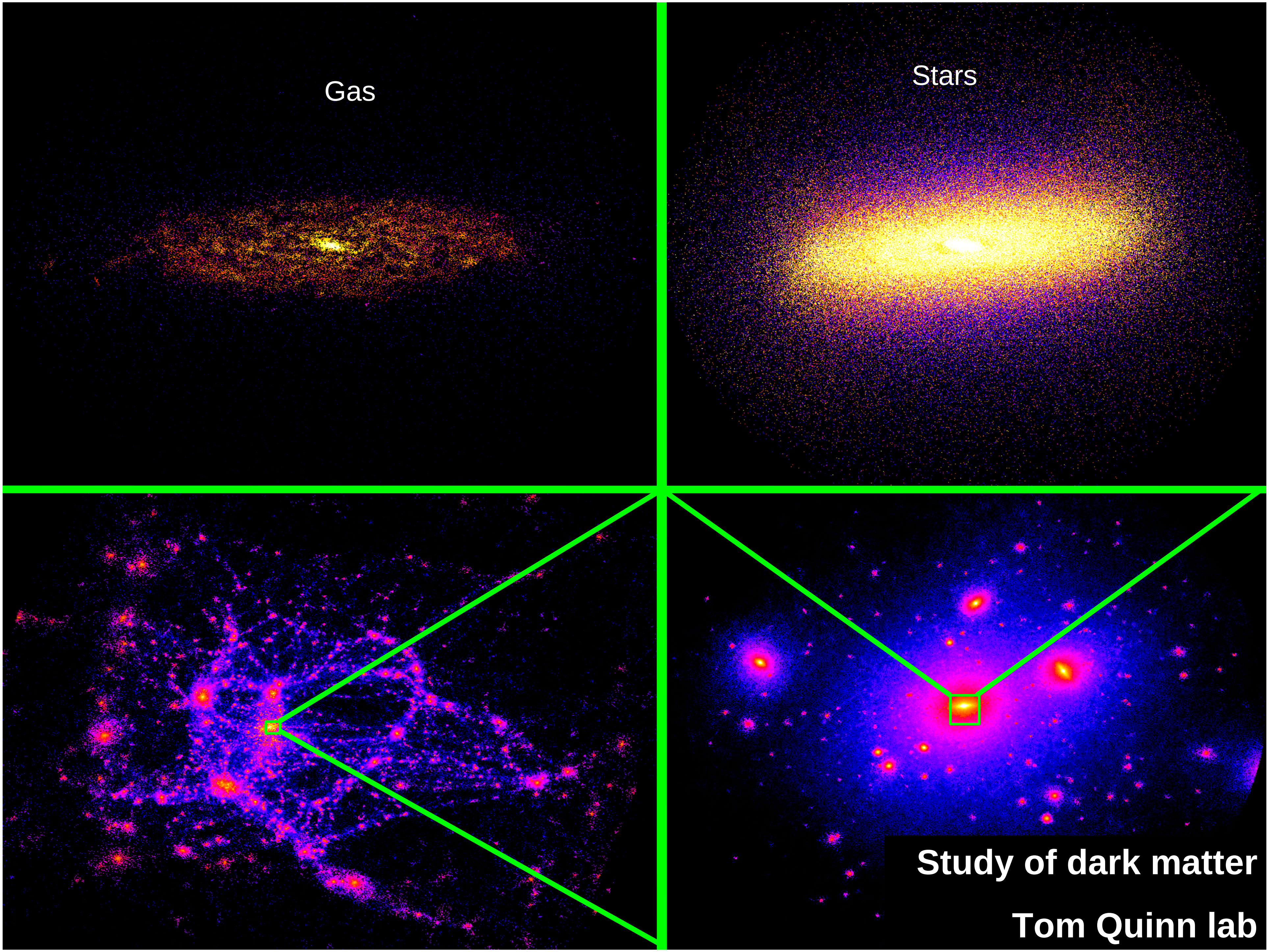
Protein interactions in striated muscles

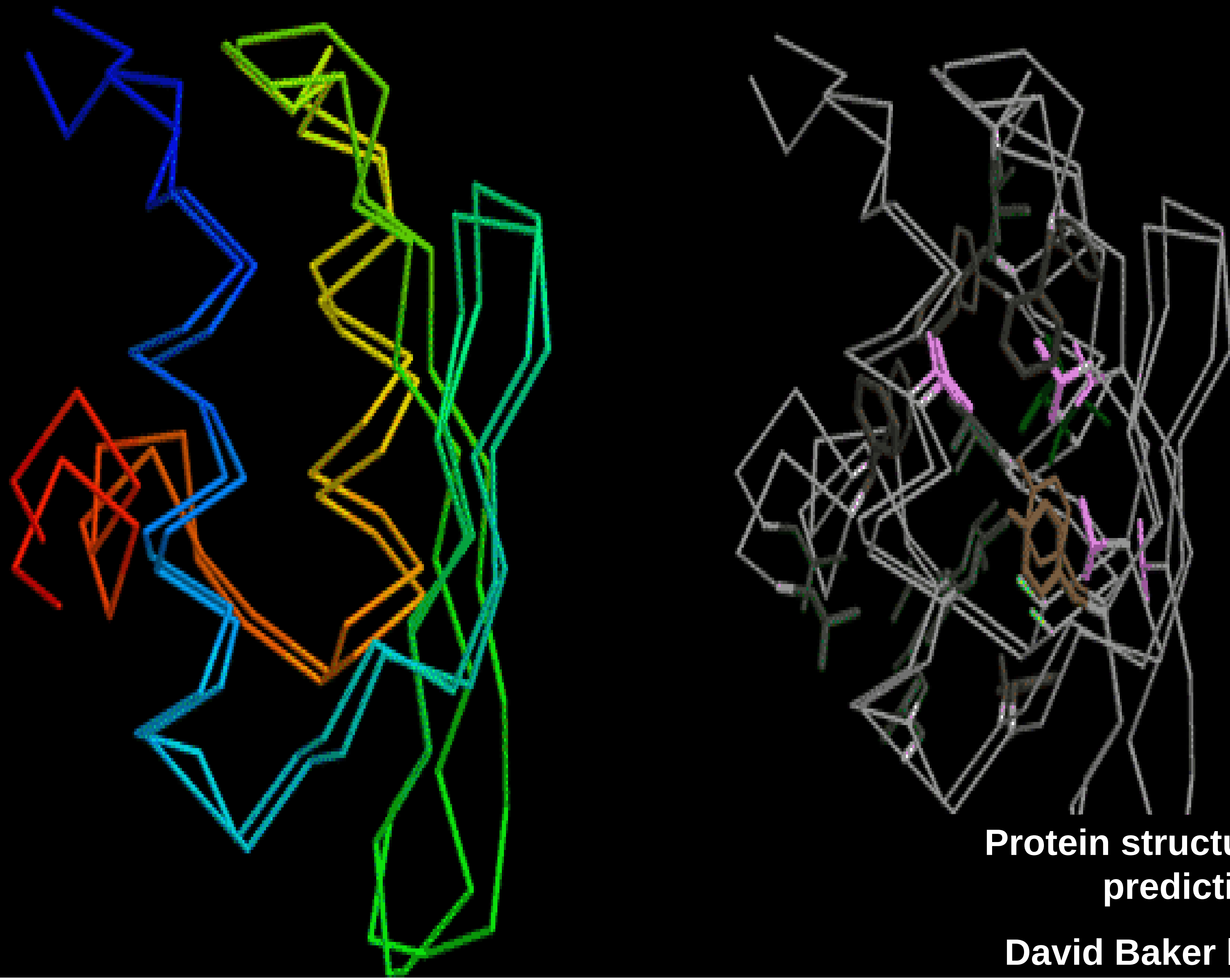
Tom Daniel lab



QCD to study interactions of nuclei

David Kaplan lab


Gas
Stars
Study of dark matter
Tom Quinn lab



Protein structure prediction

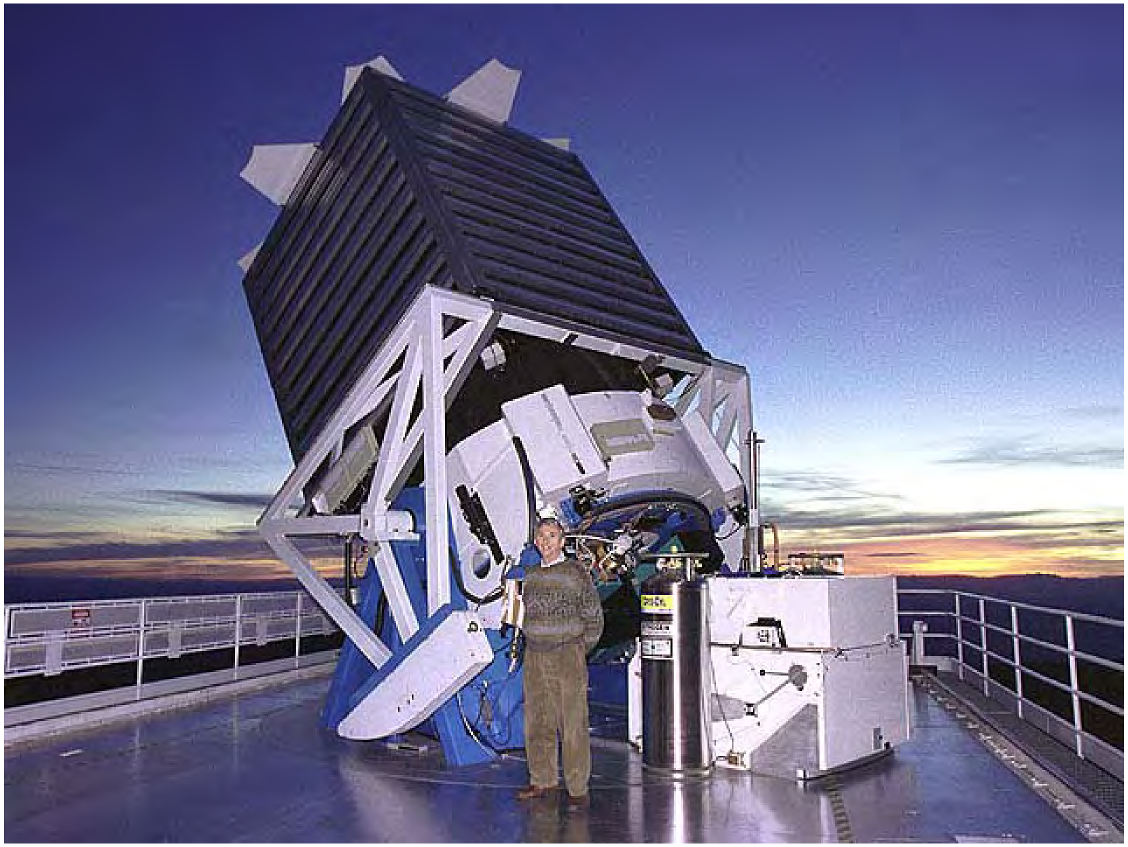
David Baker lab

Theory
Experiment
Observation
Computational Science

eScience

eScience is driven by *data*

- Massive volumes of data from sensors and networks of sensors

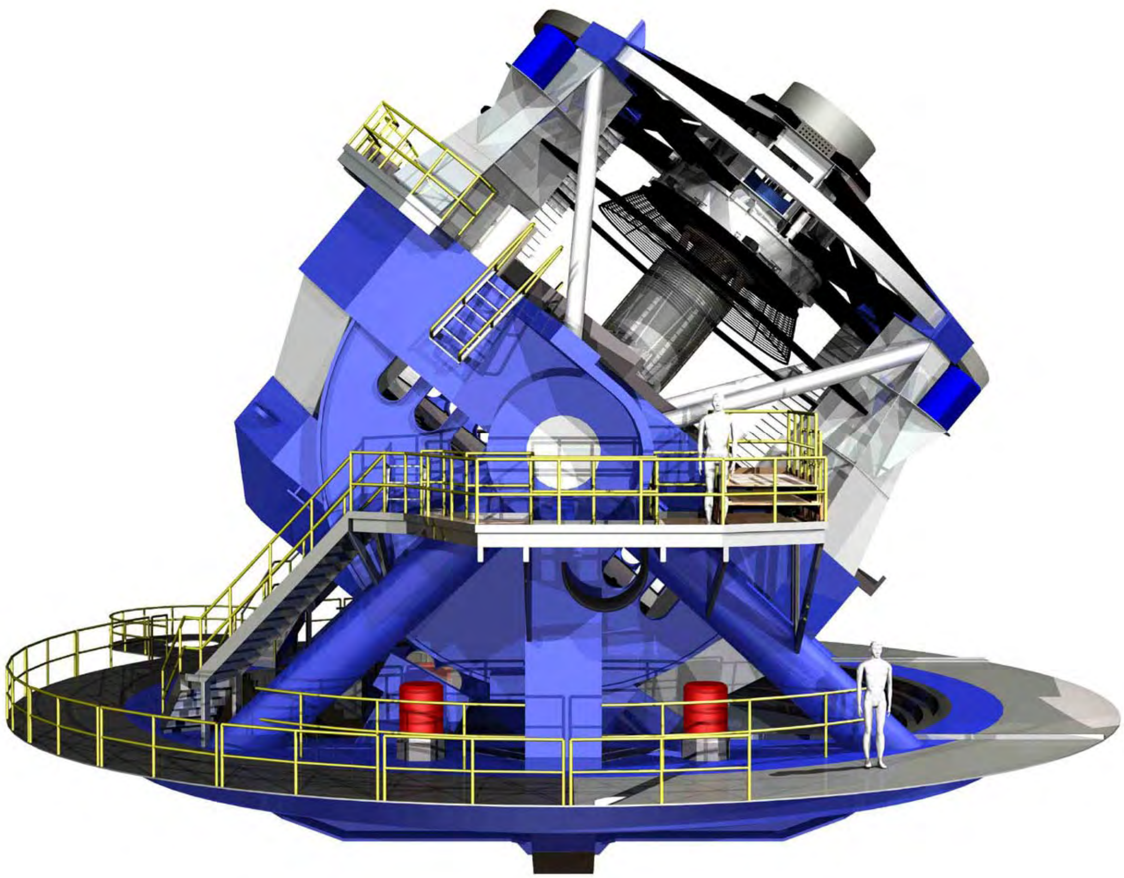


Apache Point telescope, SDSS

15TB of data (15,000,000,000,000 bytes)

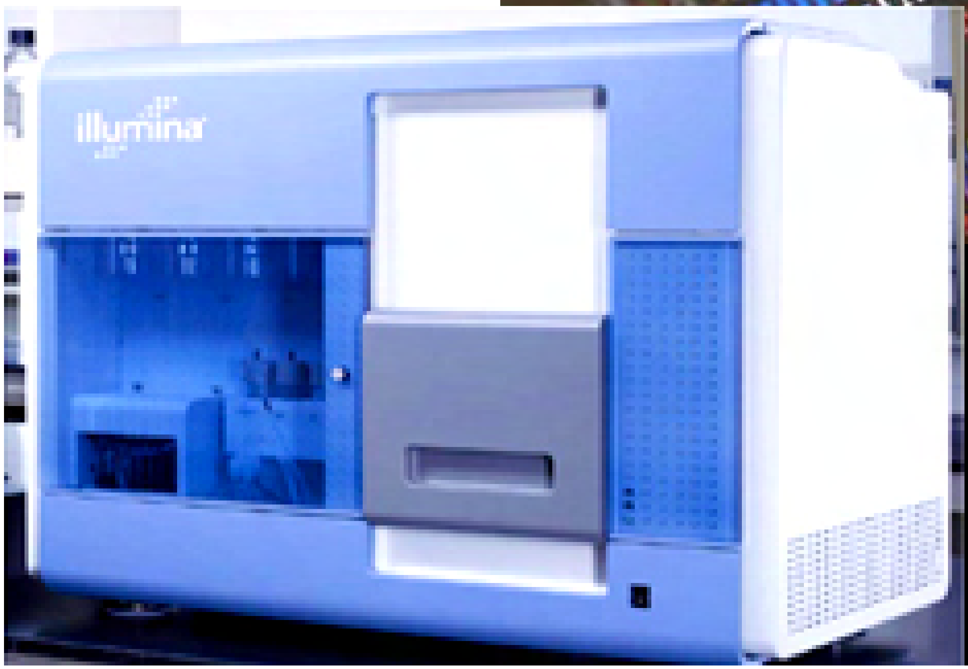
Large Synoptic Survey Telescope (LSST)

30TB/day, 60PB in its 10-year lifetime



Large Hadron Collider

700MB of data per second, 60TB/day, 20PB/year

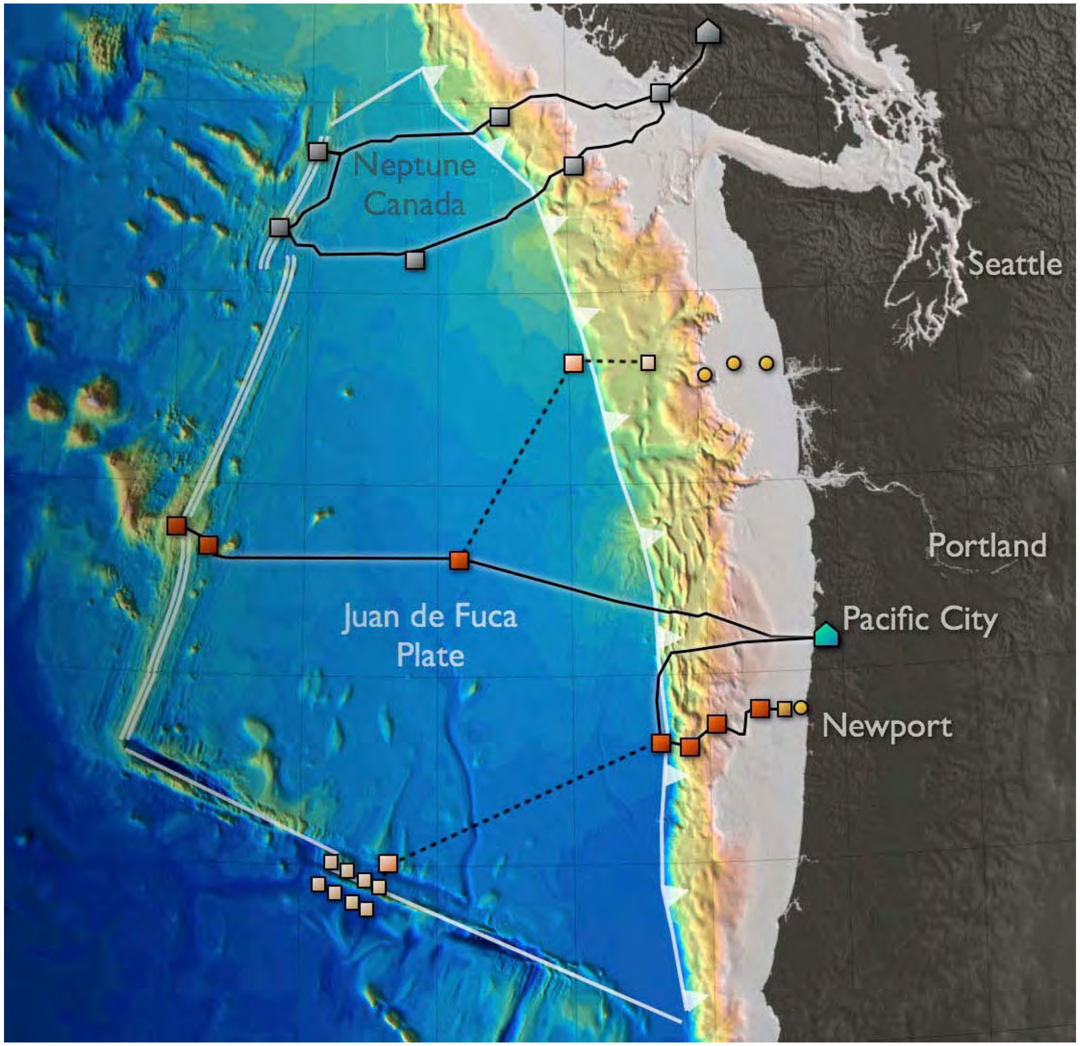


Illumina Genome Analyzer

~1TB/day

Regional Scale Nodes of the NSF Ocean Observatories Initiative

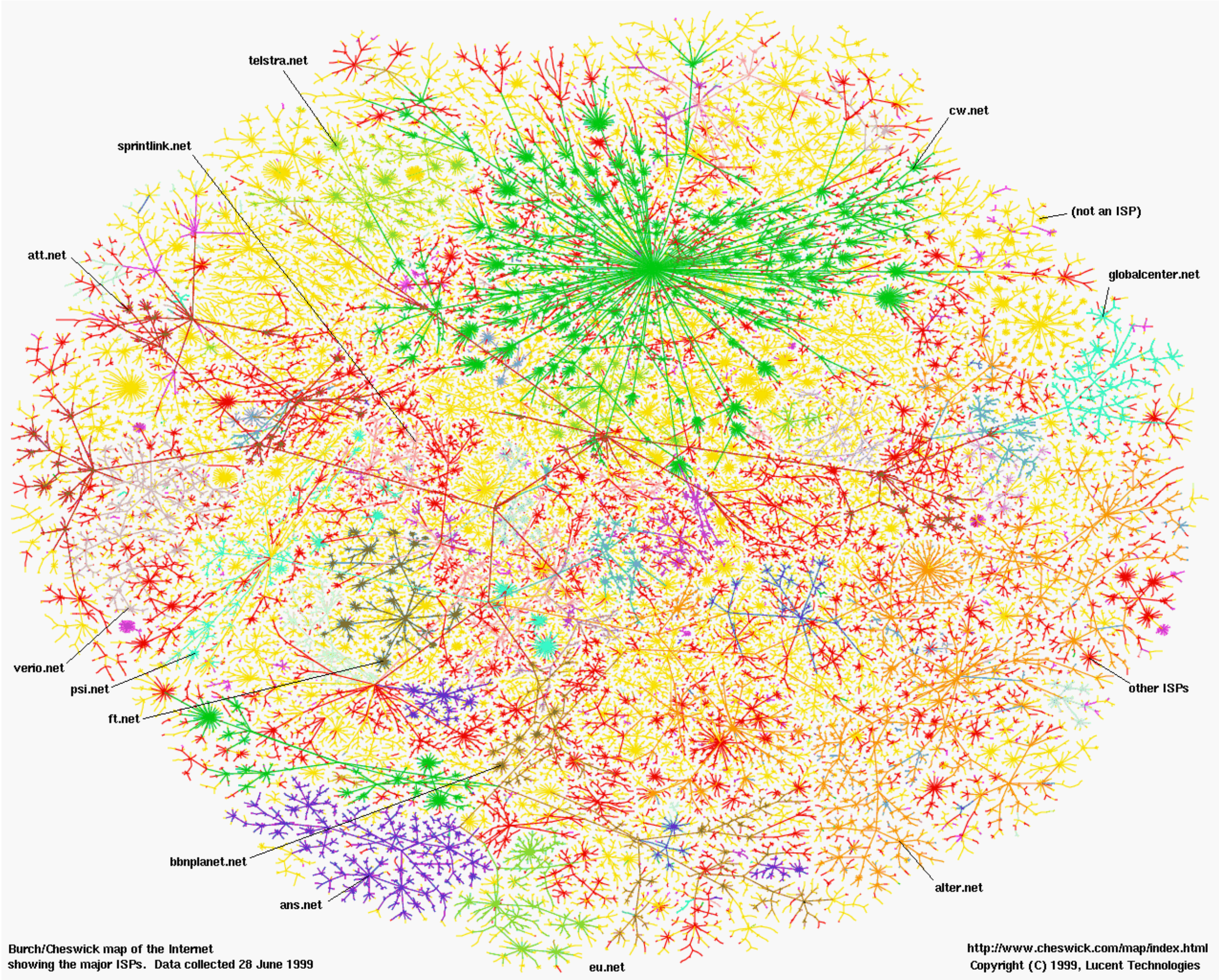
1000 km of fiber optic cable on the seafloor, connecting thousands of chemical, physical, and biological sensors



The Web

20+ billion web pages x 20KB = 400+TB

One computer can read 30-35 MB/sec from disk => 4 months just to read the web



eScience is about the *analysis* of data

- The automated or semi-automated extraction of knowledge from massive volumes of data
  - There's simply too much of it to look at
- It's not just a matter of volume
  - Volume
  - Rate
  - Complexity / dimensionality

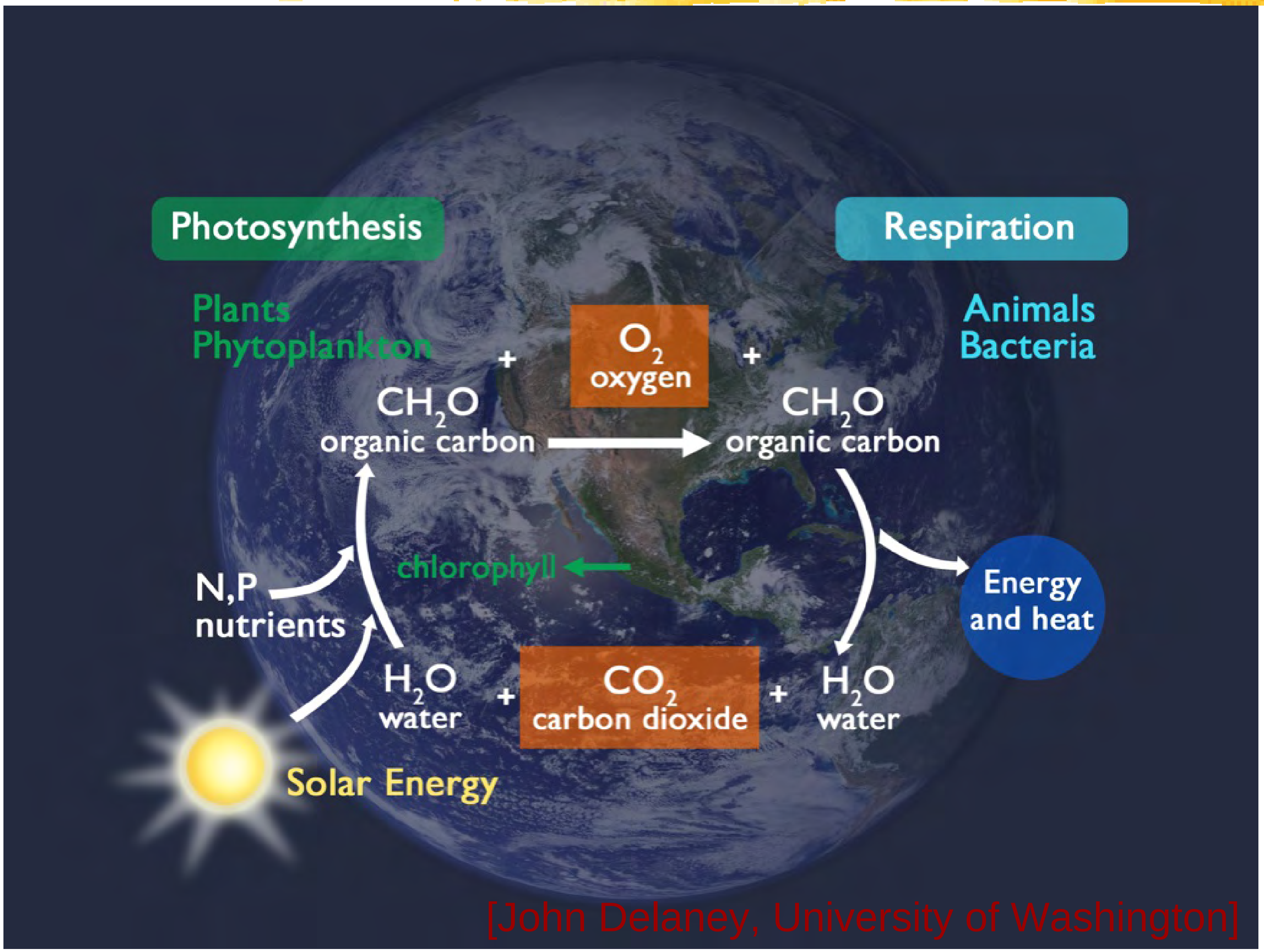
The technologies of eScience

- Sensors and sensor networks
- Databases
- Data mining
- Machine learning
- Data visualization
- Cluster computing at enormous scale

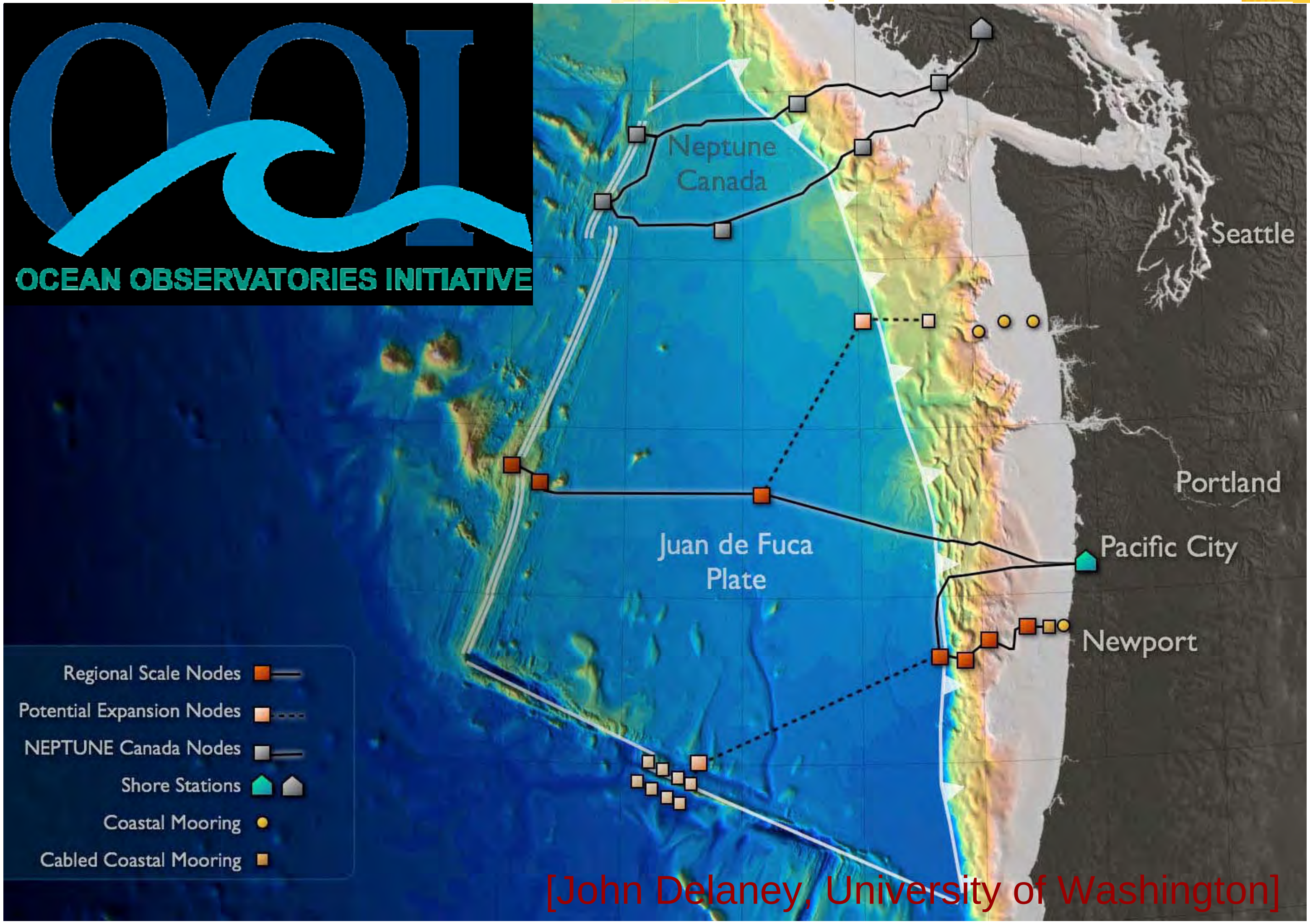
eScience will be pervasive

- Computational science has been transformational, but it was a niche
  - As an institution (e.g., a university), you didn't need to excel in order to be competitive
- eScience capabilities must be broadly available in any organization
  - If not, the organization will simply cease to be competitive

Example: The NSF Ocean Observatories Initiative



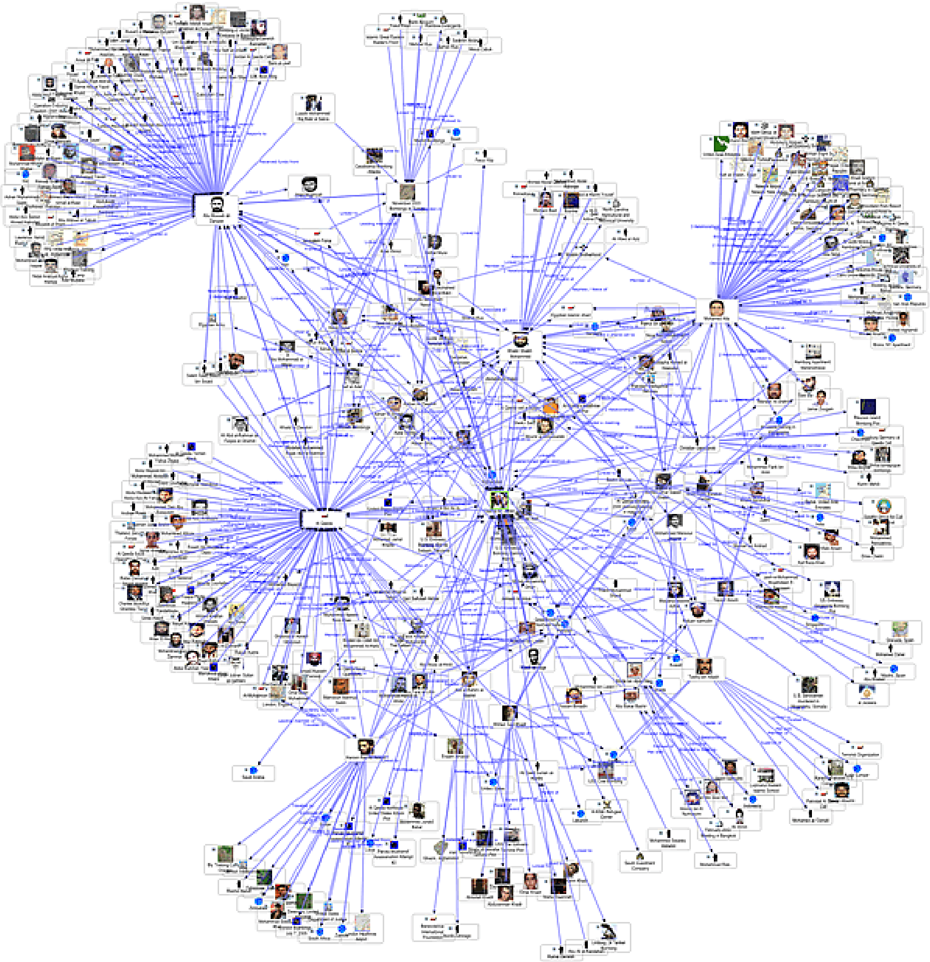
[John Delaney, University of Washington]


OOI
OCEAN OBSERVATORIES INITIATIVE
Neptune Canada
Seattle
Portland
Pacific City
Newport
Juan de Fuca Plate
Regional Scale Nodes
Potential Expansion Nodes
NEPTUNE Canada Nodes
Shore Stations
Coastal Mooring
Cabled Coastal Mooring
[John Delaney, University of Washington]

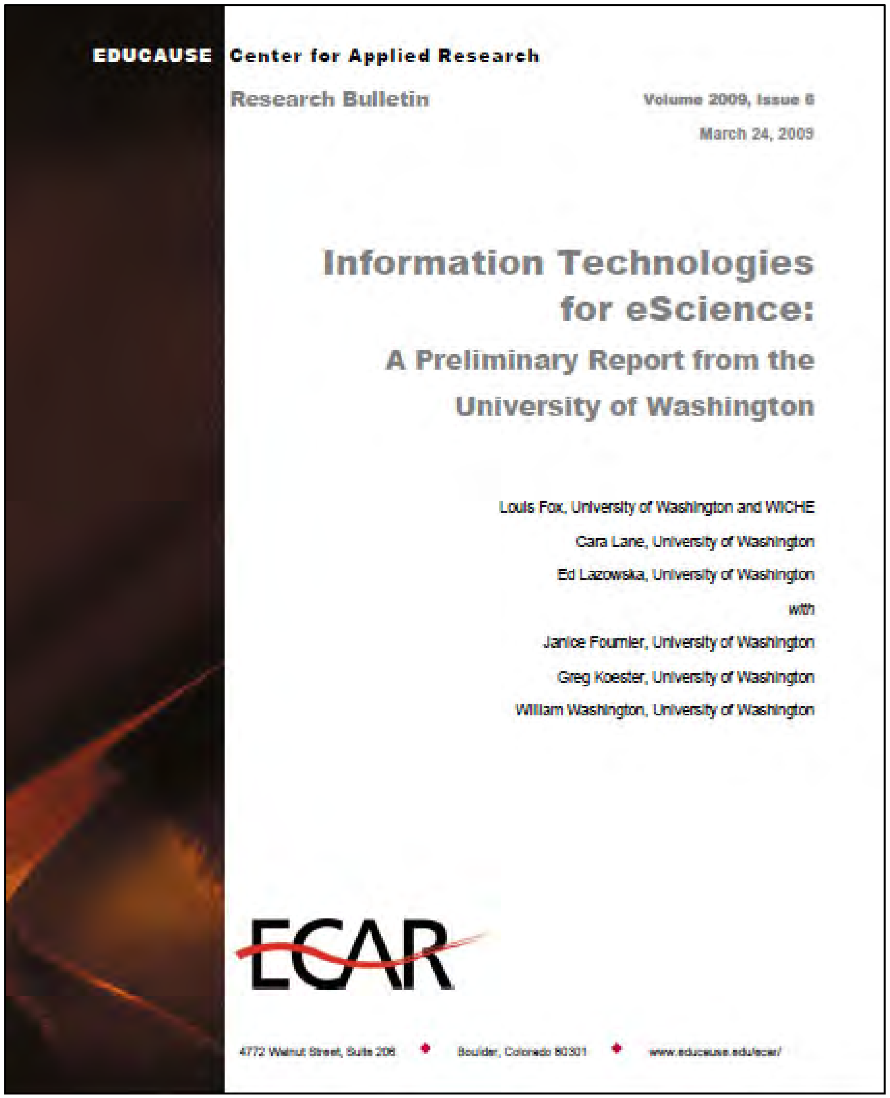
Example: Social network analysis

- 2000

- 2010



Top faculty across all disciplines understand and fear the coming data tsunami



EDUCAUSE Center for Applied Research

Research Bulletin

Volume 2009, Issue 6

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Information Technologies for eScience:

A Preliminary Report from the University of Washington

Louis Fox, University of Washington and WICHE

Cara Lane, University of Washington

Ed Lazowska, University of Washington

with

Janice Fournier, University of Washington

Greg Koester, University of Washington

William Washington, University of Washington

ECAR

4772 Walnut Street, Suite 206 ♦ Boulder, Colorado 80301 ♦ www.educause.edu/ecar/

- Survey of 125 top investigators
  - "Data, data, data"
- Excel is the data management tool of choice
  - Great for Microsoft … lousy for science!
- Typical science workflow:
  - 2 years ago: 1/2 day/week
  - Now: 1 FTE
  - In 2 years: 10 FTE
- Need tools, tools, tools!

The University of Washington eScience Institute

- Mission
  - Help position the University of Washington at the forefront of research both in modern eScience techniques and technologies, and in the fields that depend upon these techniques and technologies
- Strategy
  - Increase the sharing of expertise and facilities
  - Bootstrap a cadre of Research Scientists
  - Add faculty in key fields
  - Make the entire University more effective
- Launched in July 2008 with $1 million in permanent funding from the Washington State Legislature
  - Many grants received since then

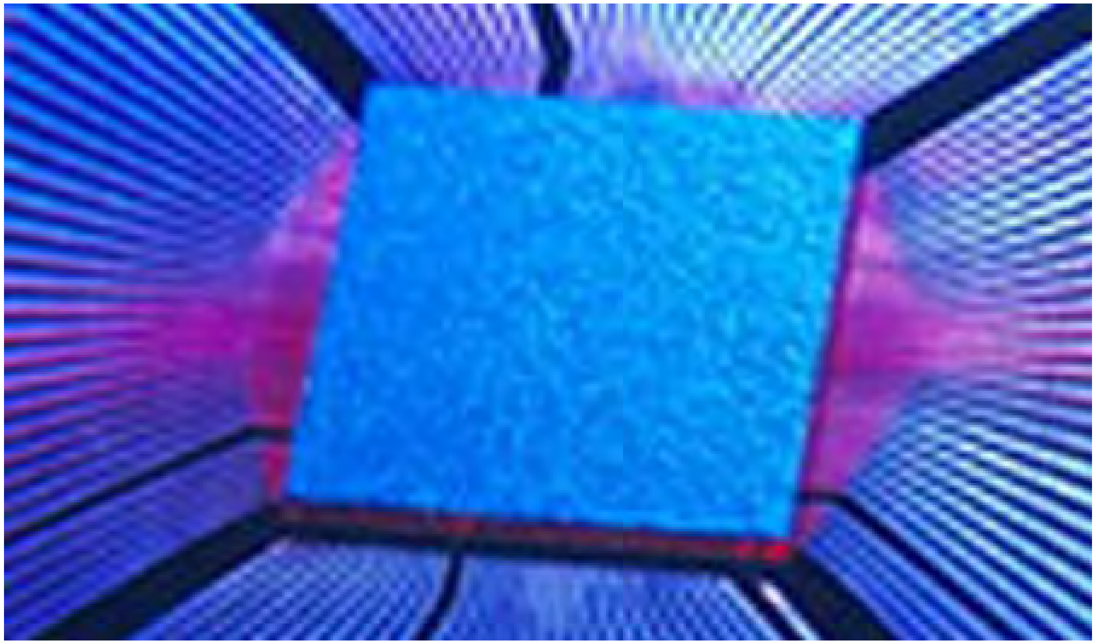
Questions for you …

- How does your institution track the IT needs – present and future – of its leading researchers?
- To what extent are you meeting these needs, and in what critical areas are you falling short?
- How well does your technology staff understand the institution's research and disciplinary directions and their IT implications?
- What potential resources, other than those currently in place, can be used to provide broad-based IT support for eScience and eScholarship?

More on the enablement of eScience

- Ten quintillion: $10*10^{18}$
  - The number of grains of rice harvested in 2004

- Ten quintillion: $10*10^{18}$
  - The number of grains of rice harvested in 2004
  - The number of transistors fabricated in 2004

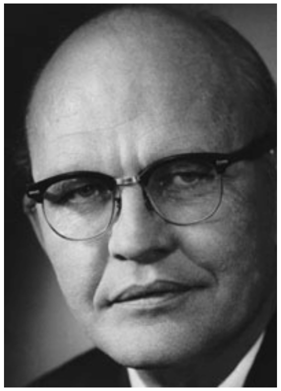


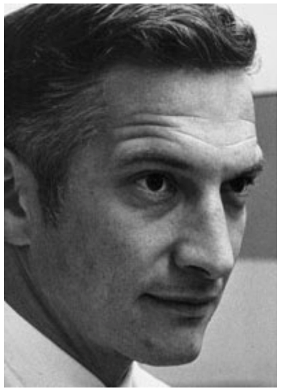
The transistor

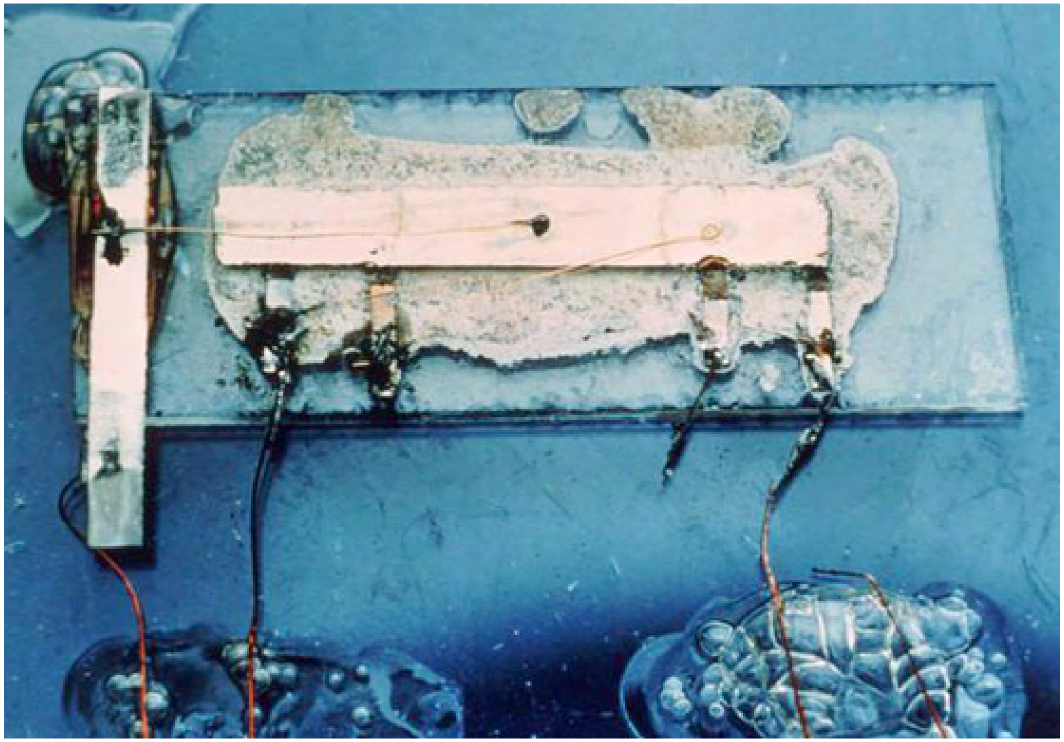
- William Shockley, Walter Brattain and John Bardeen, Bell Labs, 1947

The integrated circuit

- Jack Kilby, Texas Instruments, and Bob Noyce, Fairchild Semiconductor Corporation, 1958

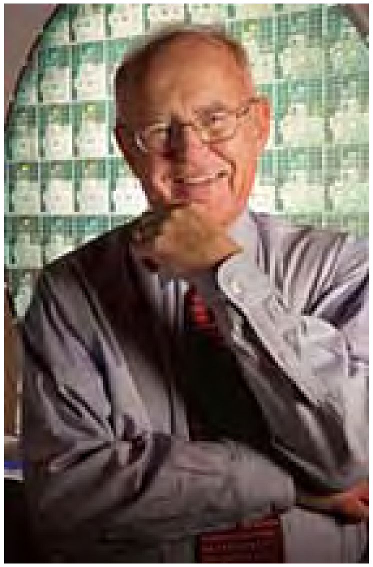


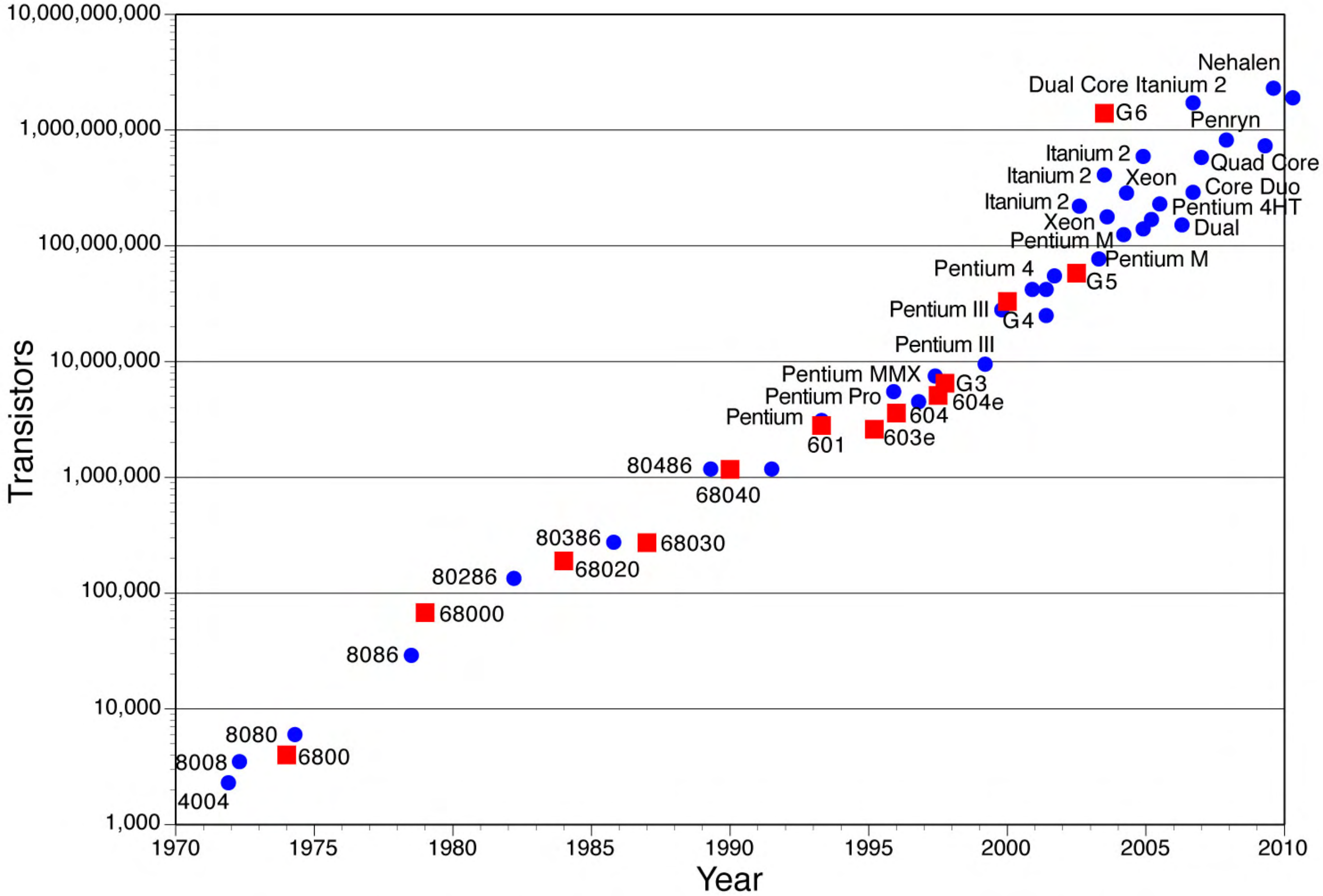




Exponential progress

- Gordon Moore, 1965





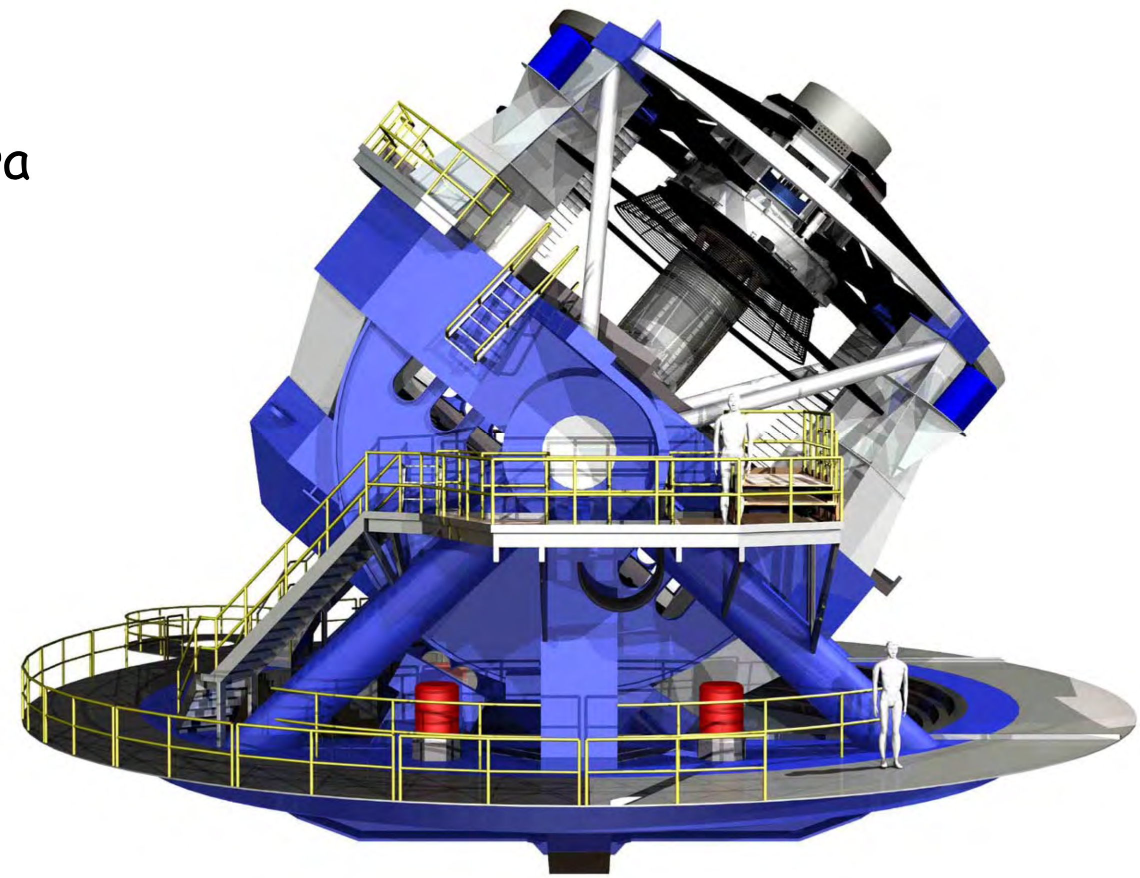

UNIVAC

Primary memory

- Primary memory – same story, same reason
  - 1972: 1MB, $1,000,000
  - 1982: 1MB, $60,000
  - 2005: 1MB, $0.40 ($400/GB)
  - 2007: 1MB, $0.15 ($145/GB)
  - 2009: 1MB, $0.015 ($16/GB)

Sensors

- Moore's Law drives sensors as well as processing and memory
  - LSST will have a 3.2 Gigapixel camera



Secondary storage

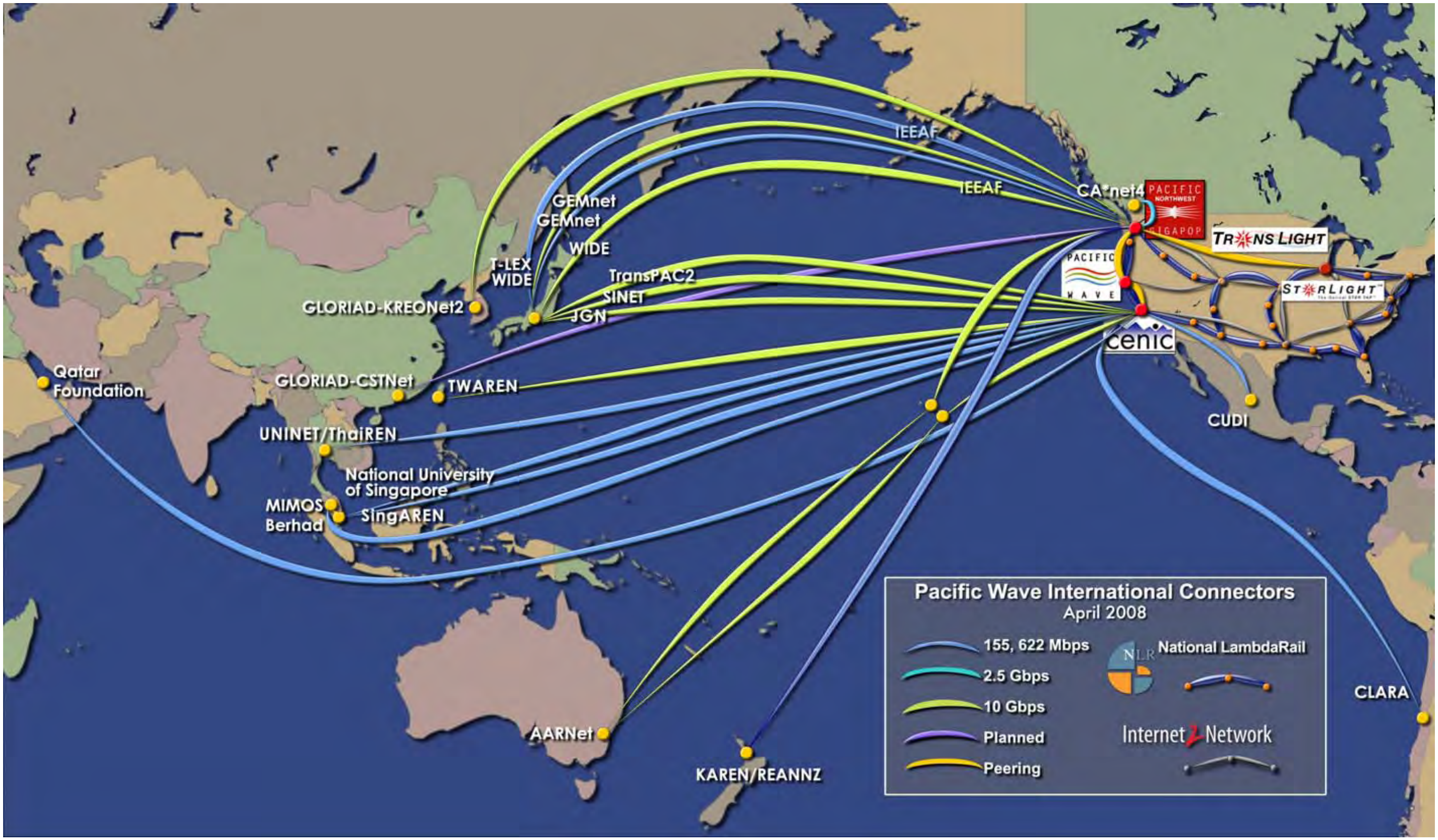
- Disk capacity, 1975-1989
  - doubled every 3+ years
- Disk capacity since 1990
  - doubling every 12 months
- Cost of 1 GB from Dell
  - 2005: $1.00 (purchase increment: 40 GB)
  - 2006: $0.50 (purchase increment: 80 GB)
  - 2008: $0.25 (purchase increment: 250 GB)

Optical bandwidth

- Doubling every 9 months
- 150% improvement each year
- Factor of 10,000 every decade
- 10x as fast as disk capacity
- 100x as fast as Moore's Law

A connected region - then

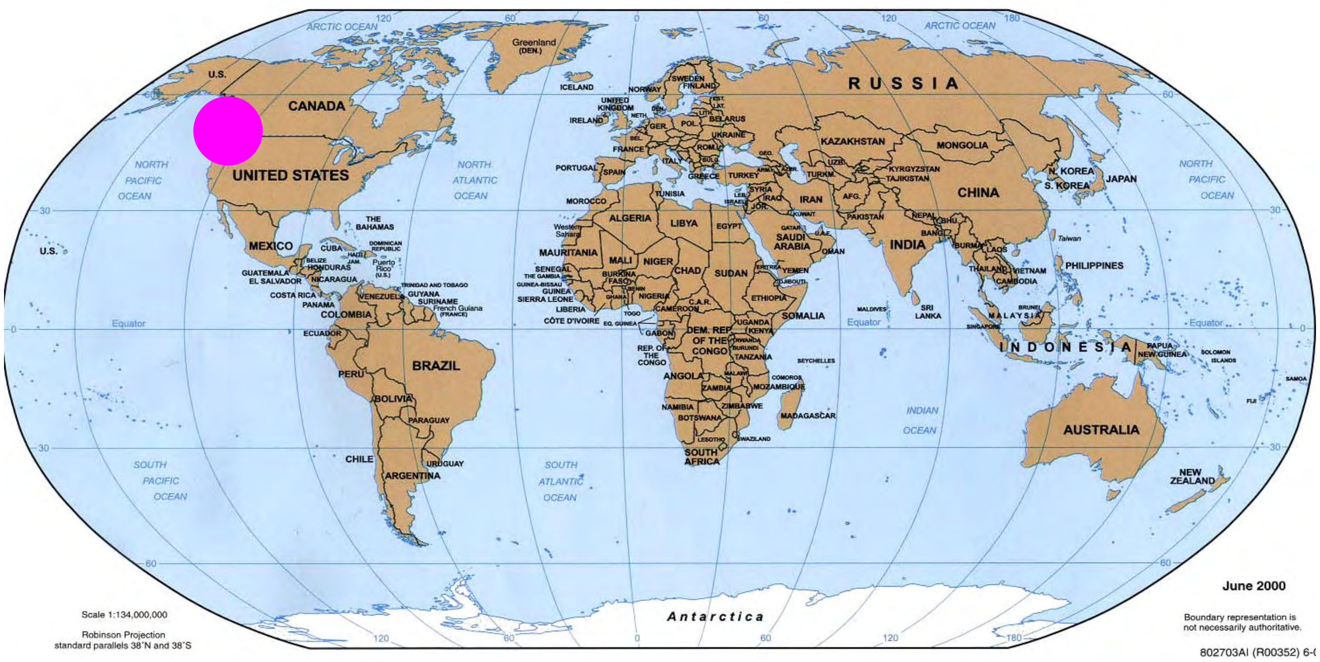
A connected region – now



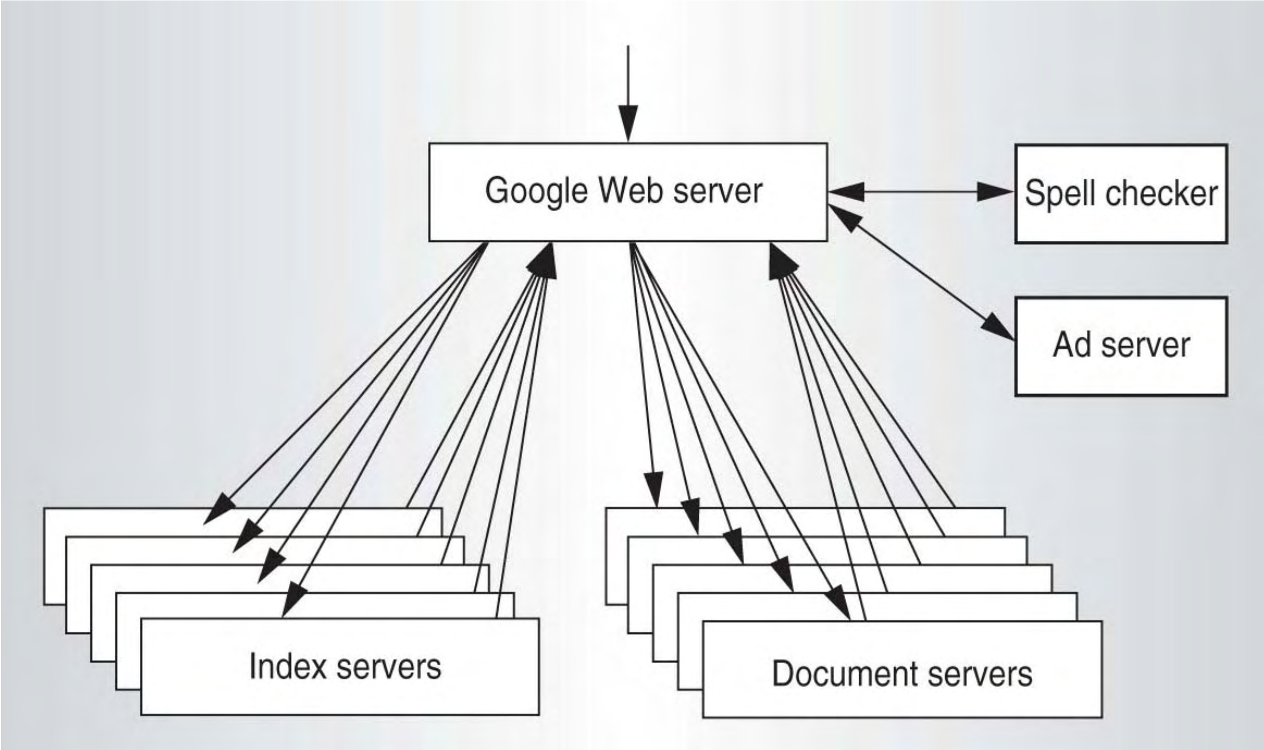
But eScience is equally enabled by *software* for *scalability* and for *discovery*

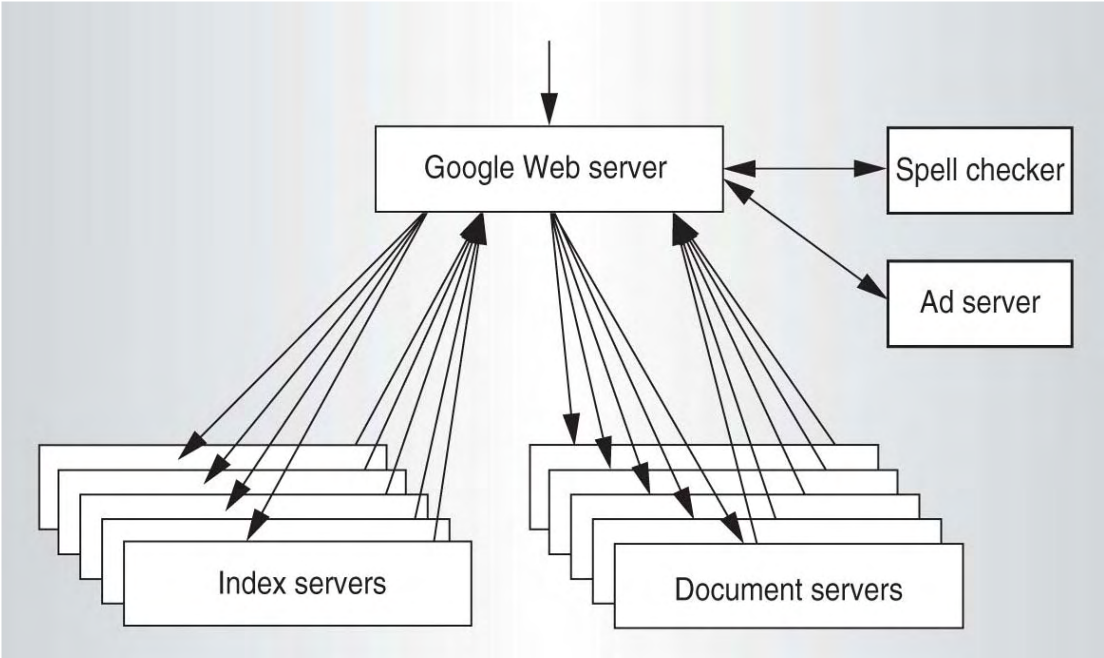
- It's likely that Google has several million machines
  - But let's be conservative – 1,000,000 machines
  - A rack holds 176 CPUs (88 1U dual-processor boards), so that's about 6,000 racks
  - A rack requires about 50 square feet (given datacenter cooling capabilities), so that's about 300,000 square feet of machine room space (more than 6 football fields of real estate – although of course Google divides its machines among dozens of datacenters all over the world)
  - A rack requires about 10kw to power, and about the same to cool, so that's about 120,000 kw of power, or nearly 100,000,000 kwh per month ($10 million at $0.10/kwh)
    - Equivalent to about 20% of Seattle City Light's generating capacity

- Many hundreds of machines are involved in a single Google search request (remember, the web is 400+TB)
  - There are multiple clusters (of thousands of computers each) all over the world
  - DNS routes your search to a nearby cluster

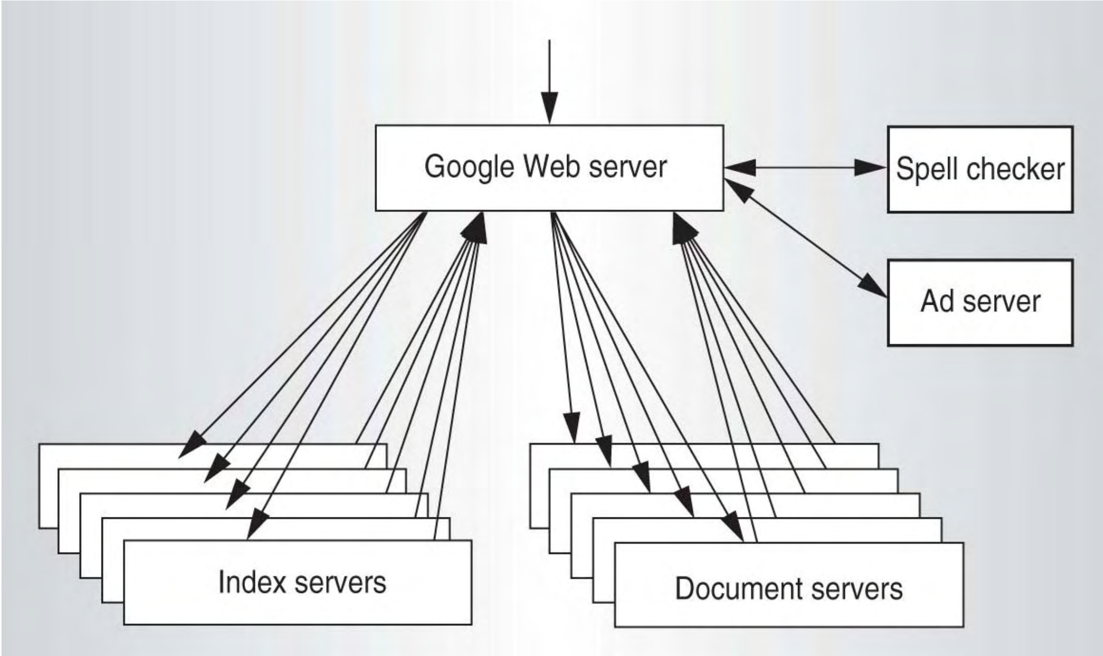


- A cluster consists of Google Web Servers, Index Servers, Doc Servers, and various other servers (ads, spell checking, etc.)
- These are cheap standalone computers, rack-mounted, connected by commodity networking gear

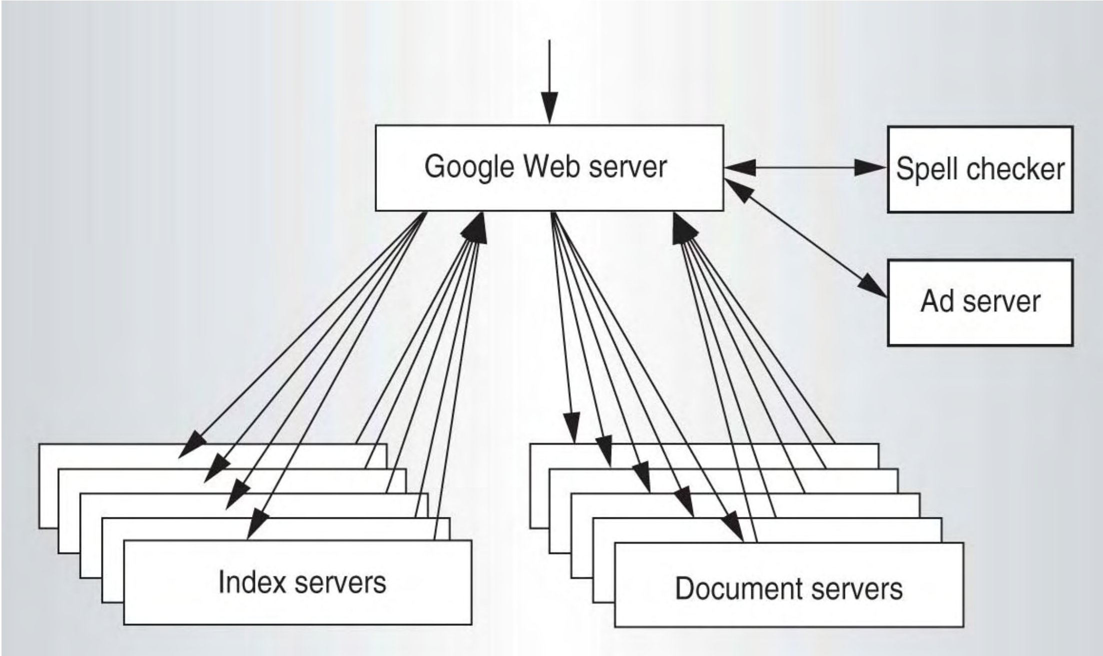




- Within the cluster, load-balancing routes your search to a lightly-loaded Google Web Server (GWS), which will coordinate the search and response
- The index is partitioned into "shards." Each shard indexes a subset of the docs (web pages). Each shard is replicated, and can be searched by multiple computers – "index servers"
- The GWS routes your search to one index server associated with each shard, through another load-balancer
- When the dust has settled, the result is an ID for every doc satisfying your search, rank-ordered by relevance



- The docs, too, are partitioned into "shards" – the partitioning is a hash on the doc ID. Each shard contains the full text of a subset of the docs. Each shard can be searched by multiple computers – "doc servers"
- The GWS sends appropriate doc IDs to one doc server associated with each relevant shard
- When the dust has settled, the result is a URL, a title, and a summary for every relevant doc



- Meanwhile, the ad server has done its thing, the spell checker has done its thing, etc.
- The GWS builds an HTTP response to your search and ships it off

- Many hundreds of computers have enabled you to search 400+TB of web in ~100 ms.

- Enormous volumes of data
- Extreme parallelism
- The cheapest imaginable components
  - Failures occur all the time
  - You couldn't afford to prevent this in hardware
- Software makes it
  - Fault-Tolerant
  - Highly Available
  - Recoverable
  - Consistent
  - Scalable
  - Predictable
  - Secure

AlphaServer 1200 product brief

Leadership

"To support our rapid growth, we had to find a highly upgradable and scaleable Internet server. The AlphaServer platform provides the upgrade path we need."

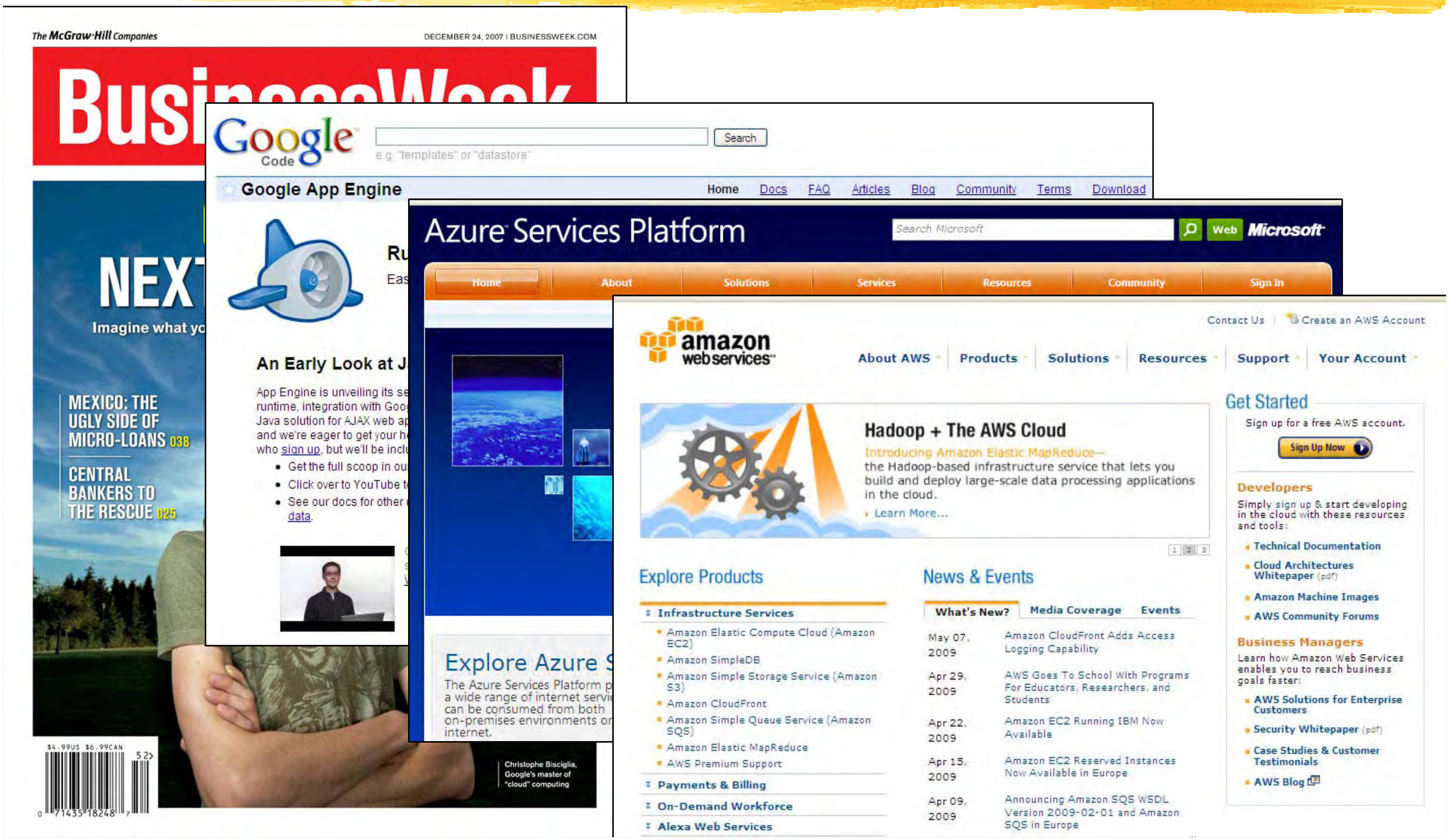
Jeff Bezos
CEO and Founder
Amazon.com

How on earth would you enable mere mortals write hairy applications such as this?

- Recognize that many Google applications have the same structure
  - Apply a “map” operation to each logical record in order to compute a set of intermediate key/value pairs
  - Apply a “reduce” operation to all the values that share the same key in order to combine the derived data appropriately
- Example: Count the number of occurrences of each word in a large collection of documents
  - Map: Emit <word, 1> each time you encounter a word
  - Reduce: Sum the values for each word

- Build a runtime library that handles all the details, accepting a couple of customization functions from the user – a Map function and a Reduce function
- That's what MapReduce is
  - Supported by the Google File System and the Chubby lock manager
  - Augmented by the BigTable not-quite-a-database system

eScience utilizes the Cloud: Scalable computing for everyone



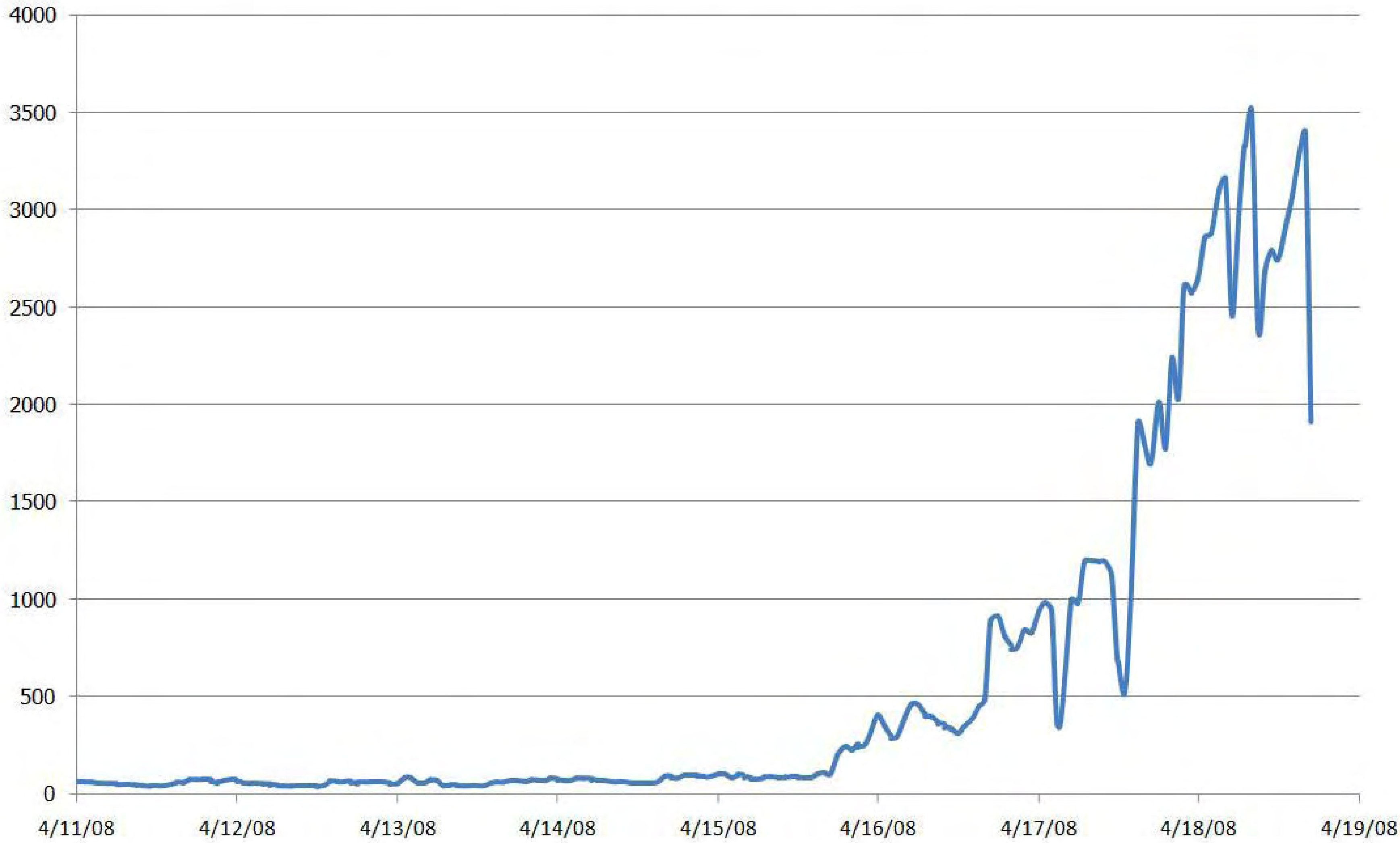
Amazon Elastic Compute Cloud (EC2)

- $0.68 per hour for
  - 8 cores of 3 GHz 64-bit Intel or AMD
  - 7 GB memory
  - 1.69 TB scratch storage
- Need it 24x7 for a year?
  - $3000

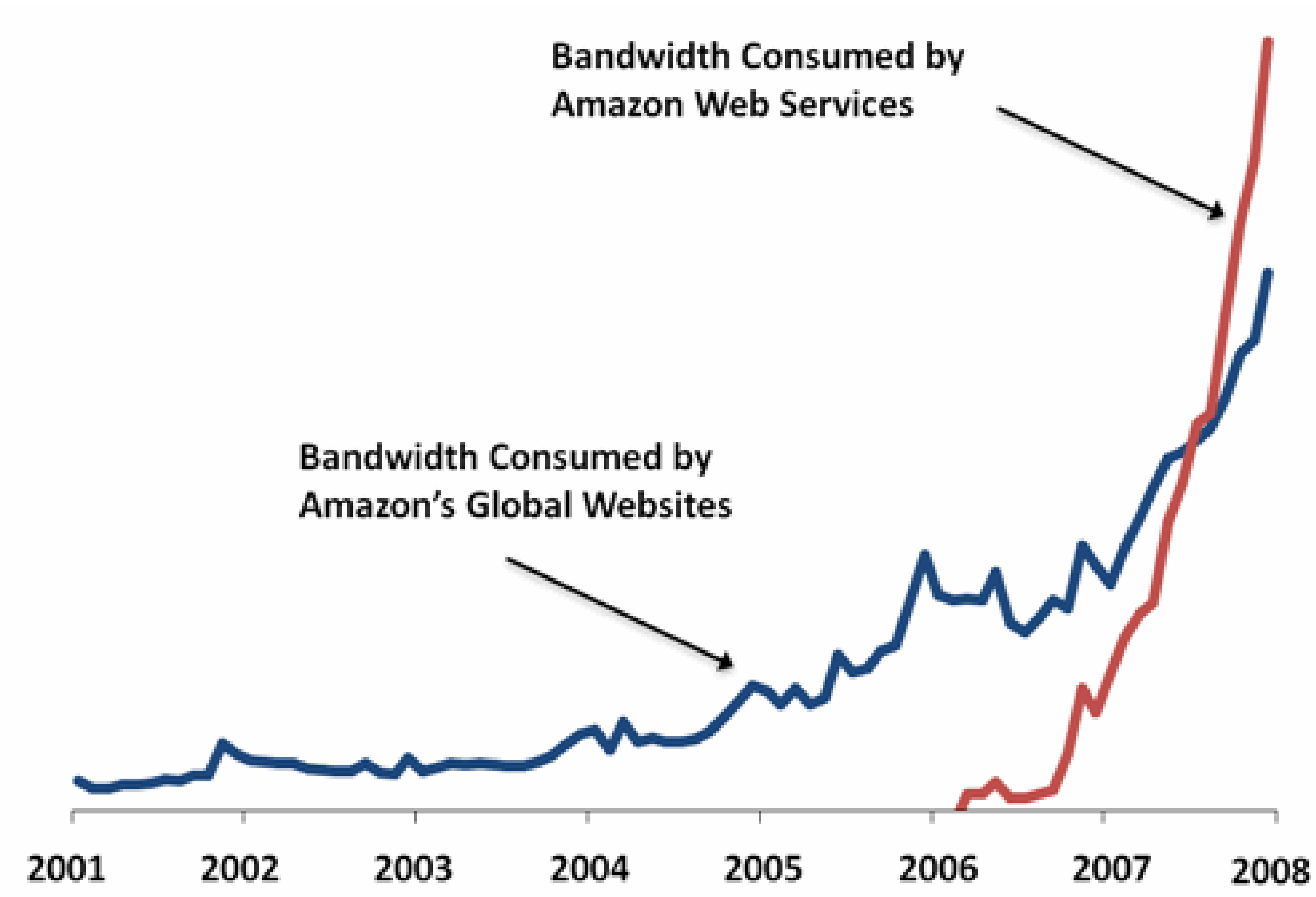
- $0.085 per hour for
  - 1 core of 1.2 GHz 32-bit Intel or AMD (1/20th the above)
  - 1.7 GB memory
  - 160 GB scratch storage
- Need it 24x7 for a year?
  - $379

- This includes
  - Purchase + replacement
  - Housing
  - Power
  - Operation
  - Reliability
  - Security
  - Instantaneous expansion and contraction
- 1000 computers for a day costs the same as one computer for 1000 days – revolutionary!

Animoto: EC2 Instance Usage

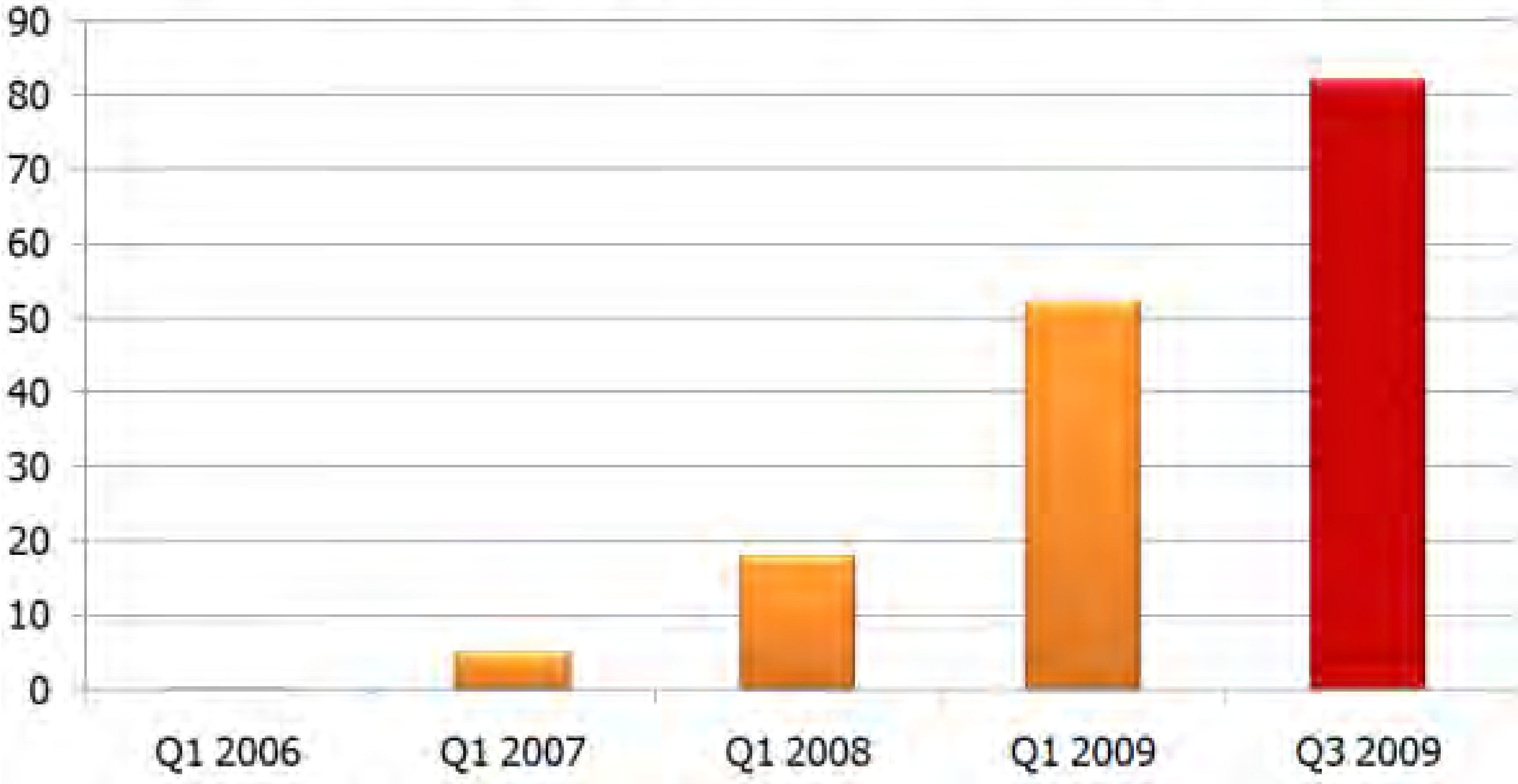


[Werner Vogels, Amazon.com]



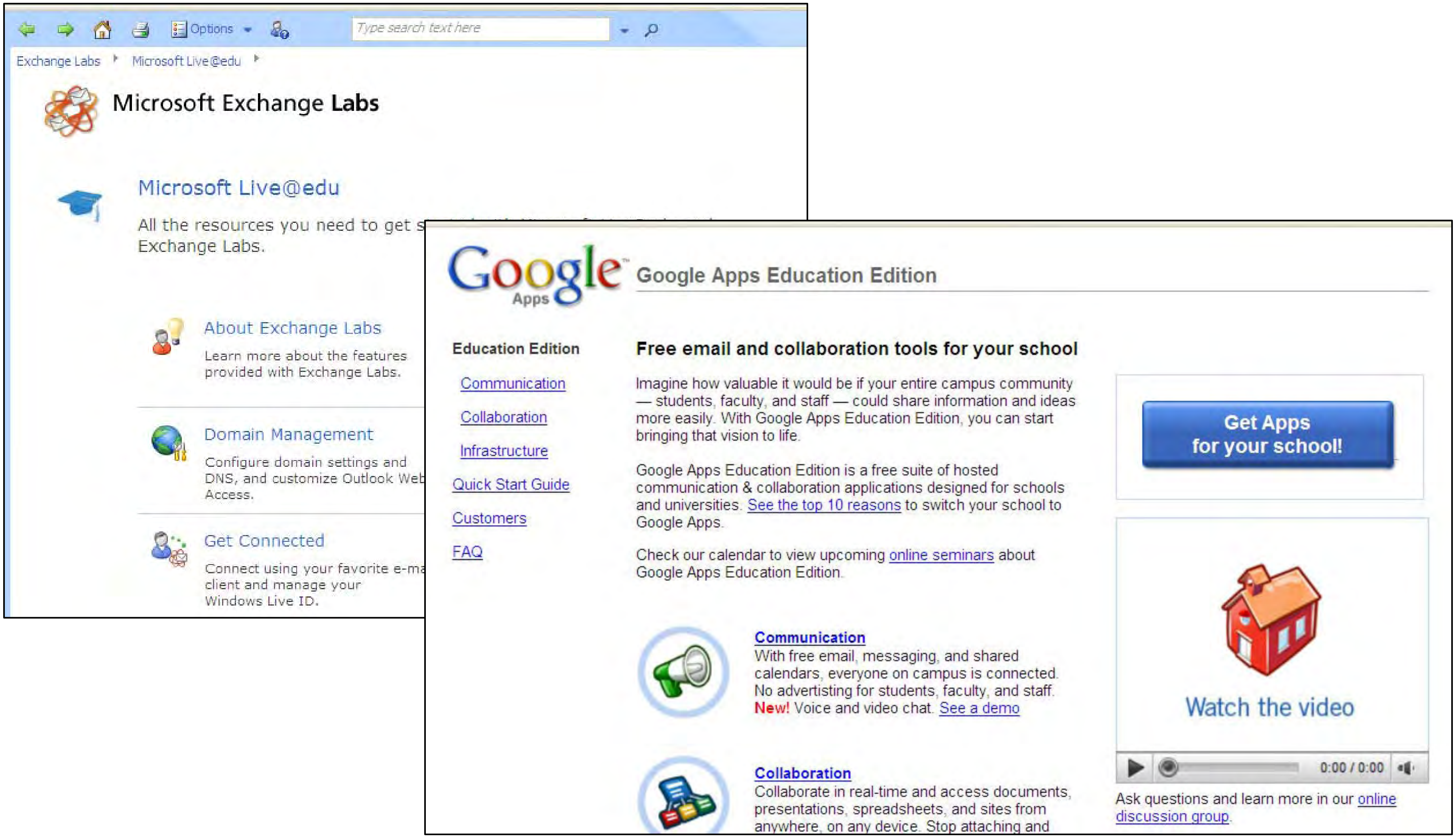
[Werner Vogels, Amazon.com]

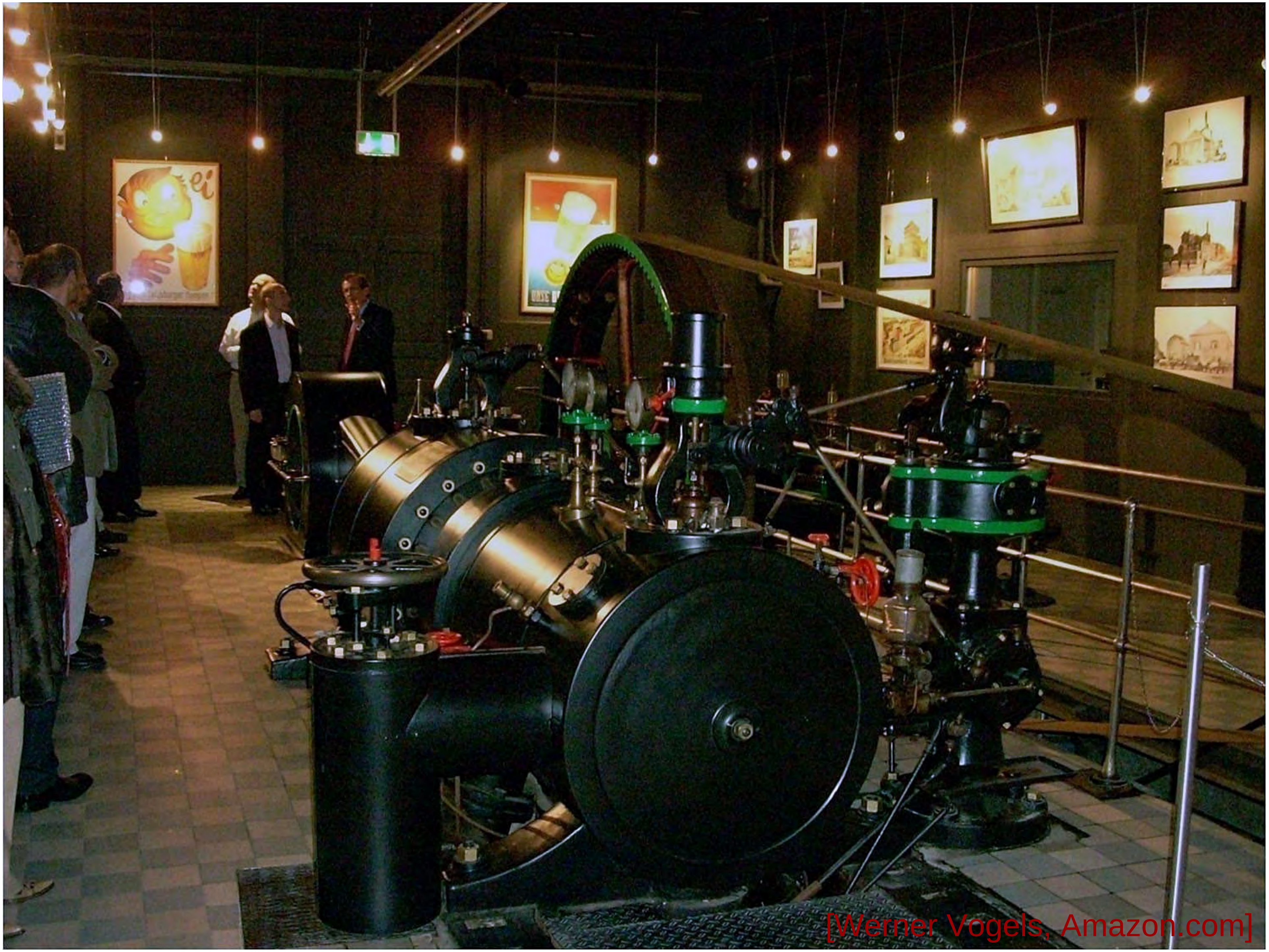
82 Billion Objects in Amazon S3



[Werner Vogels, Amazon.com]

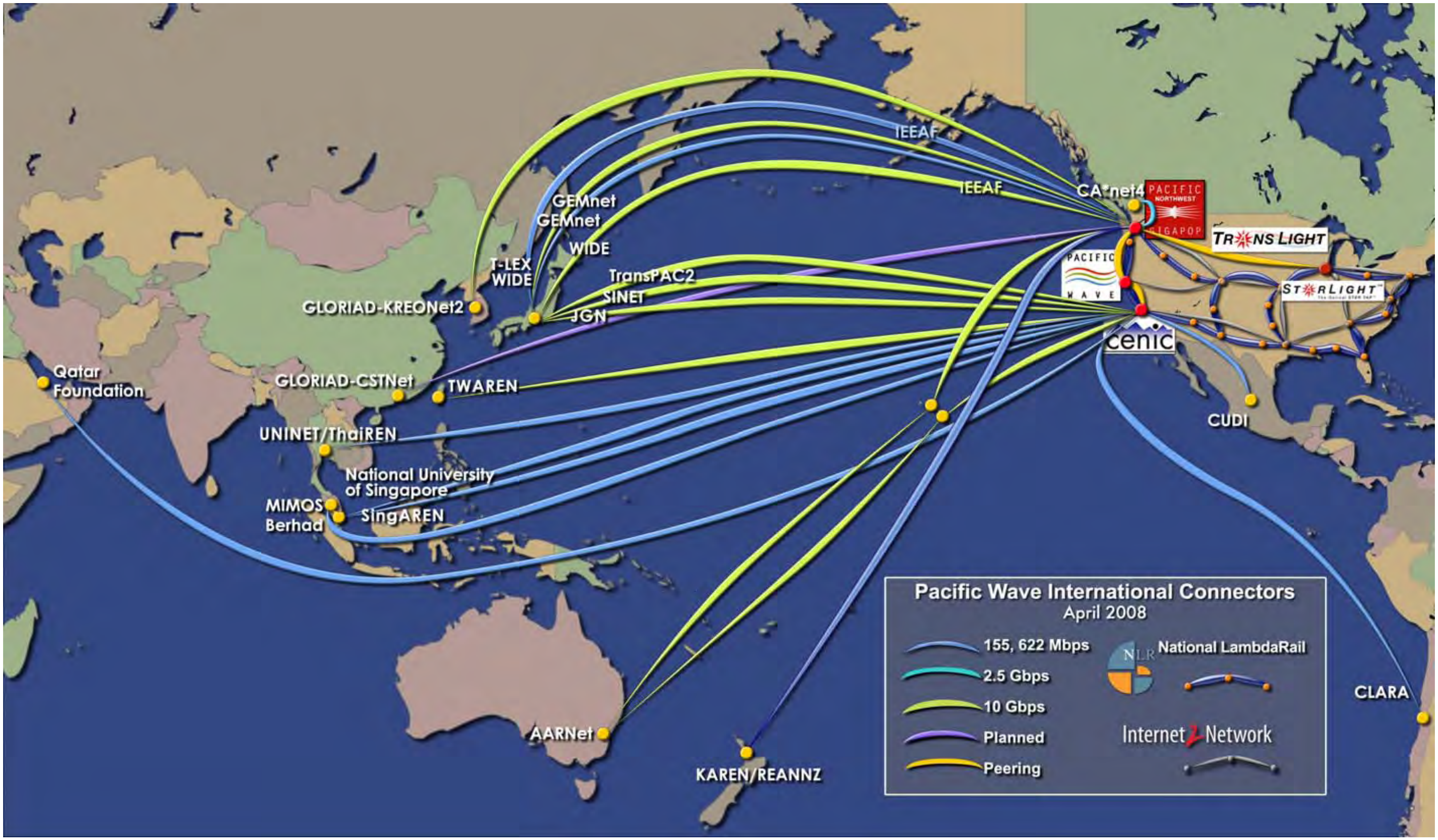
Still running your own email servers?



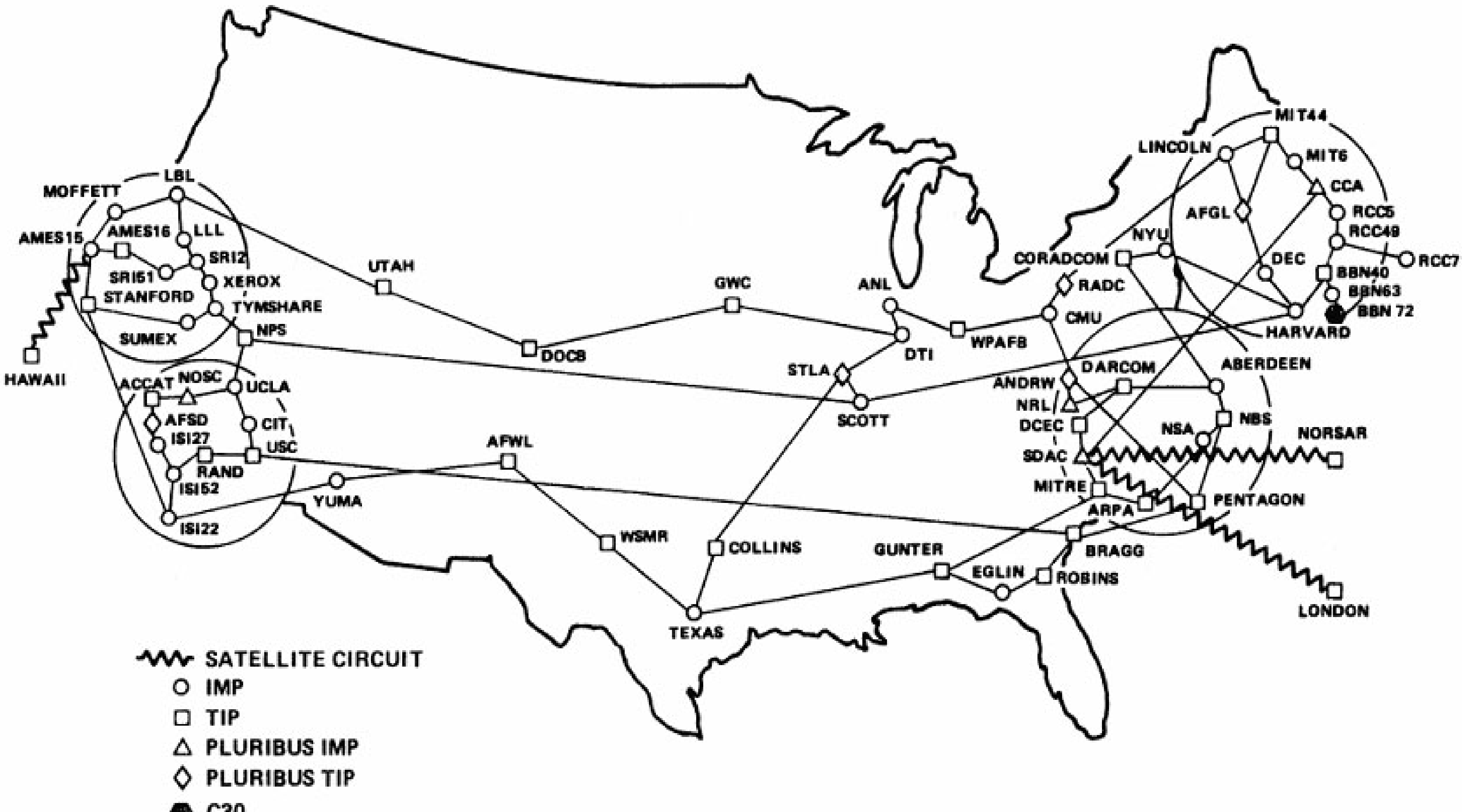


[Werner Vogels, Amazon.com]

Broadband, and the role of higher education

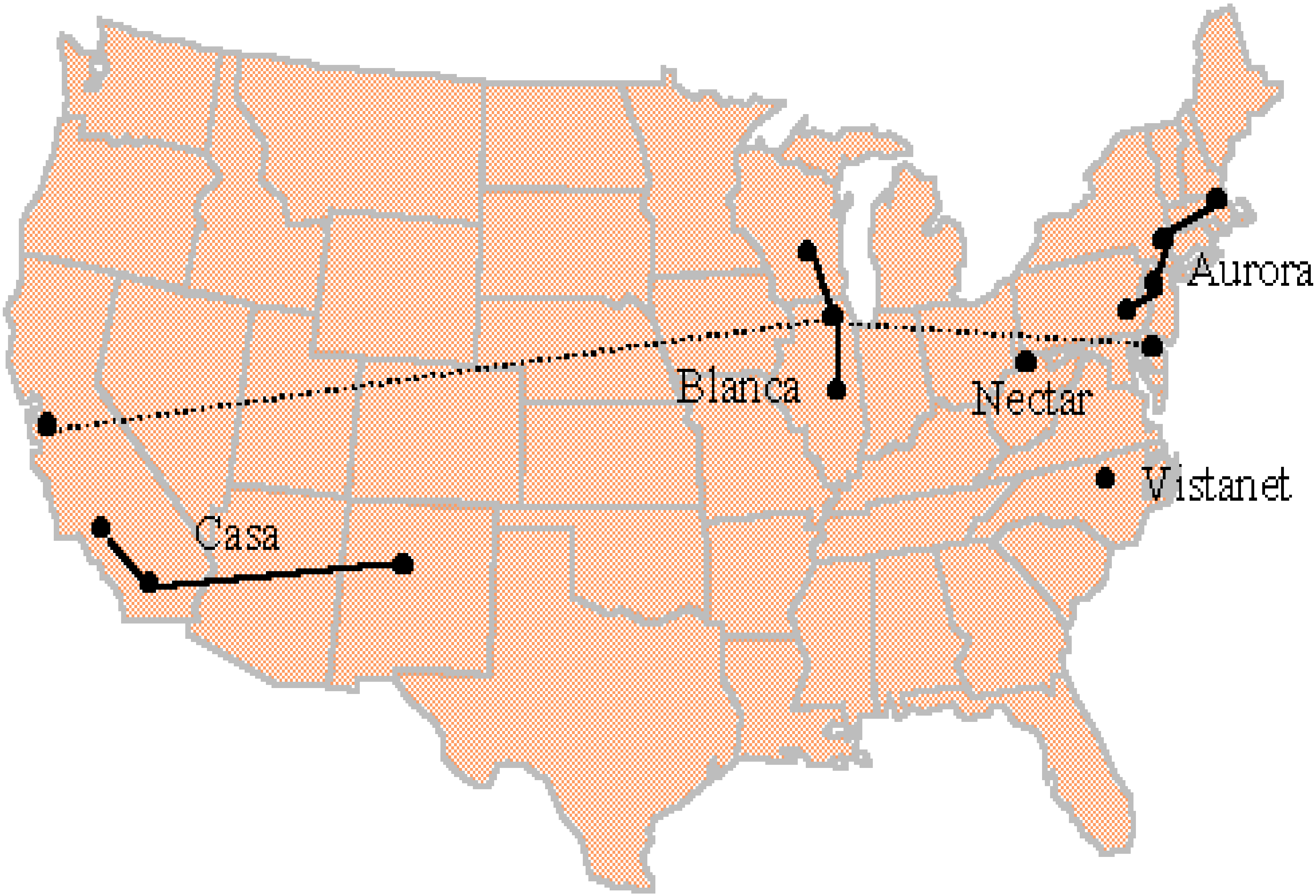


ARPANET GEOGRAPHIC MAP, OCTOBER 1980

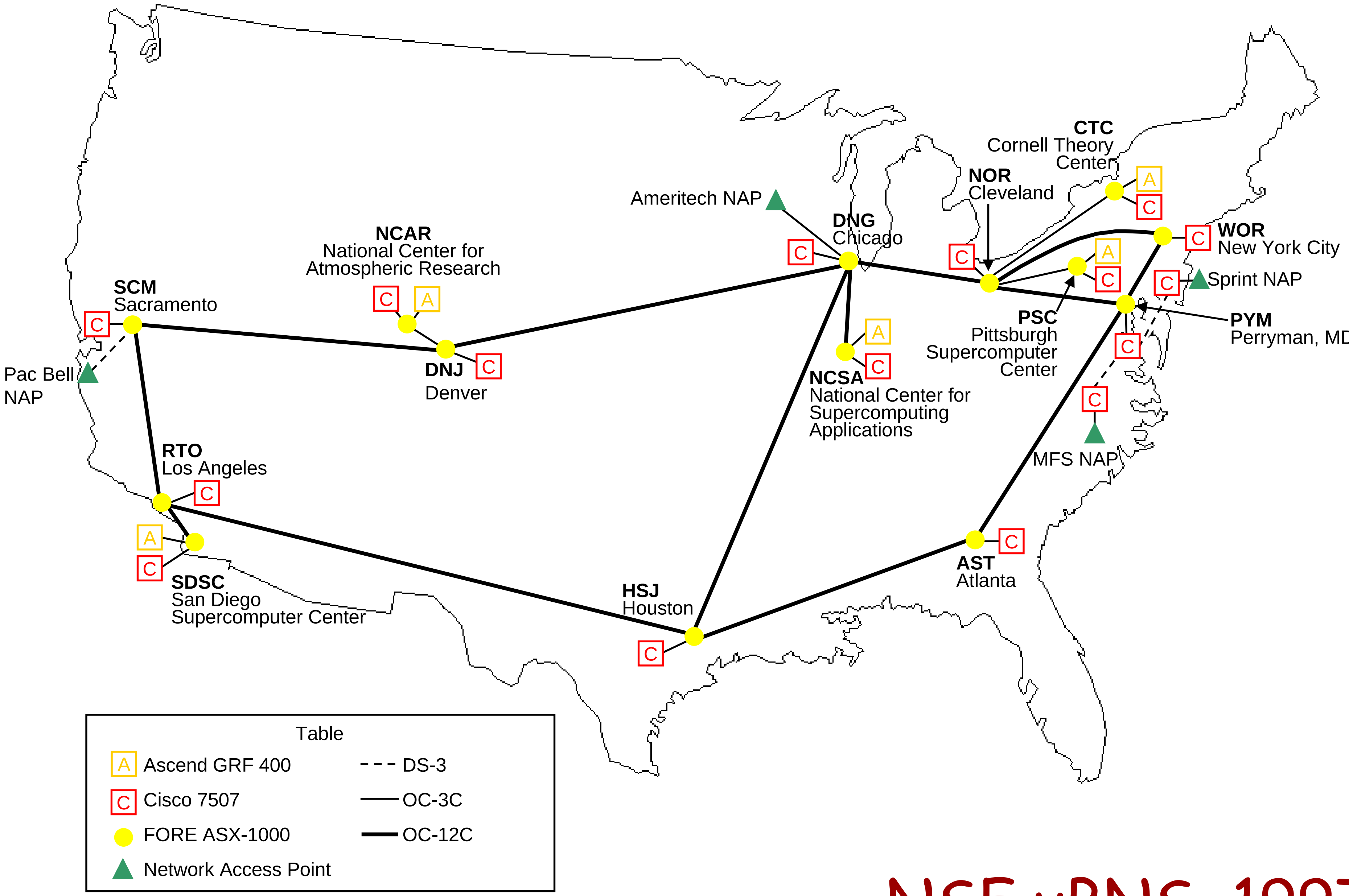


(NOTE: THIS MAP DOES NOT SHOW ARPA'S EXPERIMENTAL SATELLITE CONNECTIONS)
NAMES SHOWN ARE IMP NAMES, NOT (NECESSARILY) HOST NAMES

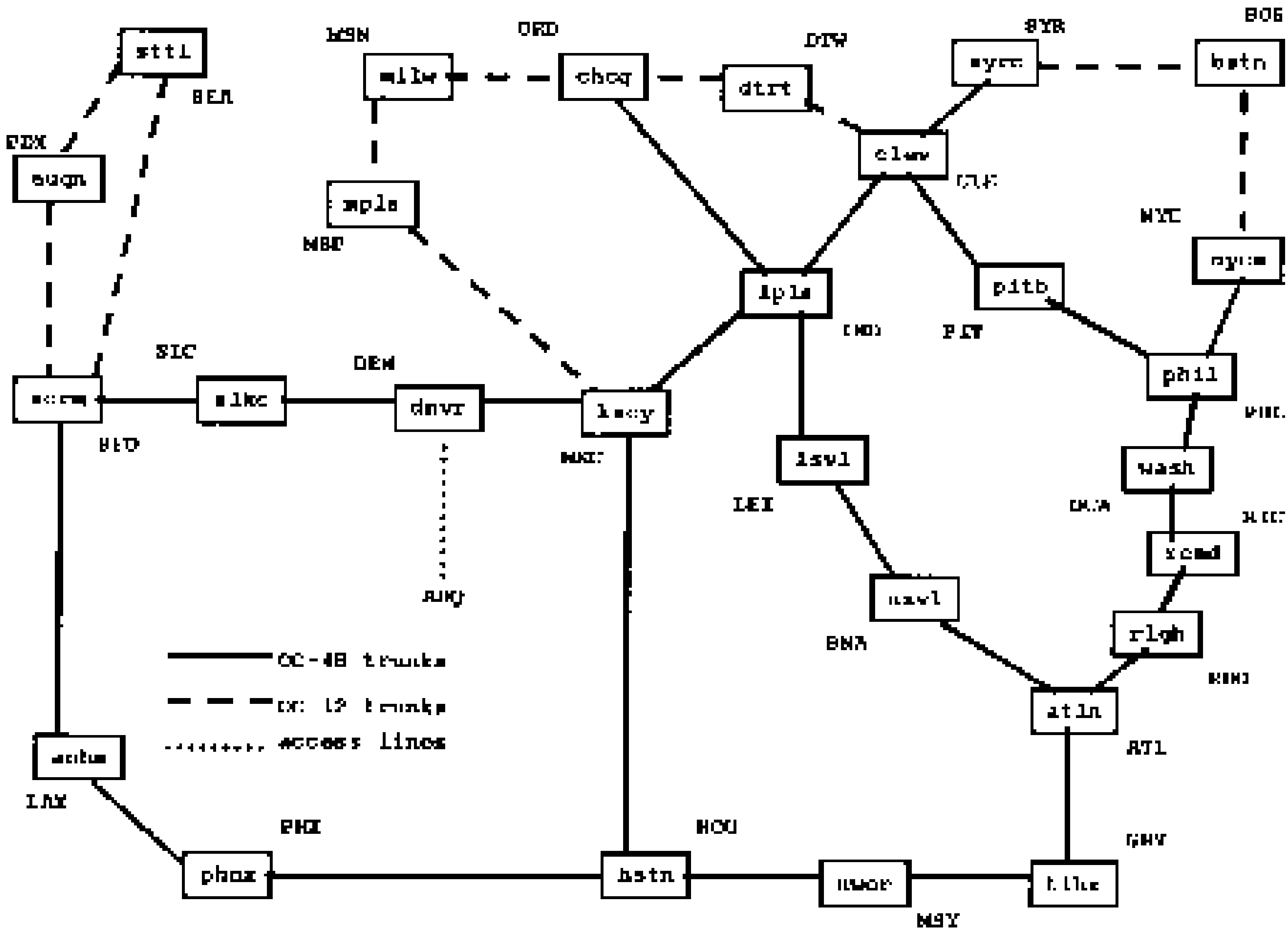
ARPANET, 1980



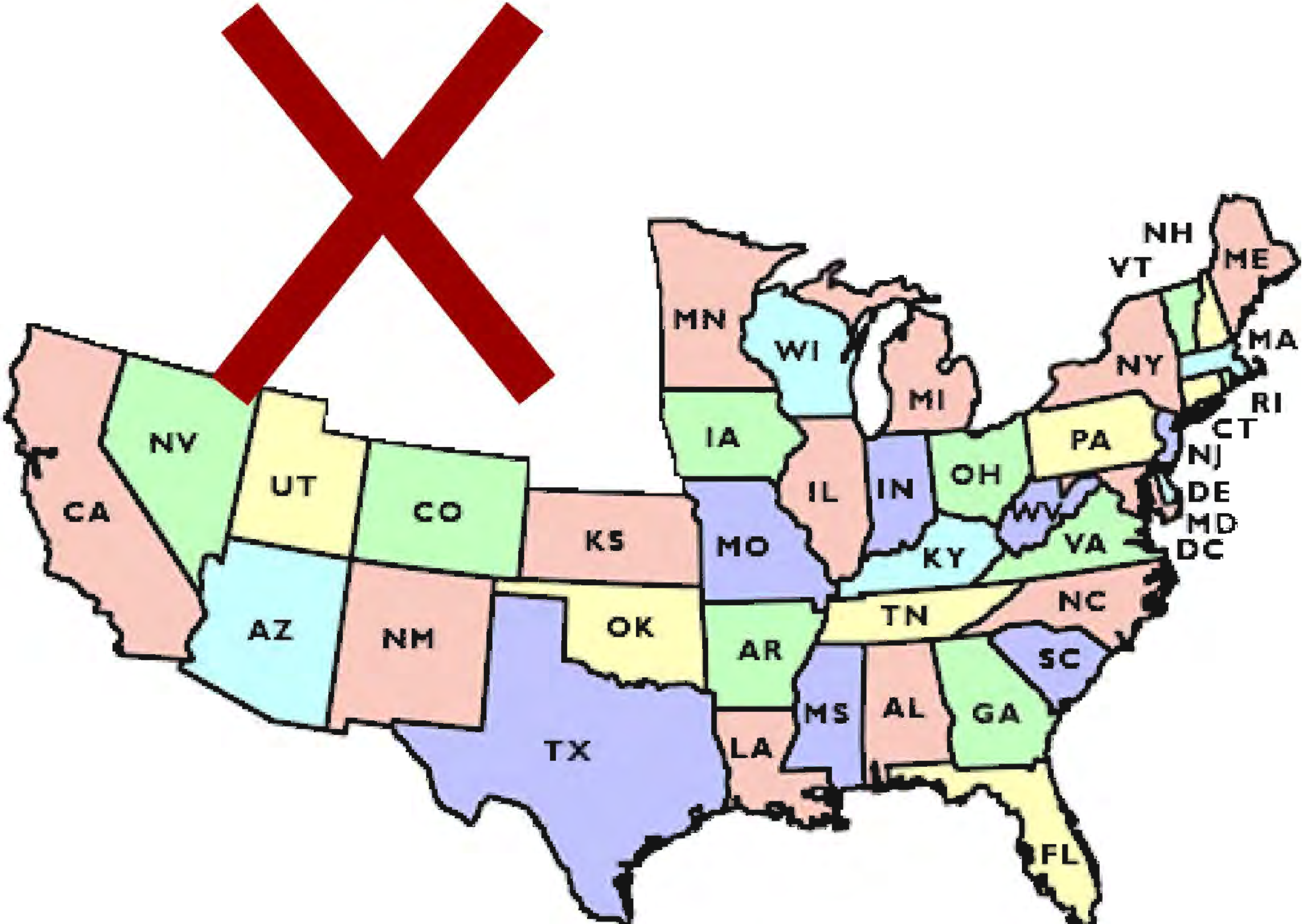
DARPA Gigabit Testbeds, mid-1990's



NSF vBNS, 1997



UCAID Abilene network, 1998


NH
VT
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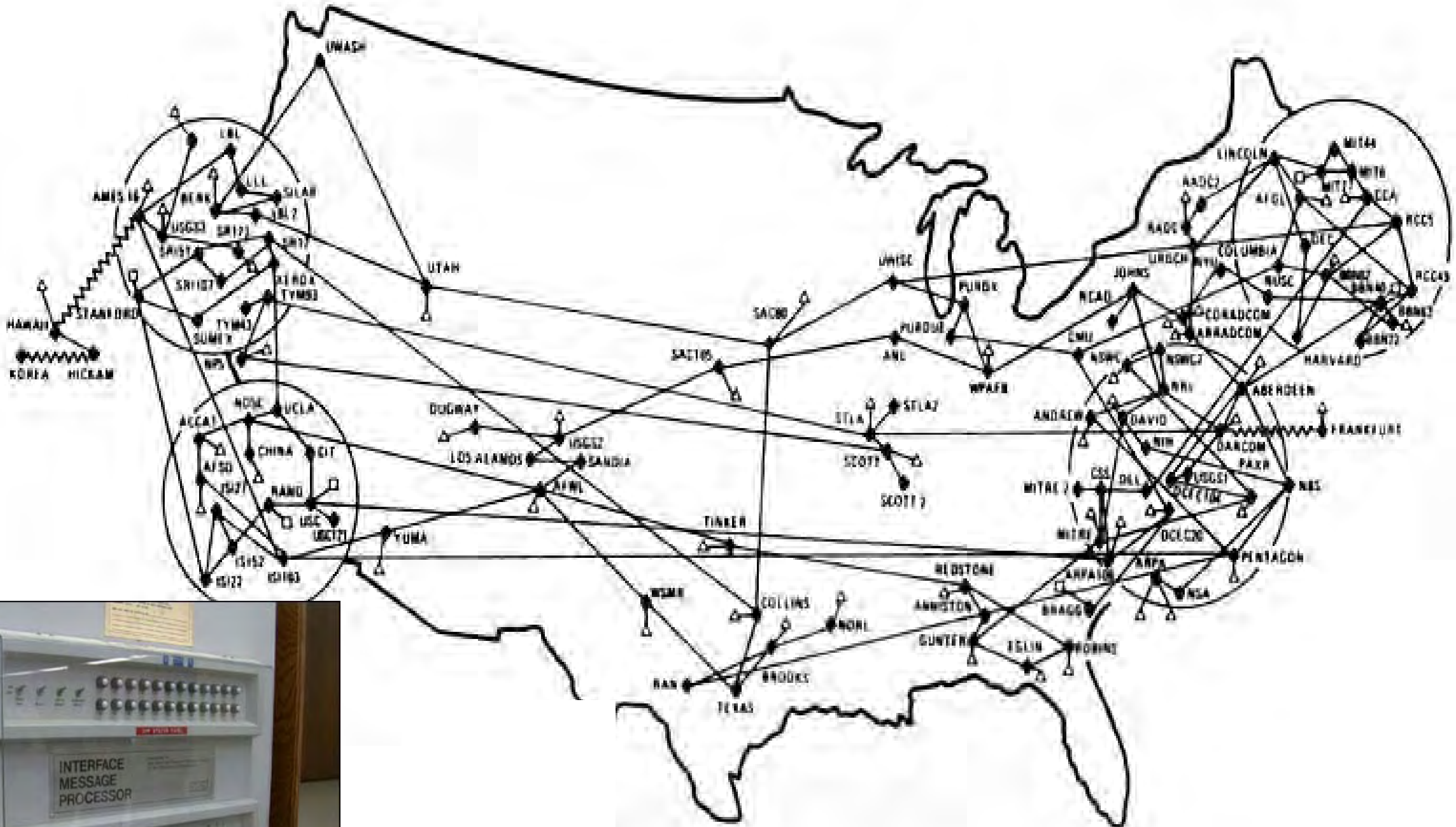
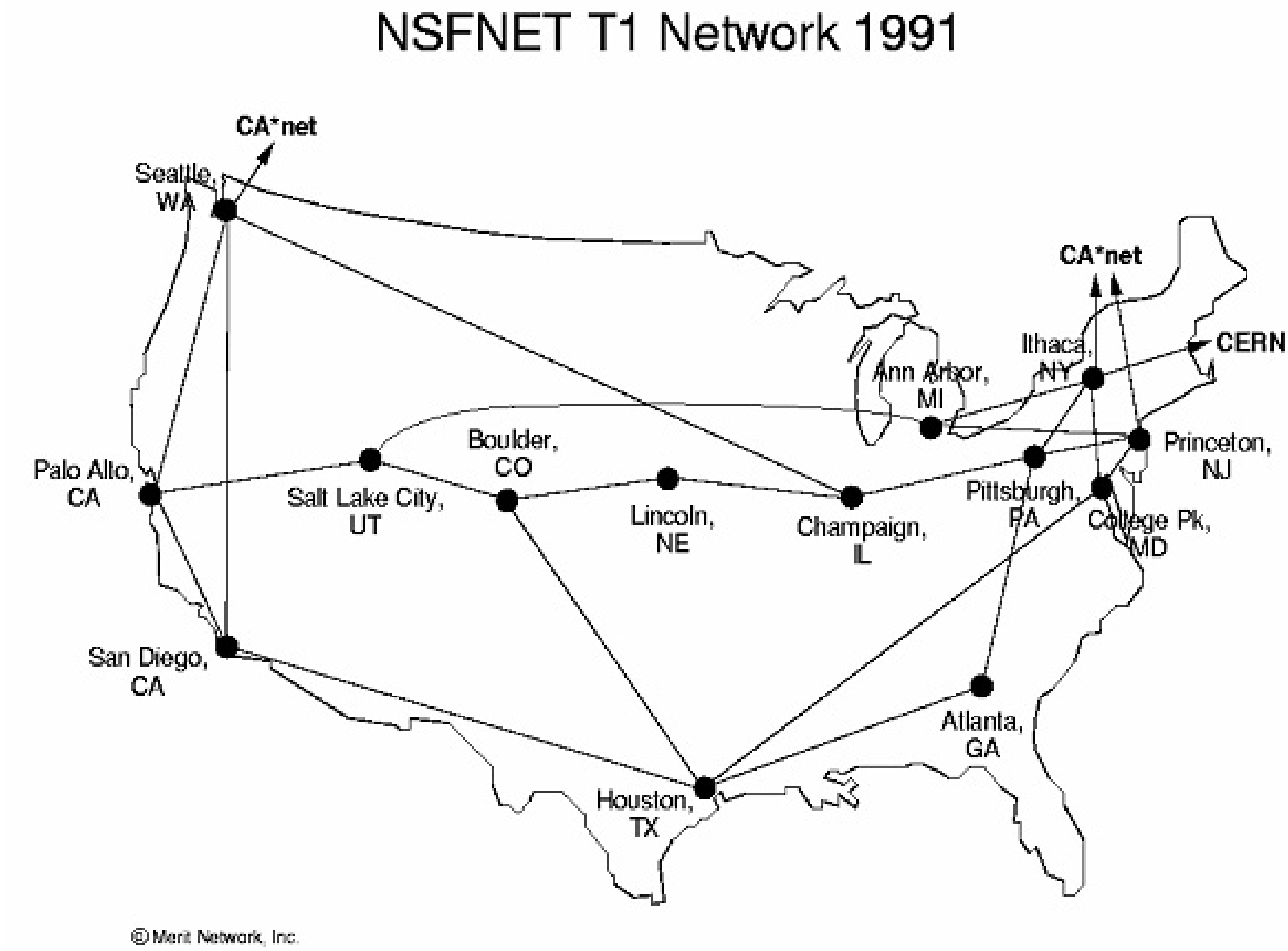
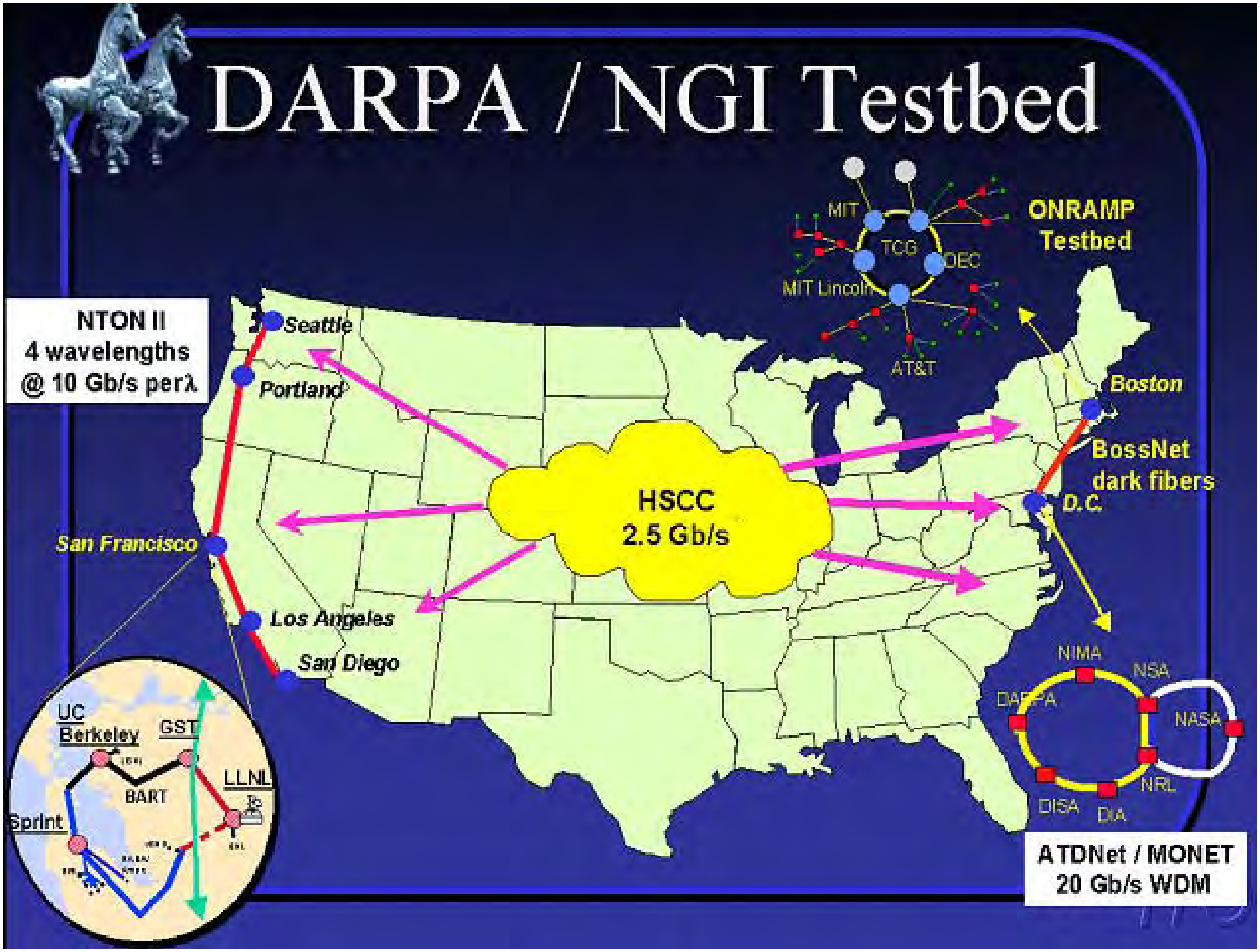


ARPANET, 1983

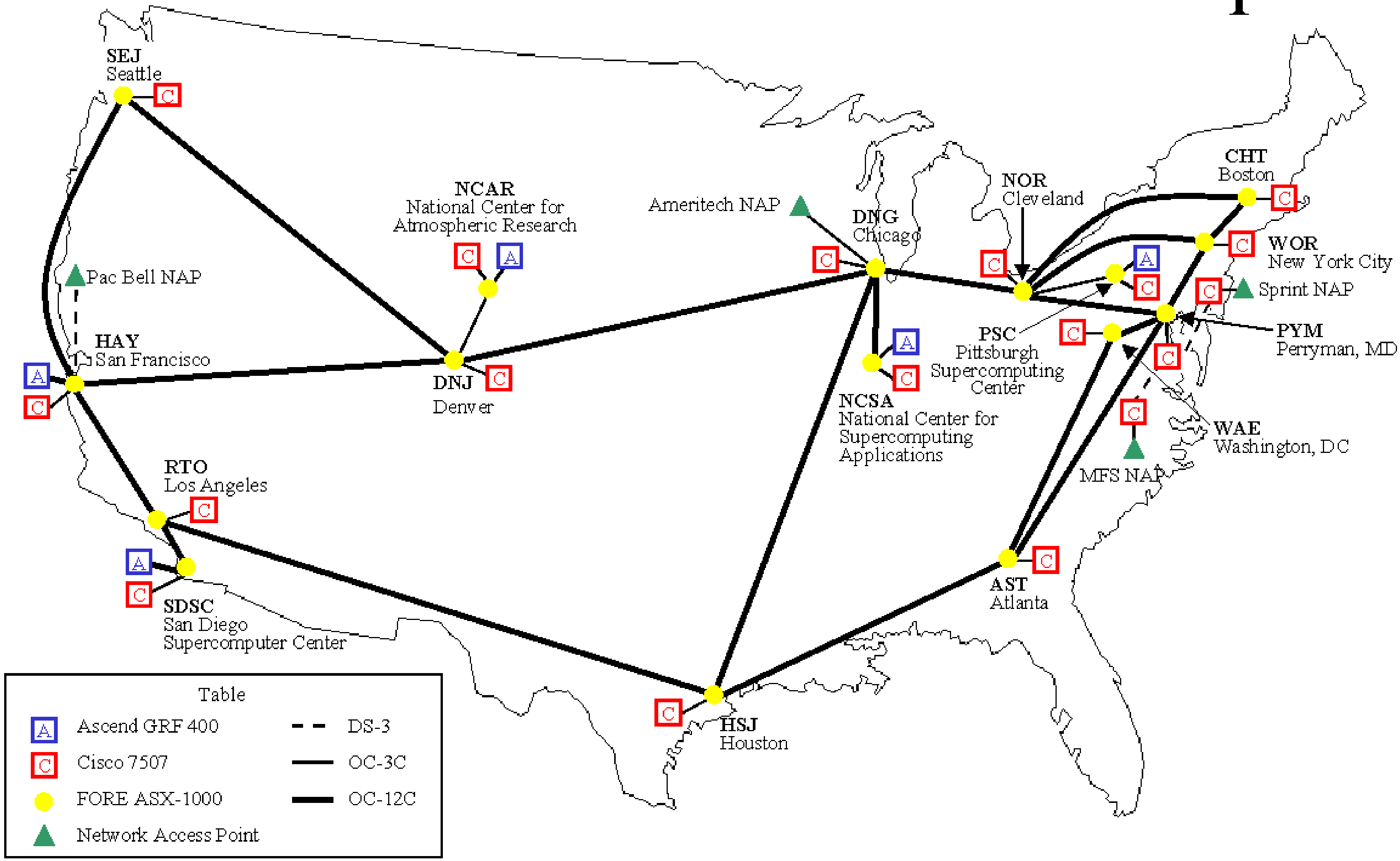

NSFNET T1 Network 1991
CA*net
Seattle, WA
CA*net
CERN
Ithaca, NY
Ann Arbor, MI
Princeton, NJ
Boulder, CO
Palo Alto, CA
Salt Lake City, UT
Lincoln, NE
Champaign, IL
Pittsburgh, PA
College Pk, MD
San Diego, CA
Atlanta, GA
Houston, TX
© Merit Network, Inc.

NSFNET, 1991

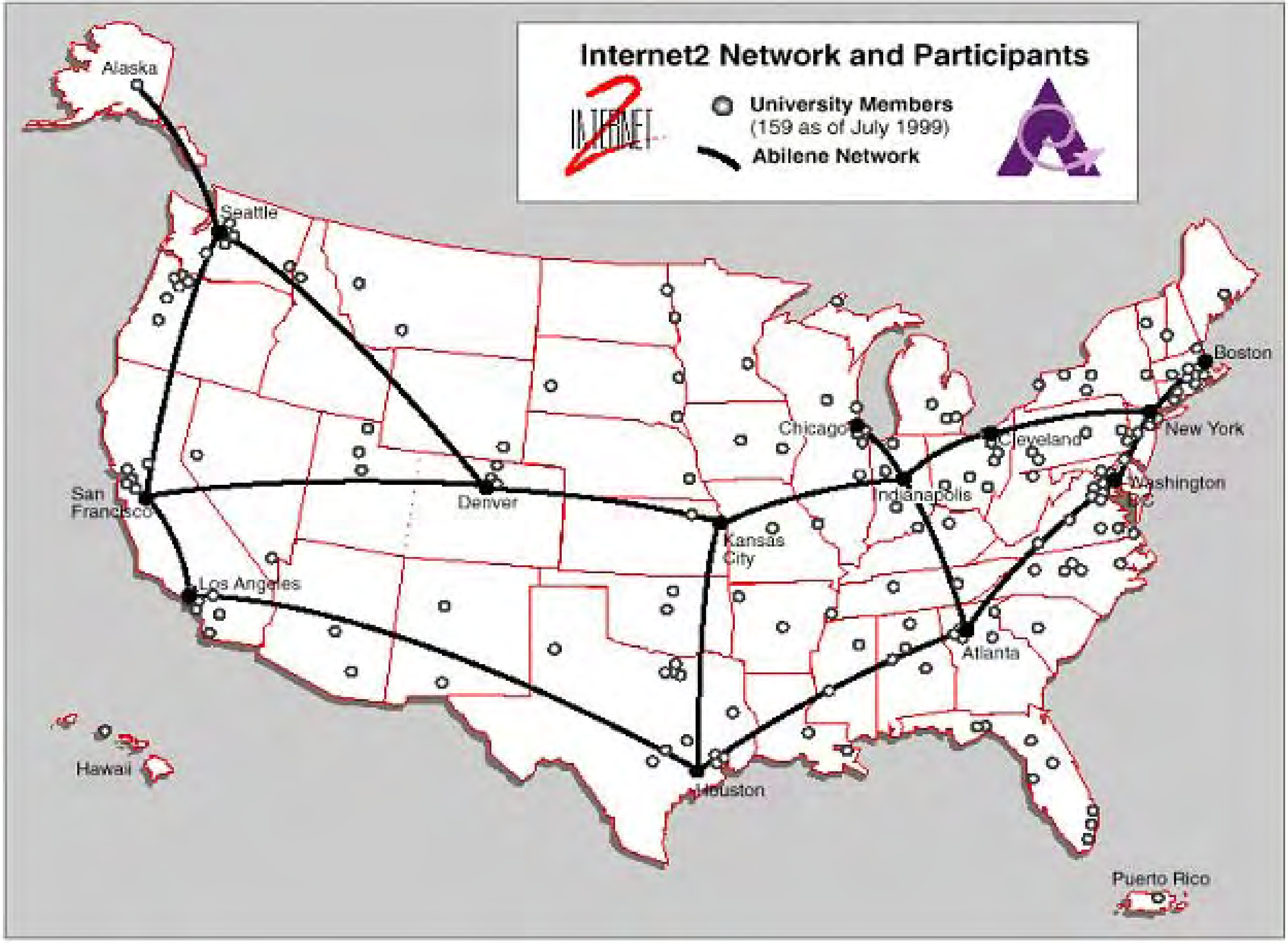


DARPA / NGI Testbed, late 1990's

vBNS Backbone Network Map



NSF vBNS, 1998

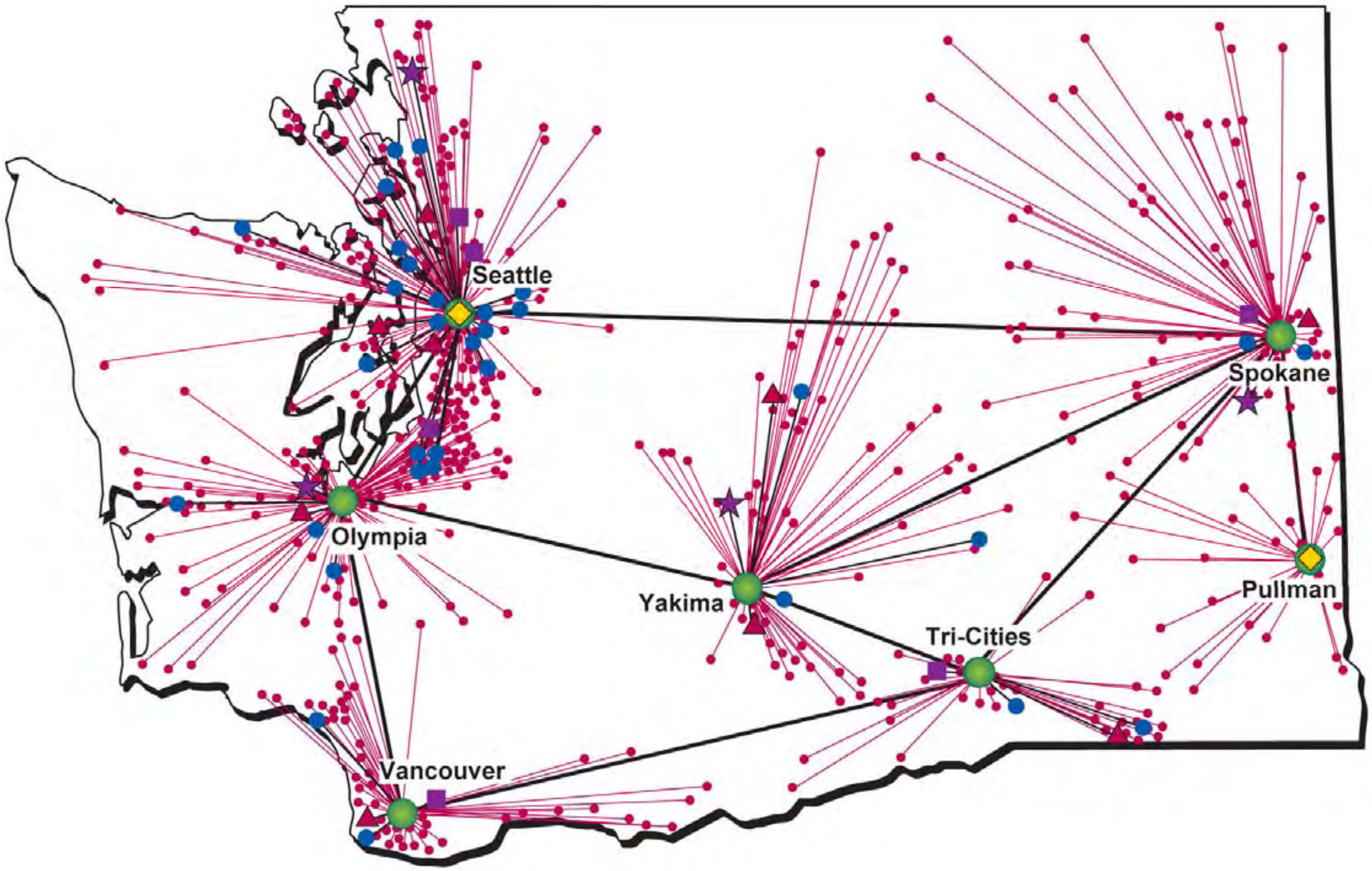


Internet2, 1999

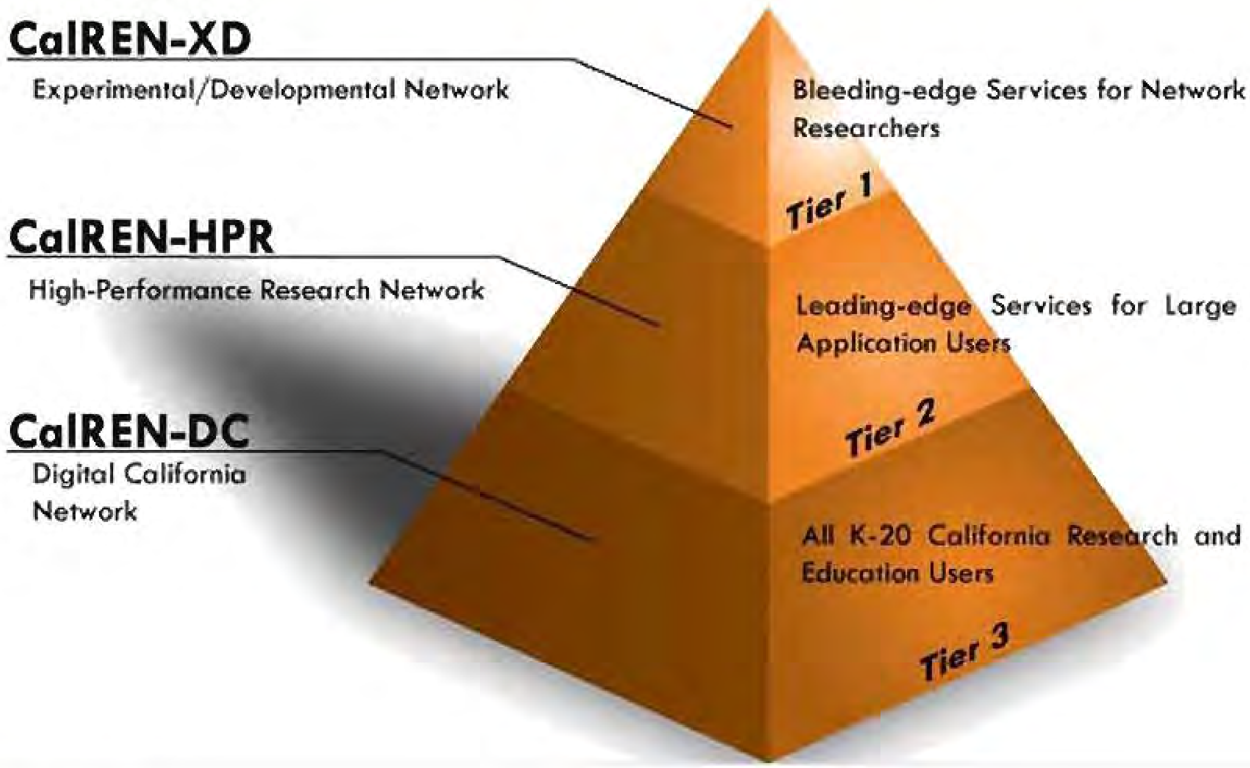
NLR – Optical Infrastructure - Phase 1

National LambdaRail, 2004

Who reaches K-12 institutions, CC's, tribal colleges, libraries, telemedicine sites?



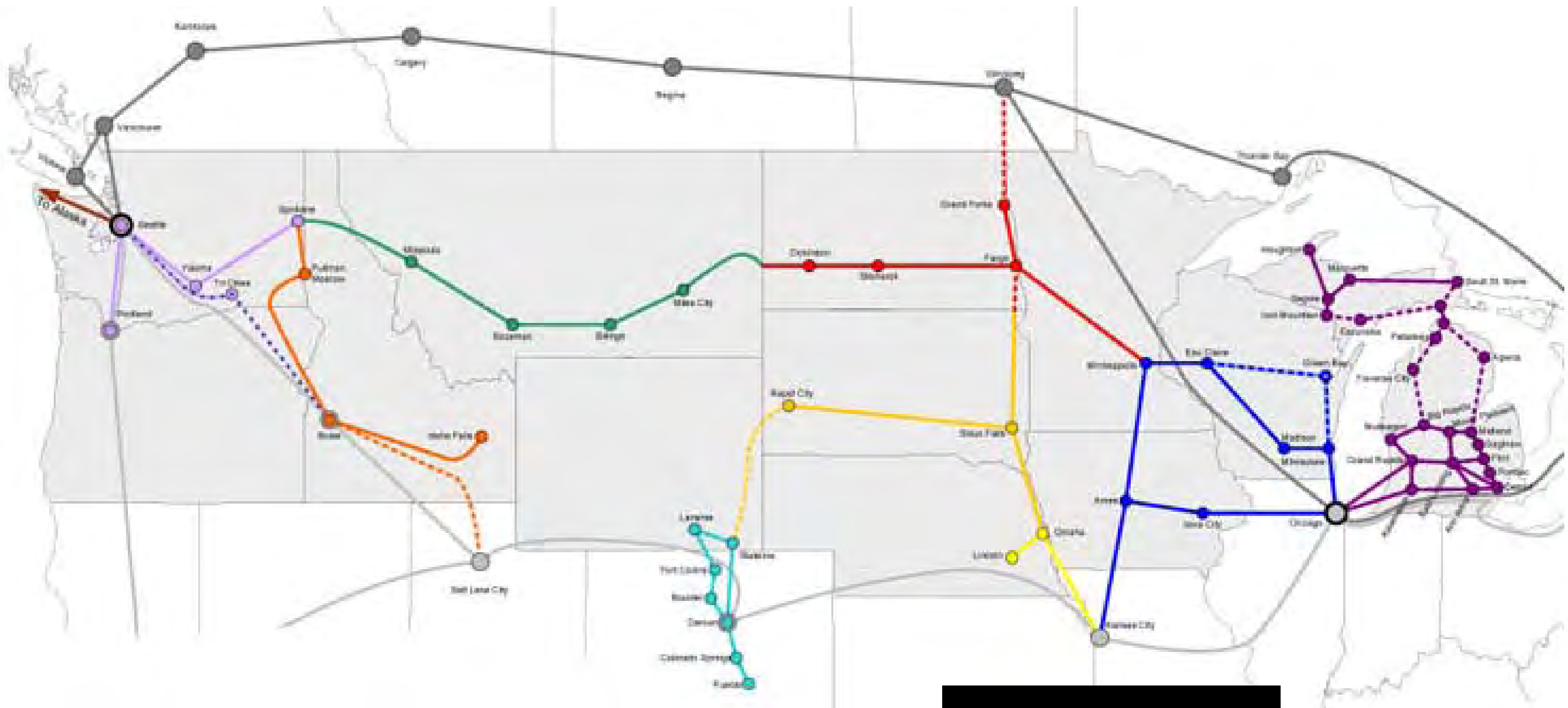
K-20 Educational Telecommunications Network



cenic

The Corporation for Education Network Initiatives in California • 16700 Valley View Ave. Ste 400 • La Mirada, CA 90638

Who reaches unserved and underserved regions?



Northern Tier Network Consortium

PACIFIC NORTHWEST GIGAPOP

The broadband stimulus

Before the

DEPARTMENT OF COMMERCE,
National Telecommunications and Information Administration,

DEPARTMENT OF AGRICULTURE,
Rural Utilities Service, and the

FEDERAL COMMUNICATIONS COMMISSION

In the matter of	)	
	)	
American Recovery and Reinvestment Act of 2009 Broadband Initiatives	)	DoC Docket No. 090309298–9299–01
	)	
The Commission's Consultative Role in the Broadband Provisions of the Recovery Act	)	FCC GN Docket No. 09-40
____	)	

CONSOLIDATED COMMENTS OF MICROSOFT CORPORATION

The broadband stimulus

Before the

DEPARTMENT OF COMMERCE,

In the m

America
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The Com
Broadba

In its recent NOI seeking input on a National Broadband Plan, the FCC acknowledges that there is not enough money in the 2009 Recovery Act to underwrite the deployment of broadband to all Americans. Microsoft agrees. Given that reality, the Administration and the FCC now face the challenge of how to derive the most social benefit from the approximately $7 billion that has been allocated for broadband. As we have stated elsewhere, we believe the highest and best use of these limited funds is, at a minimum, to ensure all the nation's schools, public libraries and hospitals have robust, affordable connections to the Internet. With such connections, all Americans will have available to them the distance learning and telemedicine capabilities that 21st century learning and healthcare require. In this regard, by focusing broadband deployment funds on these anchor institutions, the federal government also will be supporting the Administration's broader goals of modernizing our educational and healthcare systems.

By "robust" connections, we mean at least 100 Mbps, symmetrical, capacity. Only this level of capacity is capable of supporting the video and multimedia-rich scenarios that are part and parcel of e-learning and e-medical care. By "schools," we mean K-12 institutions, community colleges and at least those universities that engage in basic research and, often at the same time, serve as hubs for creating connections to other schools and colleges. By "hospitals," we mean traditional hospitals, as well as the approximately 3,500 stand-alone ambulatory care facilities that often serve as stand-ins for hospitals in rural and inner city areas. By connecting these anchor institutions to fulsome capacity, the US government can assure that every community in the nation has multiple, credible on-ramps to a new Internet "highway" system. No community will be left off the network.

The broadband stimulus

Unleashing Waves of Innovation
Transformative Broadband for America's Future

Version 18: April 18, 2009[1]

<u>Executive Summary</u>

A forward-thinking National Broadband Strategy should focus on the transformative power of advanced networks to unleash new waves of innovation, jobs, economic growth, and national competitiveness. Such a strategy should create new tools to deliver health care, education, and a low carbon economy. The American Recovery and Reinvestment Act broadband decisions should target high-impact investments with these criteria in mind. They should seek to rebuild U.S. global leadership in networking and in the economic innovations that networking can create. Broadband investments should "pull from the future."

. . .

The broadband stimulus

Unleashing Waves of Innovation
Transformative Broadband for America's Future

Executi

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should t
U.S. glo
create.

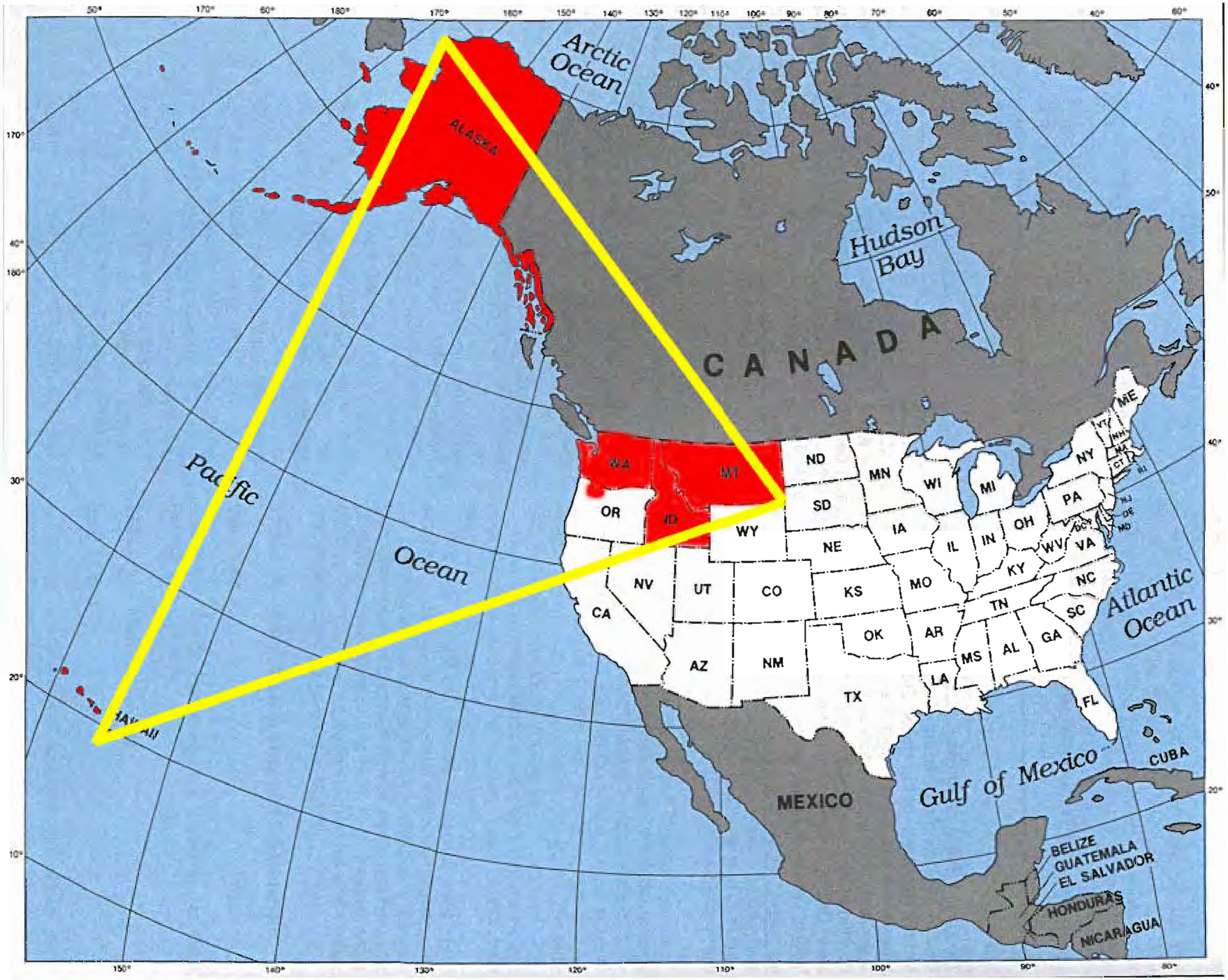
A National Broadband Strategy should begin with America's colleges and universities, community colleges, K-12 schools, public libraries, hospitals, clinics, and the state, regional and national research and education networks that connect them and extend to reach government agencies, agricultural extension sites, and community centers across the nation. A proven track record of innovating in networking and its applications, of deploying and continually upgrading advanced networks, and of extending those networks to the unserved and underserved across our nation, lies not with telephone or cable companies, nor with most state governments, but with our nation's colleges and universities and the state, regional and national research and education networks that this community has built, in many instances forged through partnerships with telecommunications providers and state agencies to achieve these goals.

INTERNET2 · COMPUTING RESEARCH ASSOCIATION CRA · EPSCoR/IDeA FOUNDATION · EDUCAUSE · NLR light the future · STATENETS America's State Education Networks · SURA · THE QUILT · WICHE

The Pacific Northwest Gigapop and CENIC

- "I come from Montana, and in Montana we have a lot of dirt between light bulbs."

  Senator Conrad Burns
  December 8, 2004
- PNWGP has water too!



Arctic Ocean
Hudson Bay
CANADA
ALASKA
HAWAII
Pacific Ocean
Atlantic Ocean
Gulf of Mexico
MEXICO
CUBA
BELIZE
GUATEMALA
EL SALVADOR
HONDURAS
NICARAGUA
WA
OR
CA
ID
MT
NV
UT
AZ
WY
CO
NM
ND
SD
NE
KS
OK
TX
MN
IA
MO
AR
LA
WI
IL
MS
MI
IN
KY
TN
AL
OH
GA
FL
PA
WV
VA
NC
SC
NY
ME
VT
NH
MA
CT
RI
NJ
DE
MD
DC

- PNWGP
  - Square miles of land (WA, MT, ID, AK, HI): 969,280
  - Carnegie "Comprehensive" and "STEM" doctoral institutions: 7
    - 1 : 138,469
  - AAU universities: 1
    - 1 : 969,280
- CENIC
  - Square miles of land (CA, AZ, NV): 388,266
  - Carnegie "Comprehensive" and "STEM" doctoral institutions: 20
    - 1 : 19,413
    - CENIC vs. PNWGP: 7 : 1
  - AAU universities: 10
    - 1 : 38,327
    - CENIC vs. PNWGP: 25 : 1

Joint CENIC/PNWGP projects: NLR, LLC

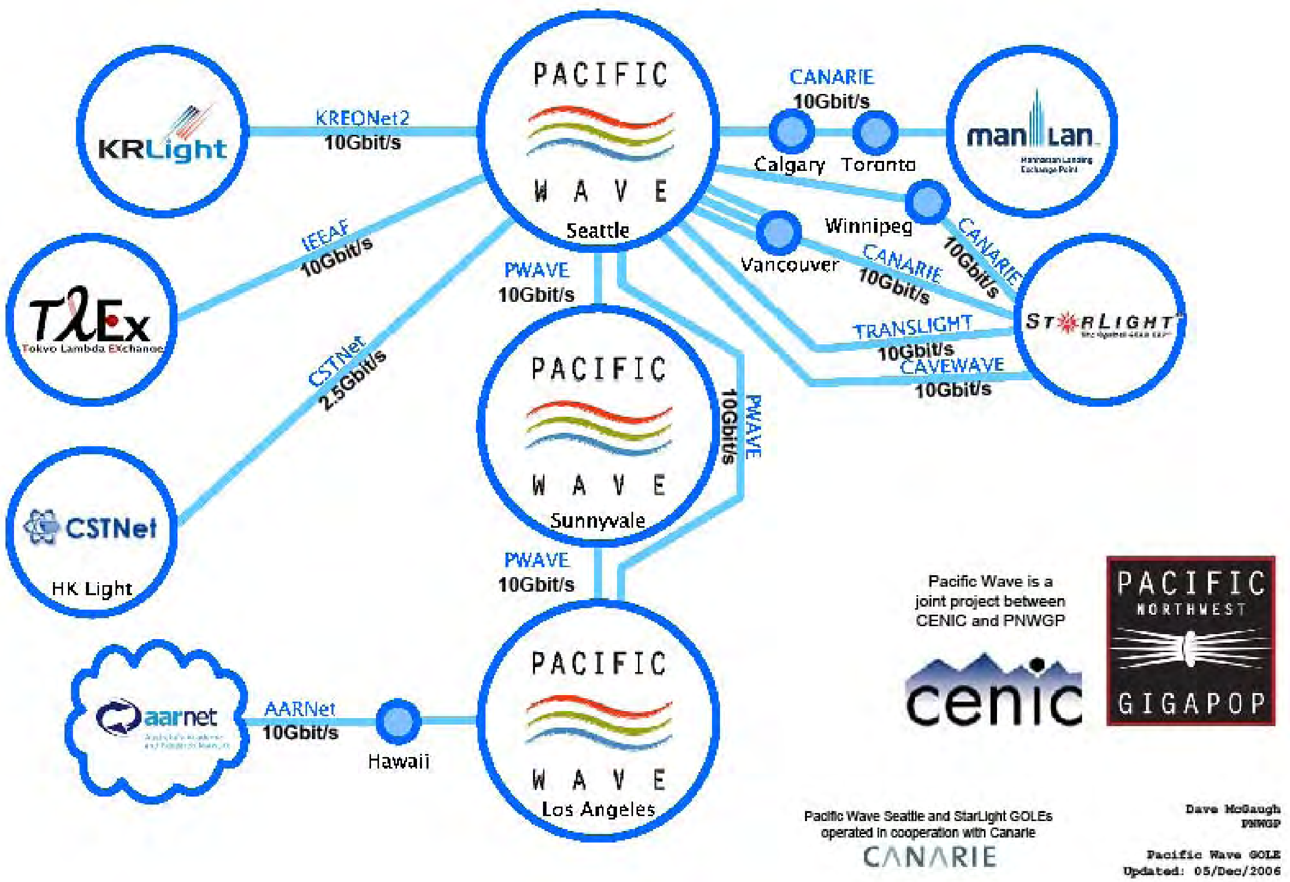
- CENIC and PNWGP agree to form joint LLC
- NLR, LLC then acquires IRUs from LA to Seattle, and Seattle to Denver (Ogden?)
- NLR, LLC then jointly purchase DWDM equipment to light the fiber and share waves
- Rights to use/access fiber paths and waves are bartered to NLR, Inc. as part of a national effort to build NLR Inc's national network.

National LamdaRail (NLR), Inc. network

Joint CENIC/PNWGP projects: PacificWave

- Using fiber and DWDM network jointly owned by CENIC and PWNGP, a shared 10Gpbs service is implemented and dubbed “PacificWave”
- Add/drop locations in LA, Sunnyvale, Seattle
- Provides low-cost 10G waves along the path
- Shared 10G layer-2 Ethernet service provides low-cost connectivity among R&E, high-tech (Amazon, Google, Microsoft), and R&E networks among Pacific Rim countries (Korea, Japan, Australia)
- PWave also acts as west-cost GLIF (Global Lambda Interchange Facility)

Pacific Wave (PWave) and the Global Lambda Integrated Facility (GLIF)



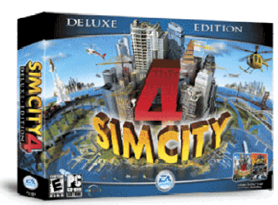
Joint CENIC/PNWGP projects: TransitRail

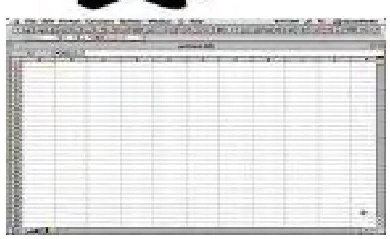
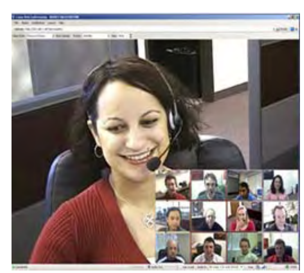
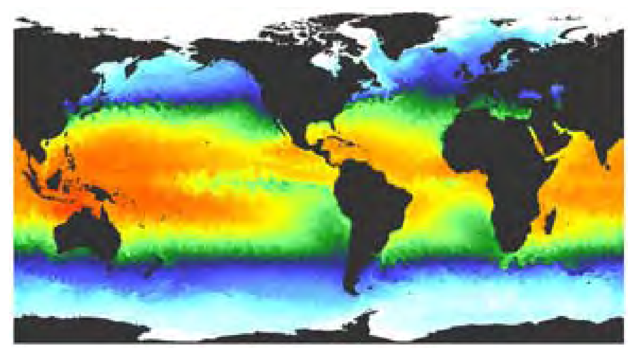
- Transit Rail: service of PNWGP, CENIC and NLR
  - CENIC and PNWGP provide peering agreements engineering, operations, administration and waves along the west coast
  - NLR, Inc. provides equipment, waves
- Peering in LA, Sunnyvale, Seattle, Chicago, D.C.
- Has provided settlement-free paths to over 50% of the commodity Internet to TR connectors
- Model has been adopted by Internet2 (CPS) and plans are in place to merge TR and CPS into one R&E peering fabric

Computer science: Changing the world

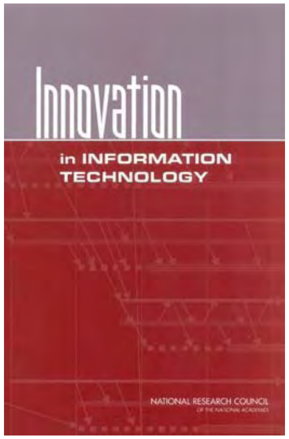
- Advances in computing change the way we live, work, learn, and communicate
- Advances in computing drive advances in nearly all other fields
- Advances in computing power our economy
  - Not just through the growth of the IT industry – through productivity growth across the entire economy

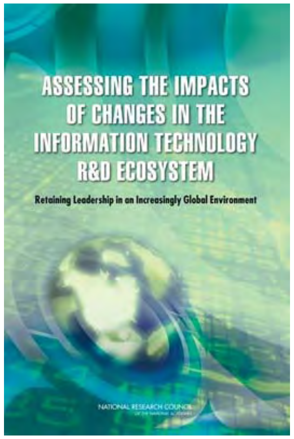


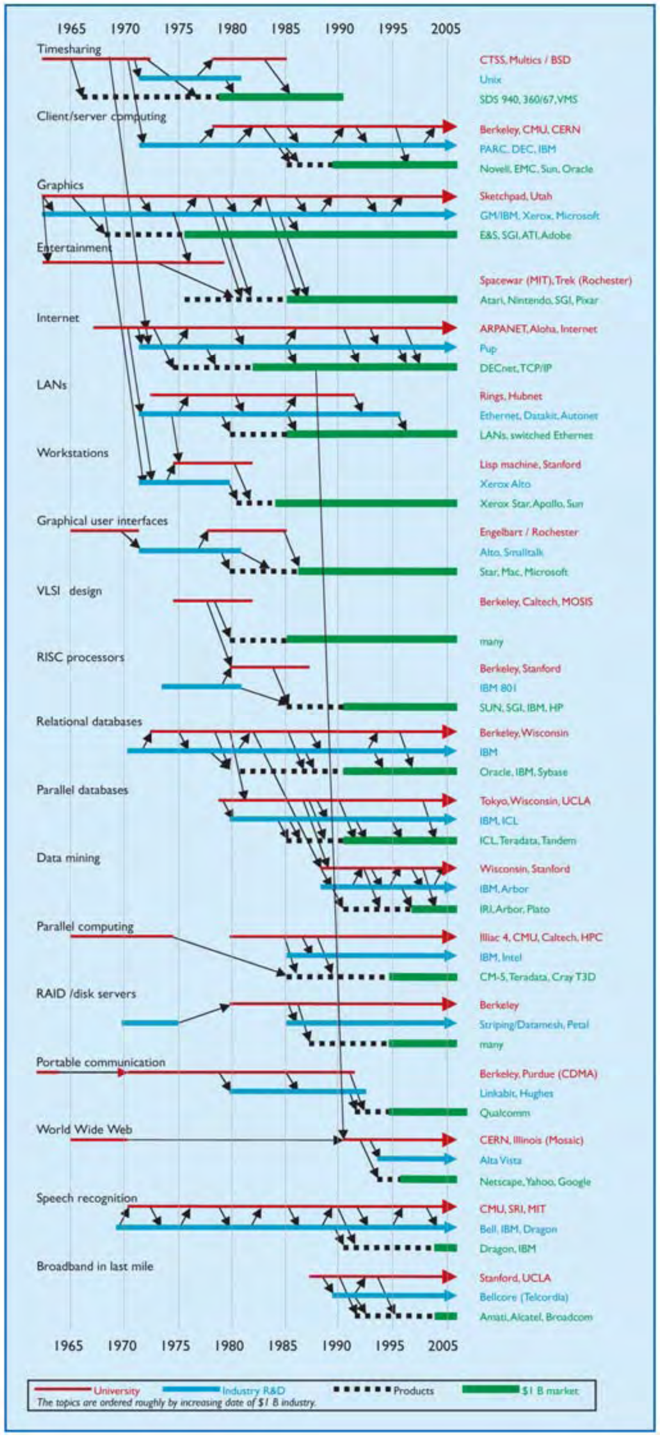


Research has built the foundation

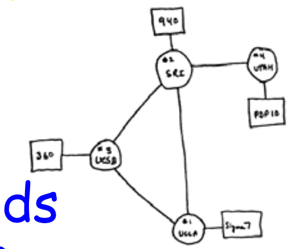
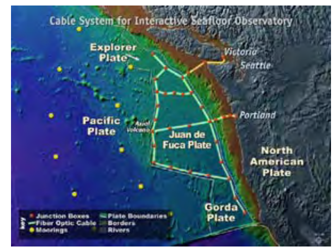




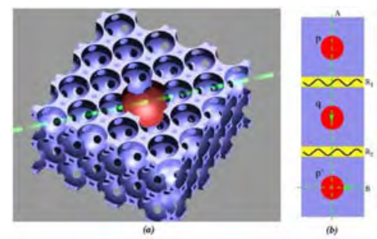


The future is full of opportunity

- Creating the future of networking
- Driving advances in all fields of science and engineering
- Revolutionizing transportation
- Personalized education
- The smart grid
- Predictive, preventive, personalized medicine
- Quantum computing
- Empowerment for the developing world
- Personalized health monitoring => quality of life
- Harnessing parallelism
- Neurobotics
- Synthetic biology

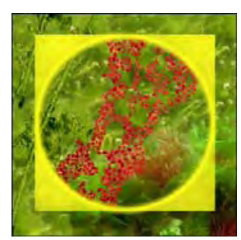













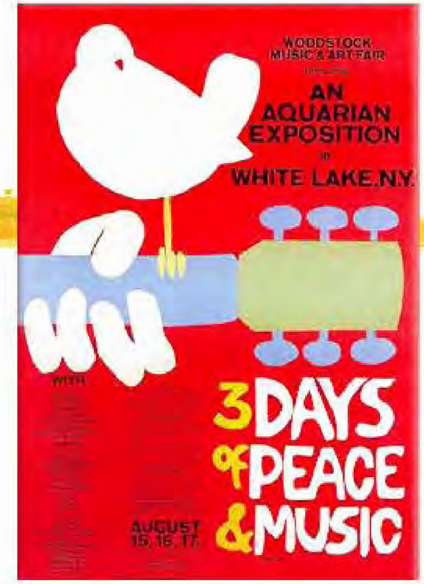

We must work together to establish, articulate, and pursue visions for the field

- The challenges that will shape the intellectual future of the field
- The challenges that will catalyze research investment and public support
- The challenges that will attract the best and brightest minds of a new generation

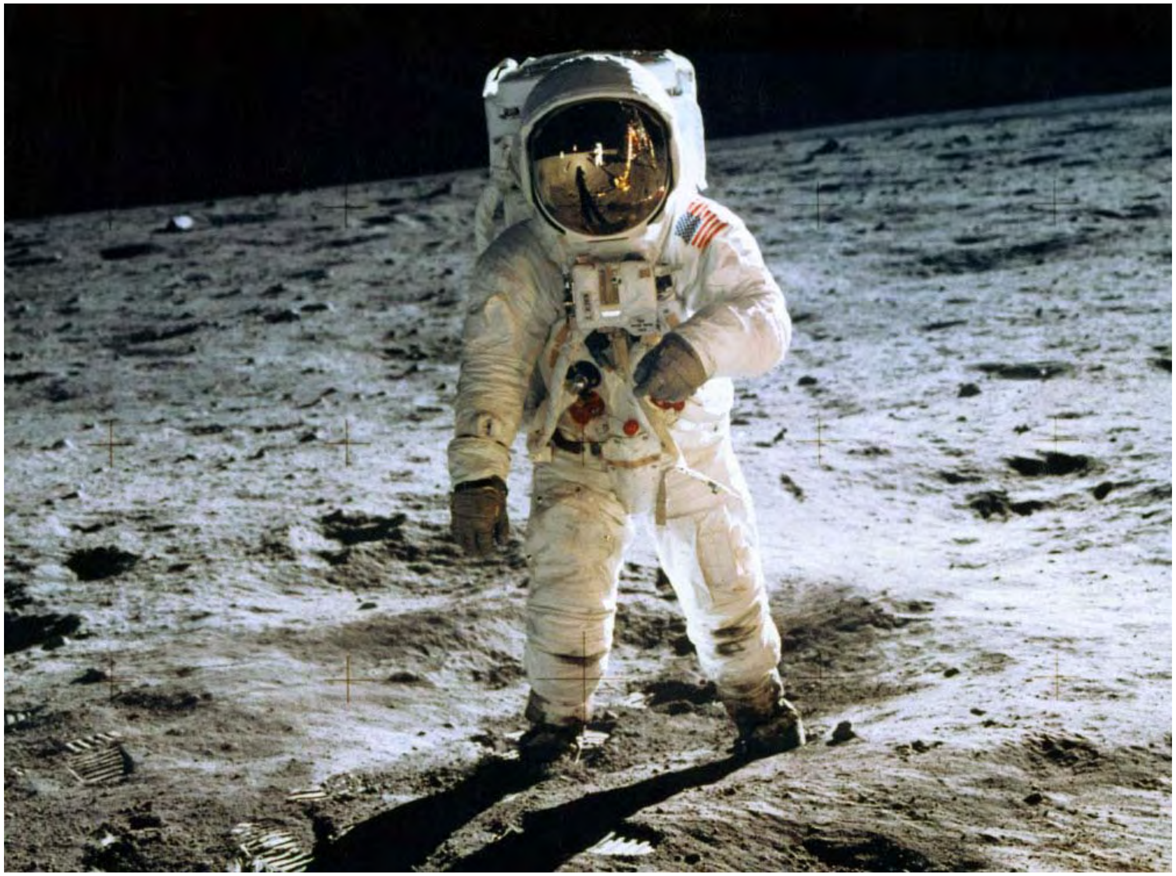
To this end, NSF asked CRA to create the Computing Community Consortium

- To catalyze the computing research community to consider such questions
  - To envision long-range, more audacious research challenges
  - To build momentum around such visions
  - To state them in compelling ways
  - To move them towards funded initiatives
  - To ensure "science oversight" of large-scale initiatives
- *A "cooperative agreement" with NSF*
  - Close coordination
- *A "standing committee" of CRA*
- Launched in 2007

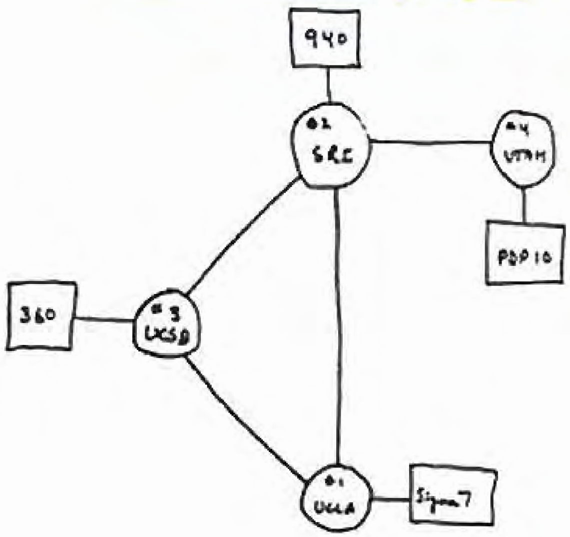
Forty years ago …


WOODSTOCK
MUSIC & ART FAIR
AN
AQUARIAN
EXPOSITION
WHITE LAKE.N.Y.
WITH
3 DAYS
of PEACE
& MUSIC
AUGUST
15, 16, 17.

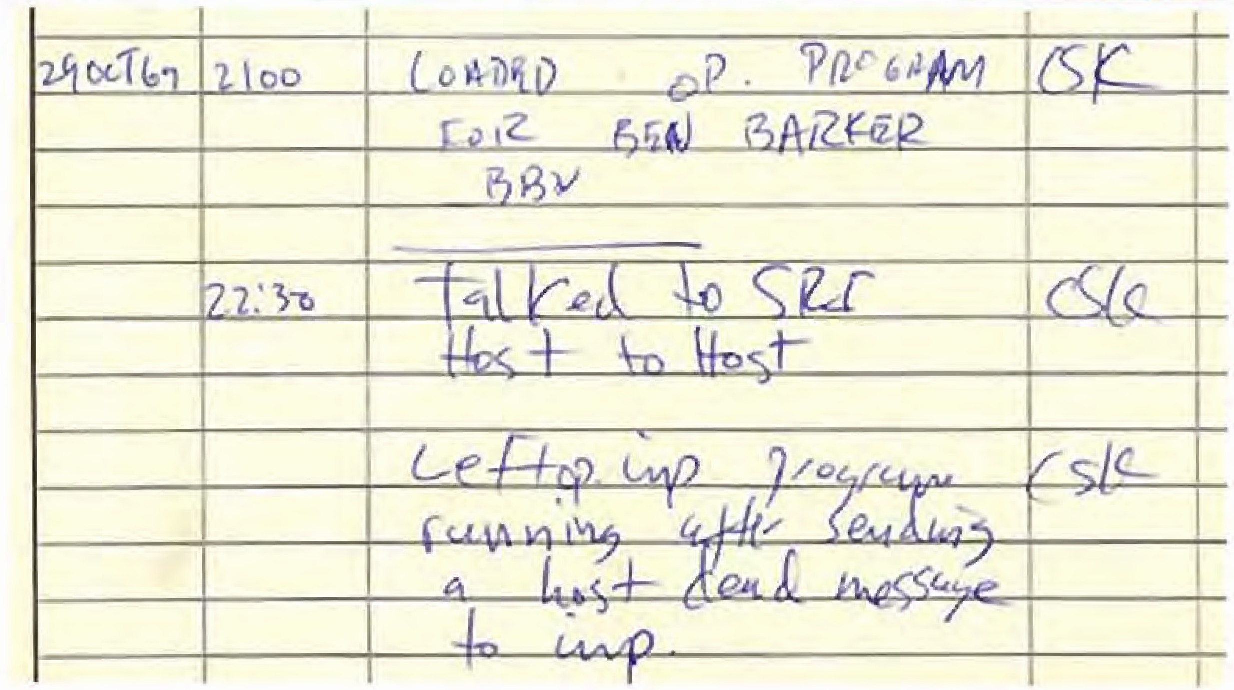

1969



[Peter Lee, DARPA, and Pat Lincoln, SRI]



THE ARPA NETWORK
DEC 1969
4 NODES



29OCT69	2100	LOADED OP. PROGRAM FOR BEN BARKER BBN	CSK
	22:30	Talked to SRI Host to Host	CSK
		Left op. imp program running after sending a host dead message to imp.	CSK

With forty years hindsight, which had the greatest impact?

- Unless you're big into Tang and Velcro (or sex and drugs), the answer is clear …

- And so is the reason …

EXPONENTIALS Я US

The past thirty years …

The New York Times

Business

THE COUNT

Internet, Mobile Phones Named Most Important Inventions

By PHYLLIS KORKKI
Published: March 7, 2009

In response to the shouted-out question, "What are some of the greatest inventions of all time?," nearby office workers in a recent informal survey gave the following answers: the wheel, the engine, the ballpoint pen, diapers and the cheese Danish.

Life Changers

The top innovations of the last 30 years, according to judges at the Wharton School of the University of Pennsylvania.

1. Internet, broadband
2. PC and laptop computers
3. Mobile phones
4. E-mail
5. DNA testing and sequencing
6. Magnetic resonance imaging
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8. Fiber optics
9. Office software
10. Laser/robotic surgery
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12. Light-emitting diodes
13. Liquid crystal display
14. GPS devices
15. E-commerce and auctions
16. Media file compression
17. Microfinance
18. Photovoltaic solar energy
19. Large-scale wind turbines
20. Internet social networking

THE NEW YORK TIMES

A panel of eight judges from the Wharton School of the University of Pennsylvania was required to go back only 30 years — not to the dawn of history — when asked a similar question. So its answers, of course, were very different.

In the survey, the Internet was voted the biggest innovation of the last three decades, followed by computers, mobile phones and e-mail. The survey was sponsored by Knowledge@Wharton, the school's business publication, and PBS's "Nightly Business Report."

Good, important choices all, but for classic, long-lasting appeal, they still can't beat the wheel. PHYLLIS KORKKI

Next Article in Business (22 of 29) »

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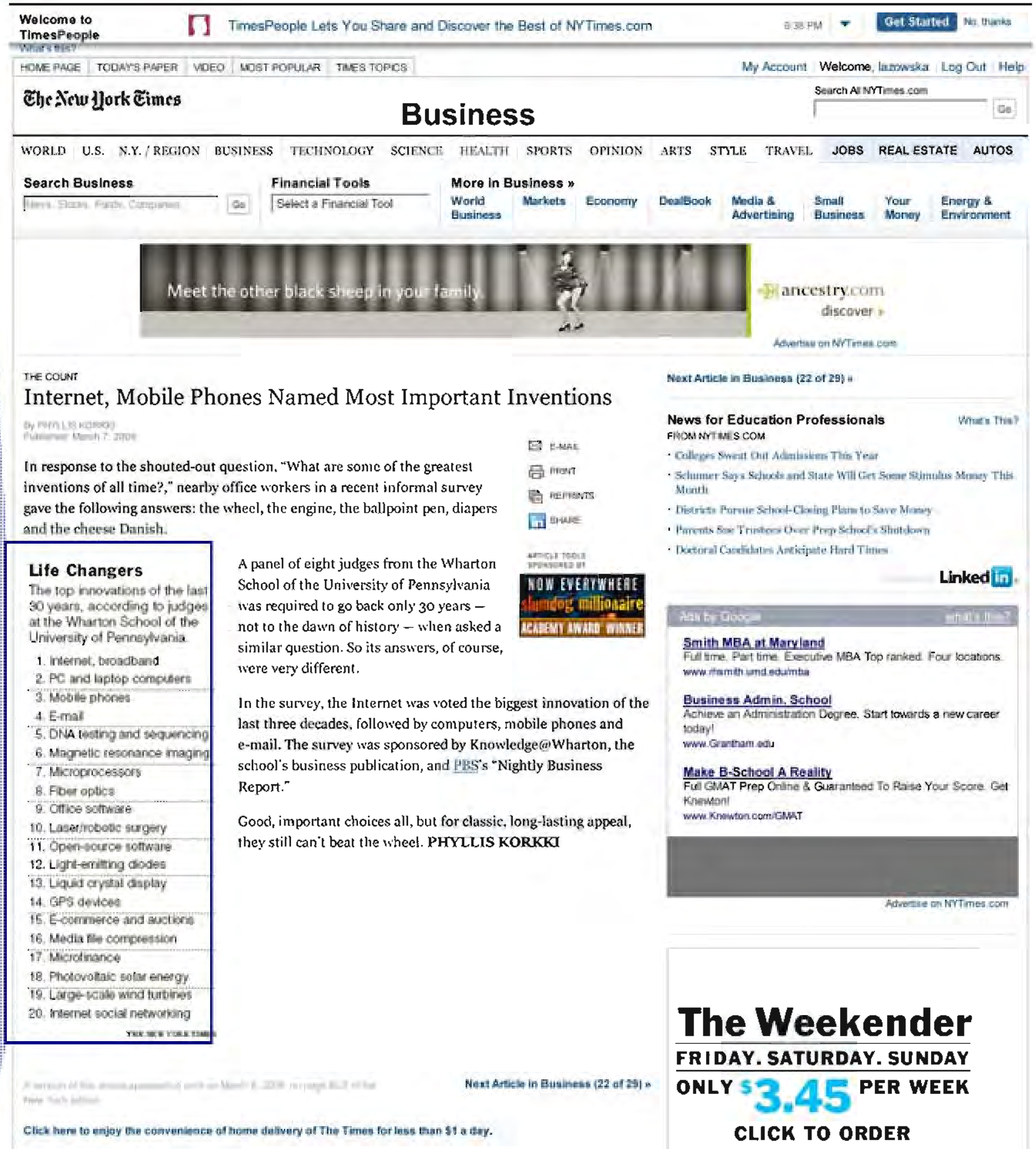

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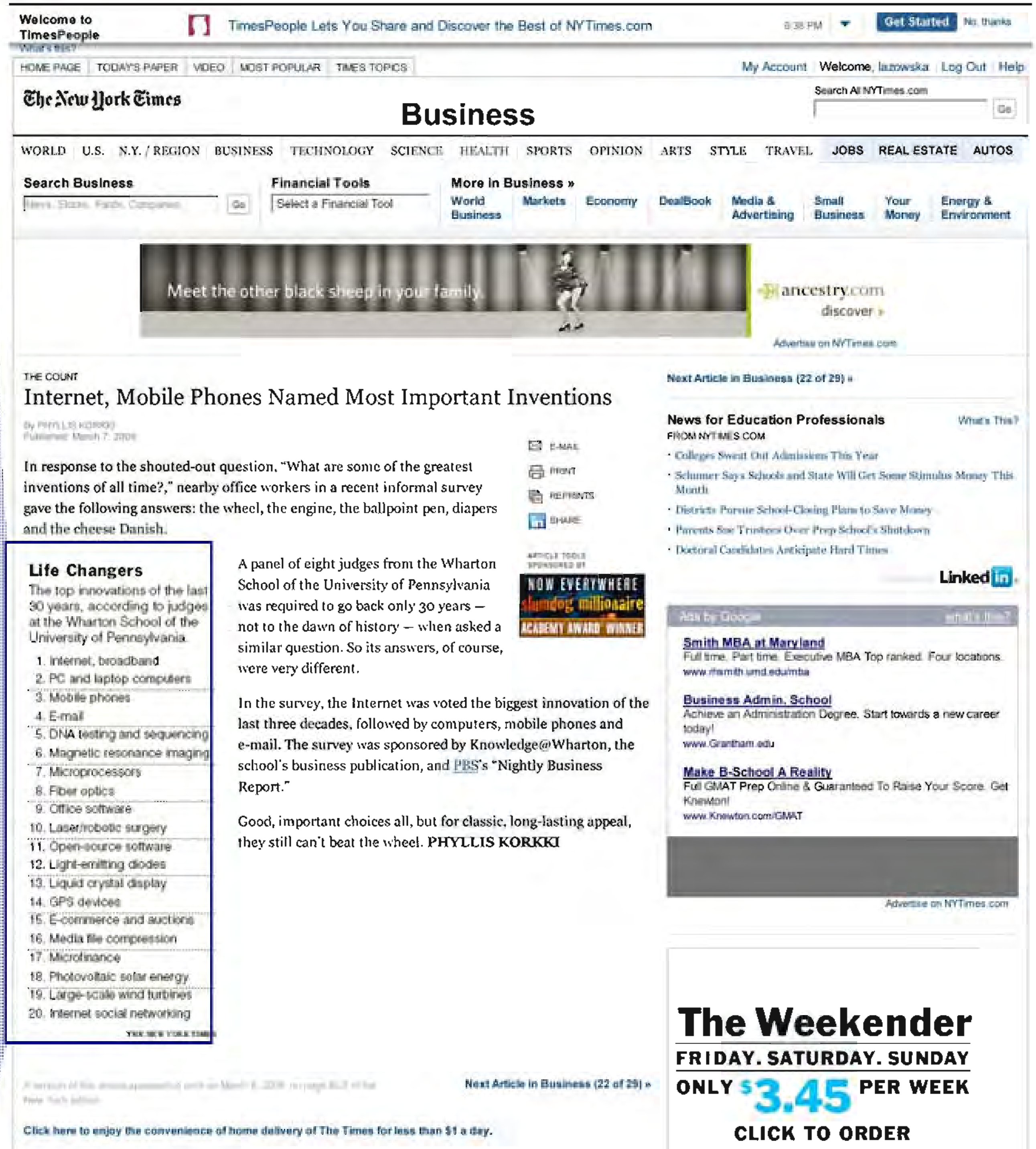
THE NEW YORK TIMES



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THE NEW YORK TIMES

Next Article in Business (22 of 29) »

The most recent ten years …

- Search
- Scalability
- Digital media
- Mobility
- eCommerce
- The Cloud
- Social networking and crowd-sourcing

Imagine spending a day without information technology

- A day without the Internet and all that it enables
- A day without diagnostic medical imaging
- A day during which automobiles lacked electronic ignition, antilock brakes, and electronic stability control
- A day without digital media – without wireless telephones, high-definition televisions, MP3 audio, DVD video, computer animation, and videogames
- A day during which aircraft could not fly, travelers had to navigate without benefit of GPS, weather forecasters had no models, banks and merchants could not transfer funds electronically, factory automation ceased to function, and the US military lacked technological supremacy

Imagine spending a day without information technology

- A day without the Internet anc
- A day without diagnostic medic
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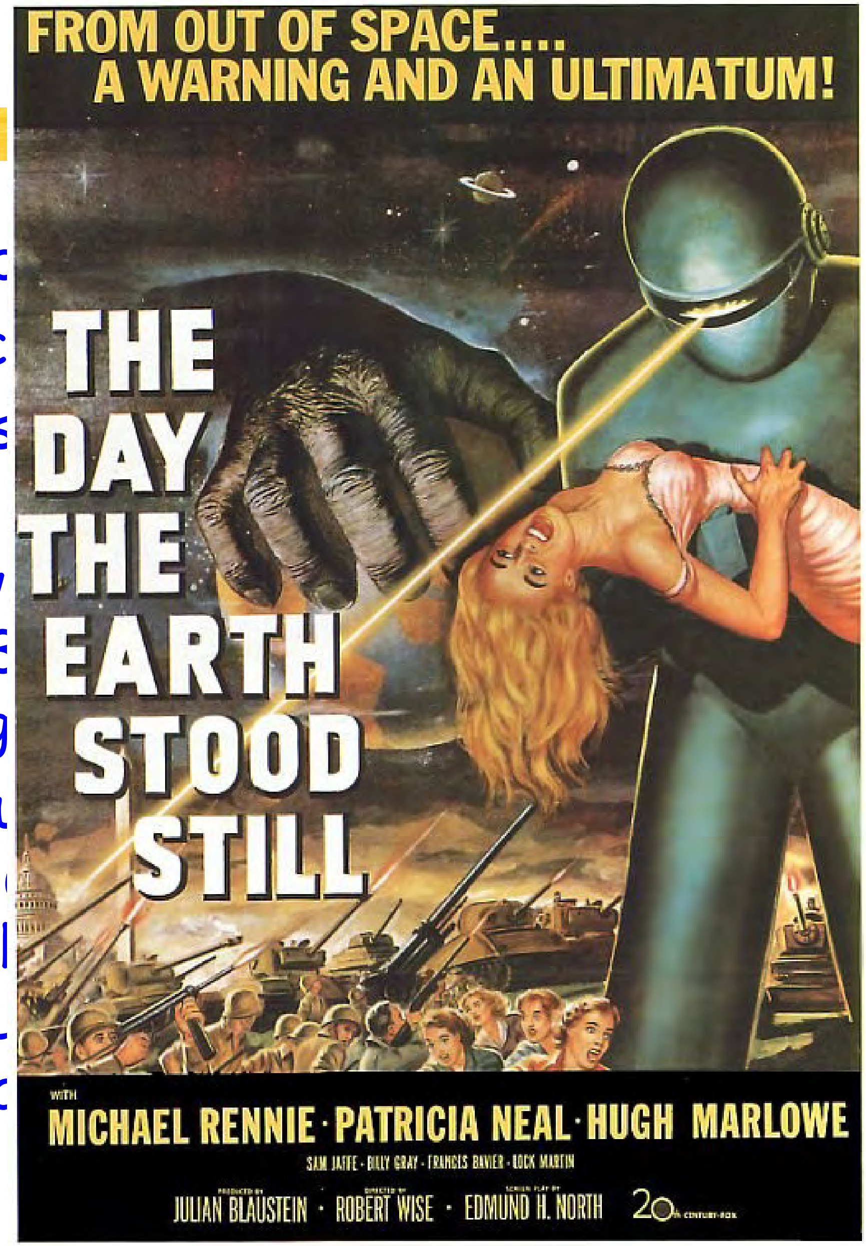


The coming decade …

NATIONAL ACADEMY OF ENGINEERING
OF THE NATIONAL ACADEMIES

CHALLENGES | IDEAS | NEXT STEPS | COMMITTEE

GRAND CHALLENGES FOR ENGINEERING


Make solar energy economical


Provide energy from fusion

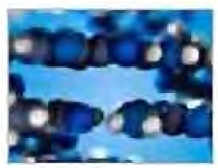

Develop carbon sequestration methods


Manage the nitrogen cycle


Provide access to clean water


Restore and improve urban infrastructure


Advance health informatics


Engineer better medicines


Reverse-engineer the brain


Prevent nuclear terror


Secure cyberspace


Enhance virtual reality


Advance personalized learning


Engineer the tools of scientific discovery


NATIONAL ACADEMY OF ENGINEERING
OF THE NATIONAL ACADEMIES
CHALLENGES
IDEAS
NEXT STEPS
COMMITTEE
GRAND CHALLENGES FOR ENGINEERING
Make solar energy economical
Provide energy from fusion
Develop carbon sequestration methods
Manage the nitrogen cycle
Provide access to clean water
Restore and improve urban infrastructure
Advance health informatics
Engineer better medicines
Reverse-engineer the brain
Prevent nuclear terror
Secure cyberspace
Enhance virtual reality
Advance personalized learning
Engineer the tools of scientific discovery
Predominant CS component
Significant CS component

We put the “smarts” in …

- Smart homes
- Smart cars
- Smart bodies
- Smart robots
- The data deluge (smart science)
- Virtual and augmented reality
- Smart crowds and human-computer systems

Is this a great time, or what?!?!