eScience: Techniques and Technologies for 21st Century Discovery

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Bill & Melinda Gates Chair in
Computer Science & Engineering

University of Washington

WICHE Commission Meeting

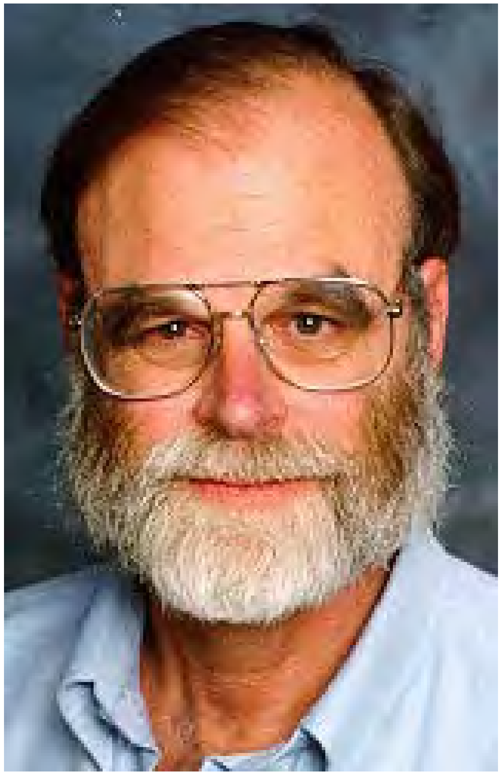
May 2009

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

This morning

- The nature of eScience
- The advances that enable it
- Scalable computing for everyone
- Networking in the West, and the broadband stimulus
- Computer science & engineering: Changing the world
- The changing nature of our economy, and of educational requirements

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



Transforming science (again!)

Theory

Experiment

Observation

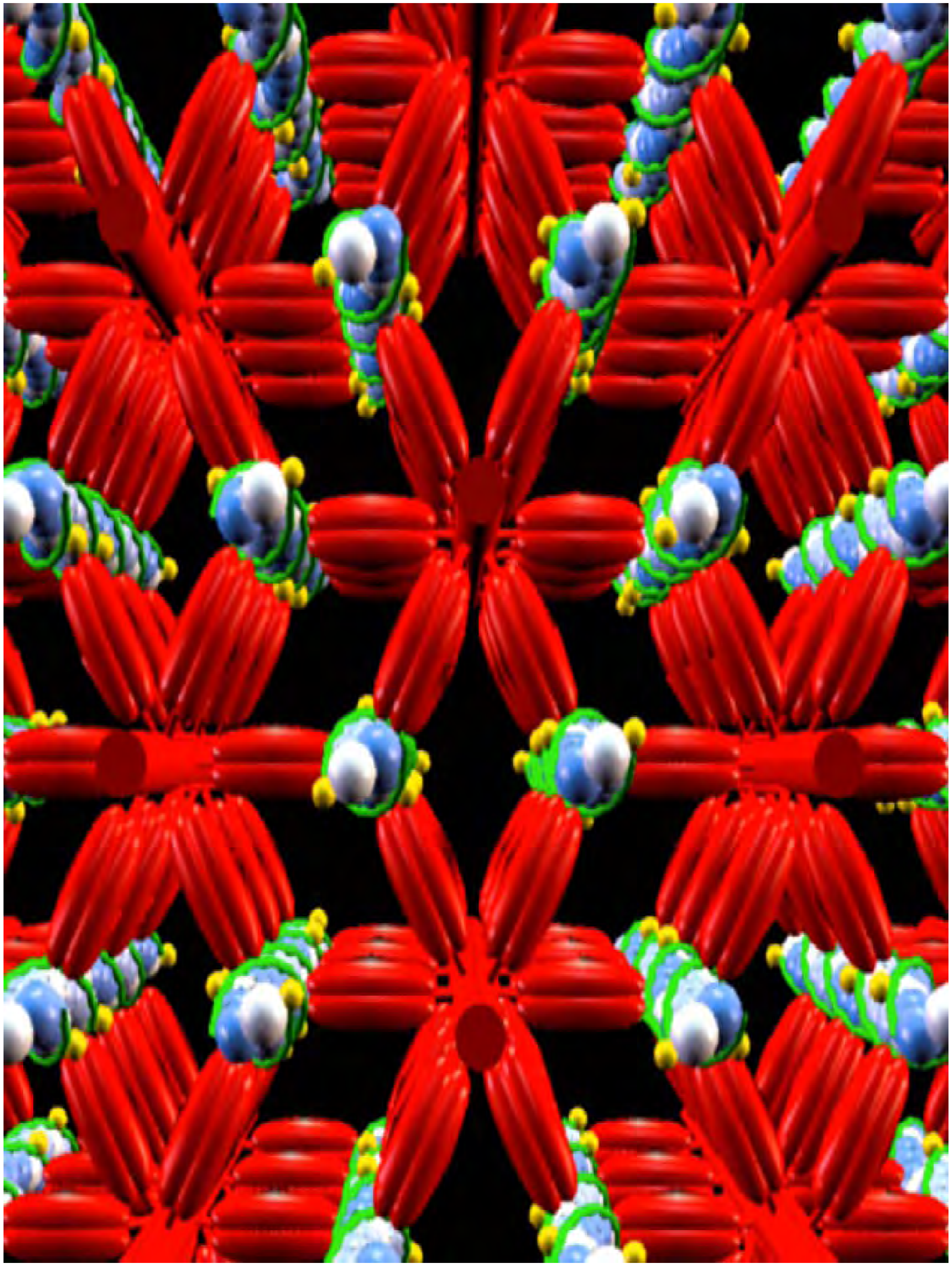
Theory

Experiment

Observation

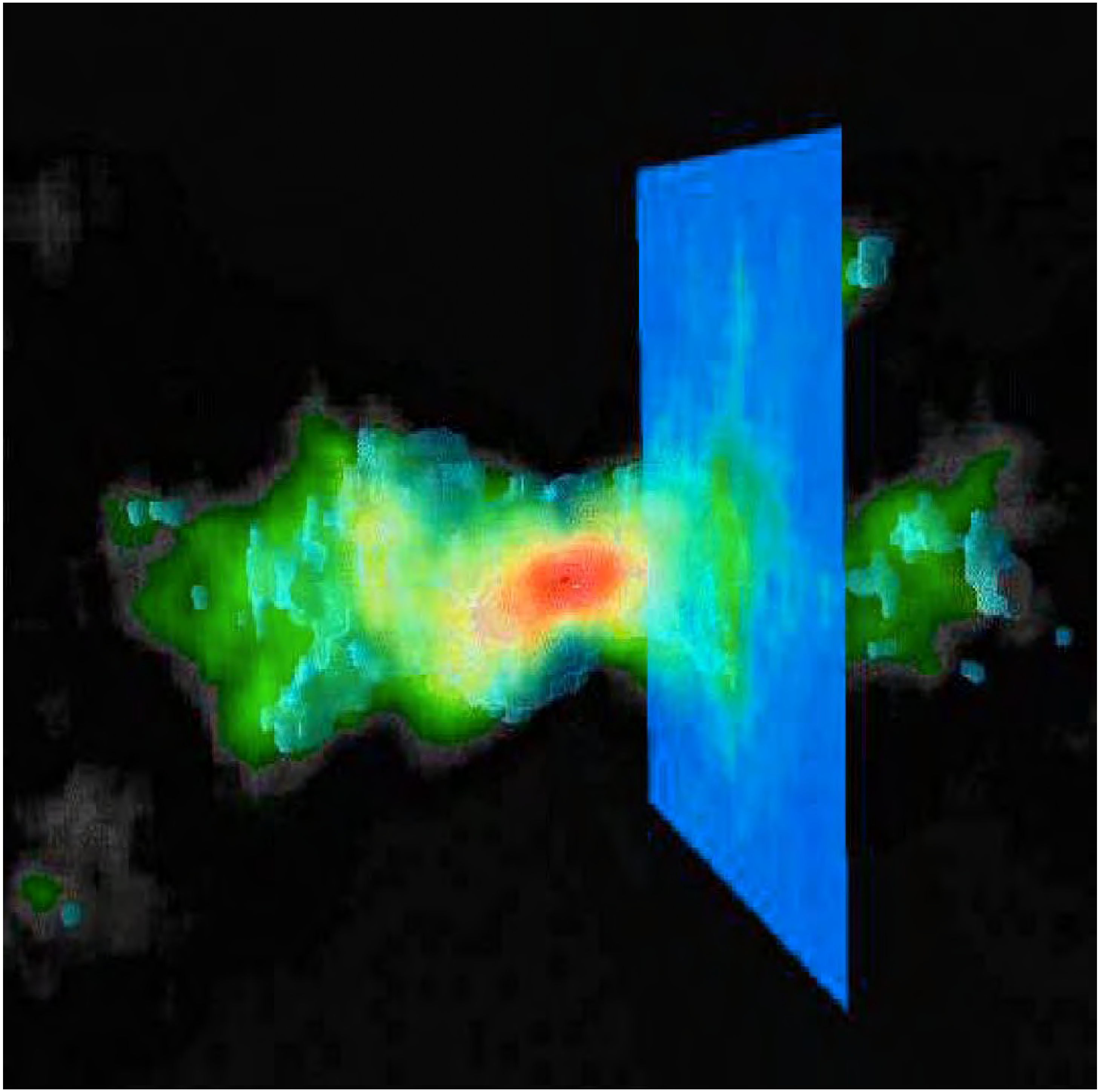

Theory
Experiment
Observation

Theory
Experiment
Observation
Computational Science



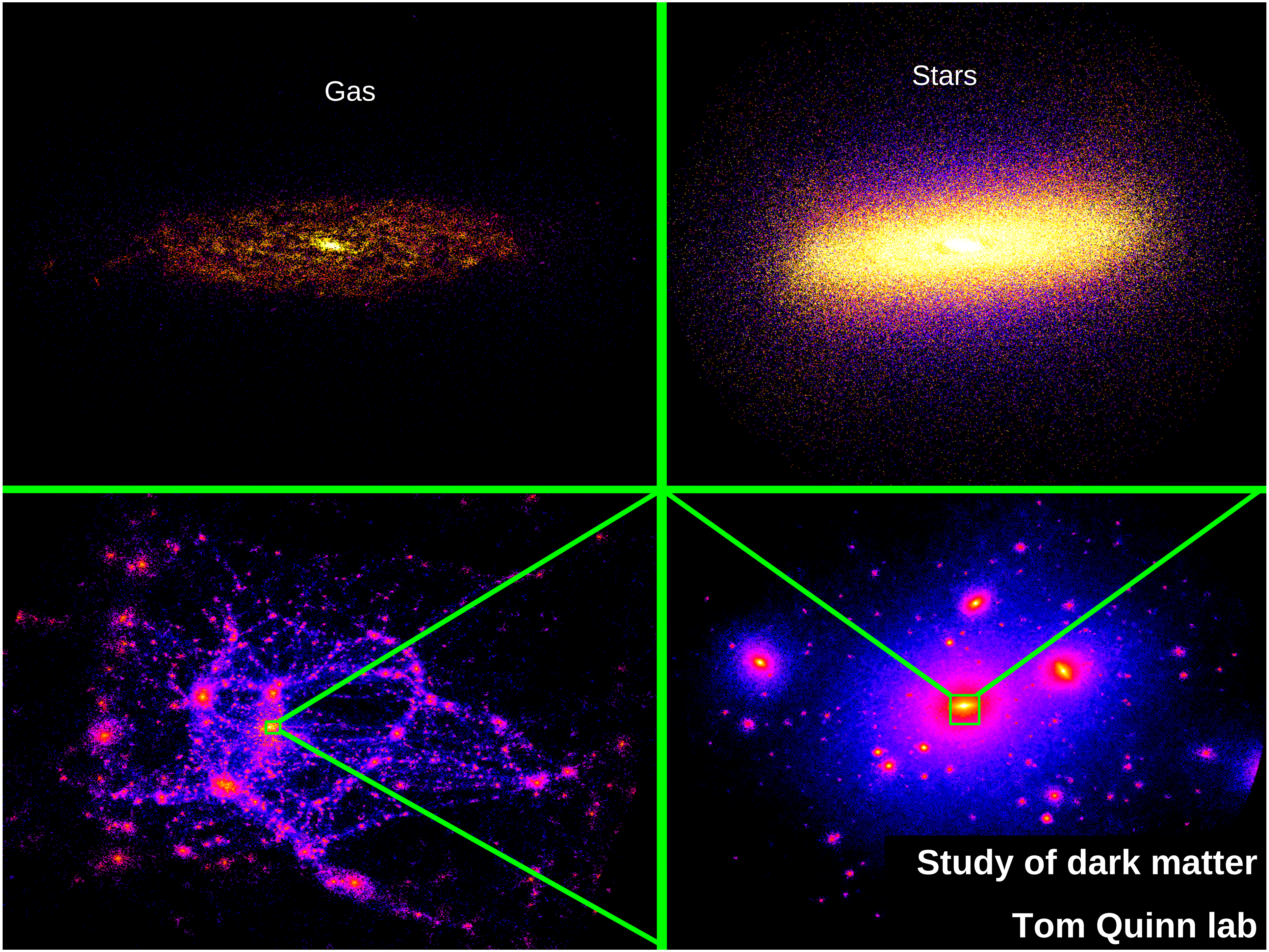
Protein interactions in striated muscles

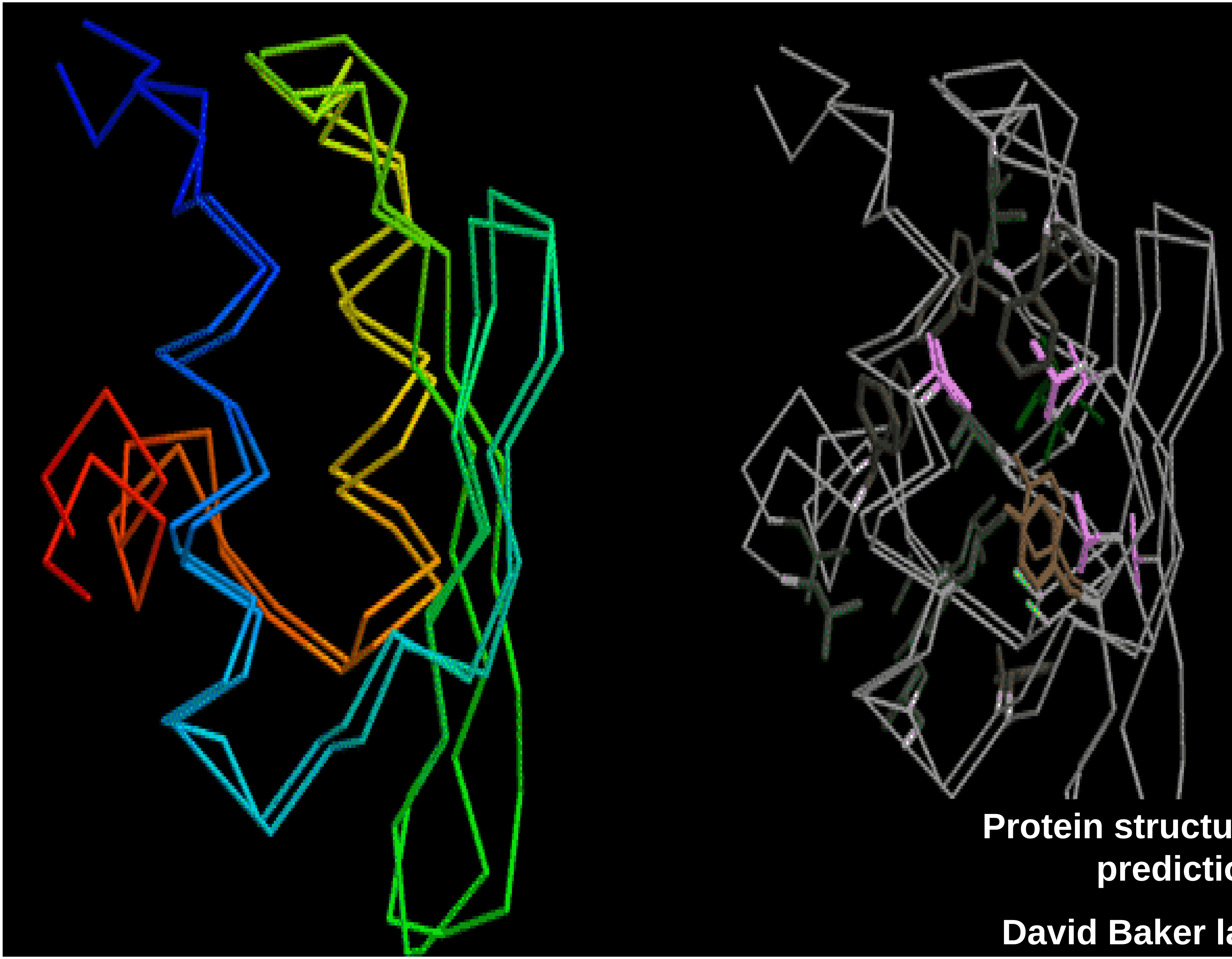
Tom Daniel lab



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

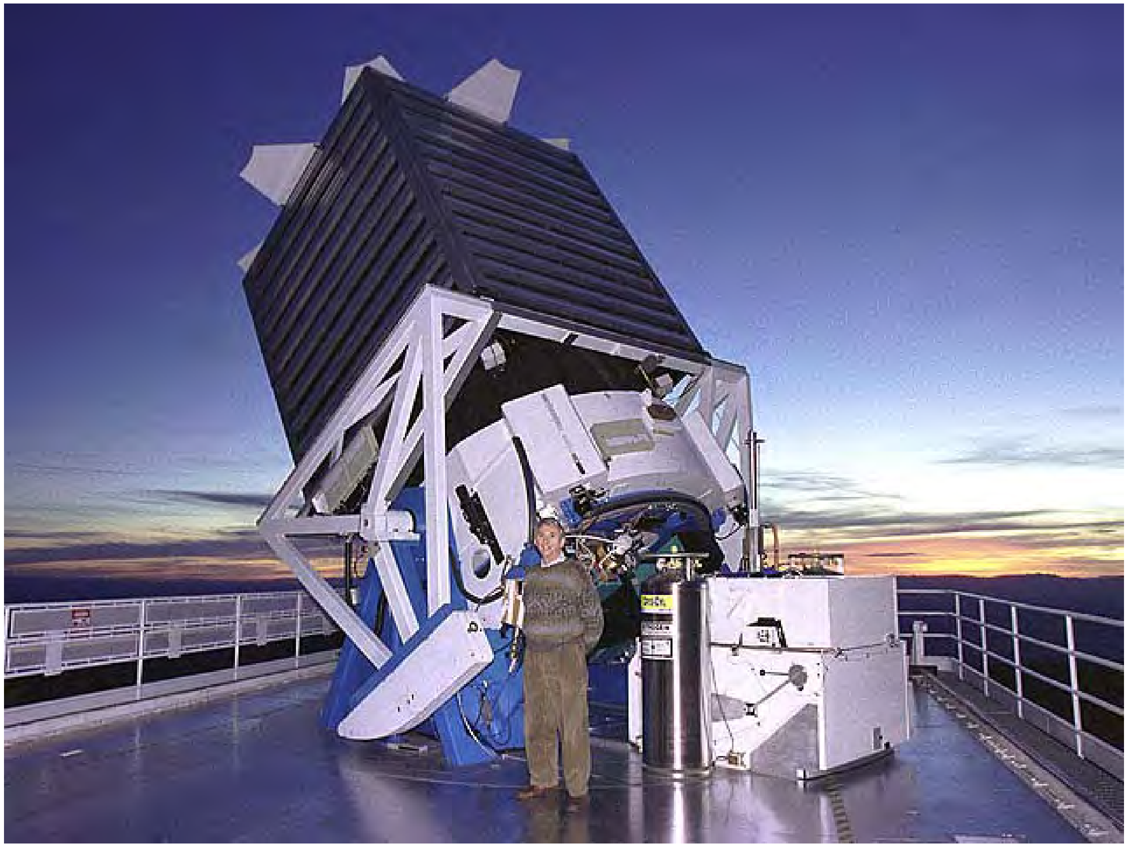
Observation

Computational Science

eScience

eScience is driven by *data*

- Massive volumes of data from sensors and networks of sensors

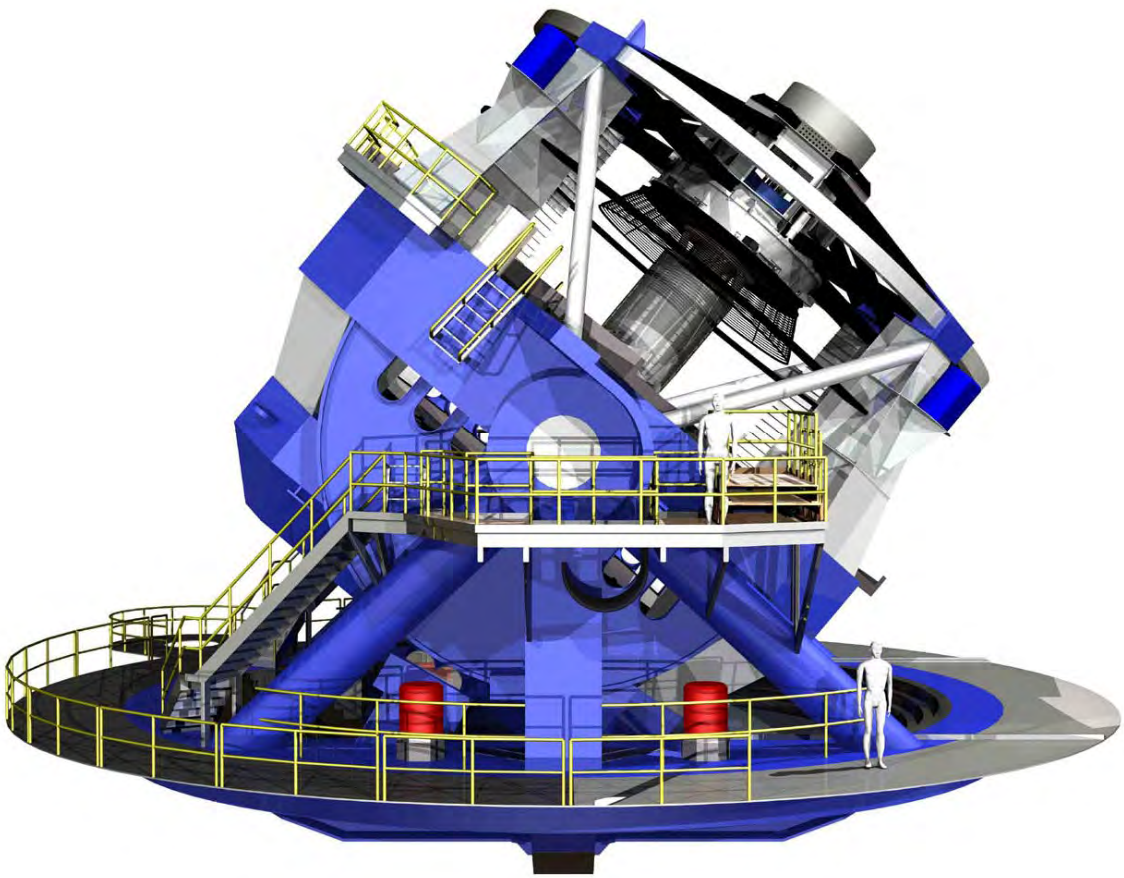


Apache Point telescope, SDSS

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

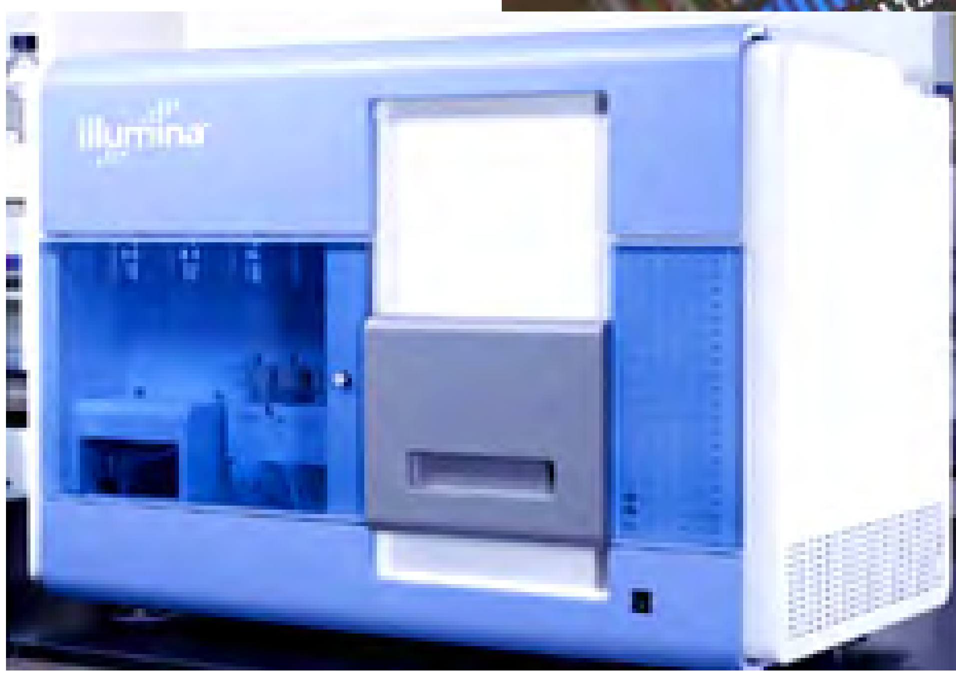
Large Synoptic Survey Telescope (LSST)

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



Large Hadron Collider

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

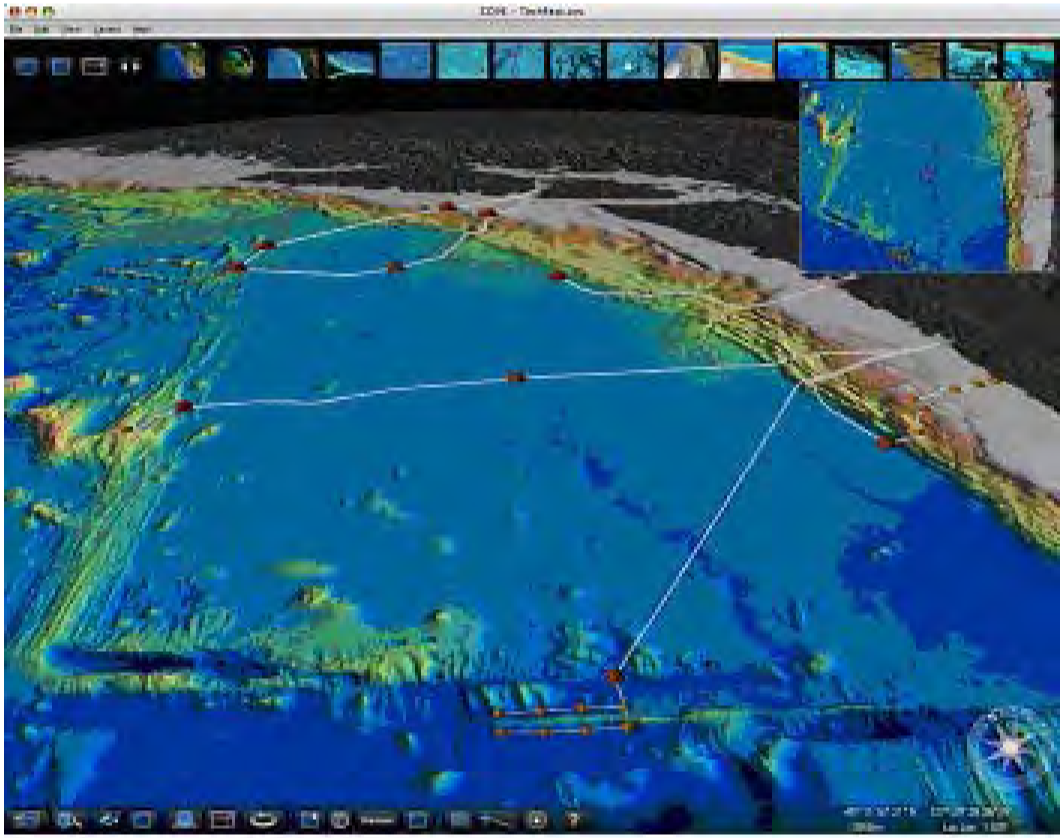


Illumina Genome Analyzer

~1TB/day

Regional Scale Nodes of the NSF Ocean Observatories Initiative

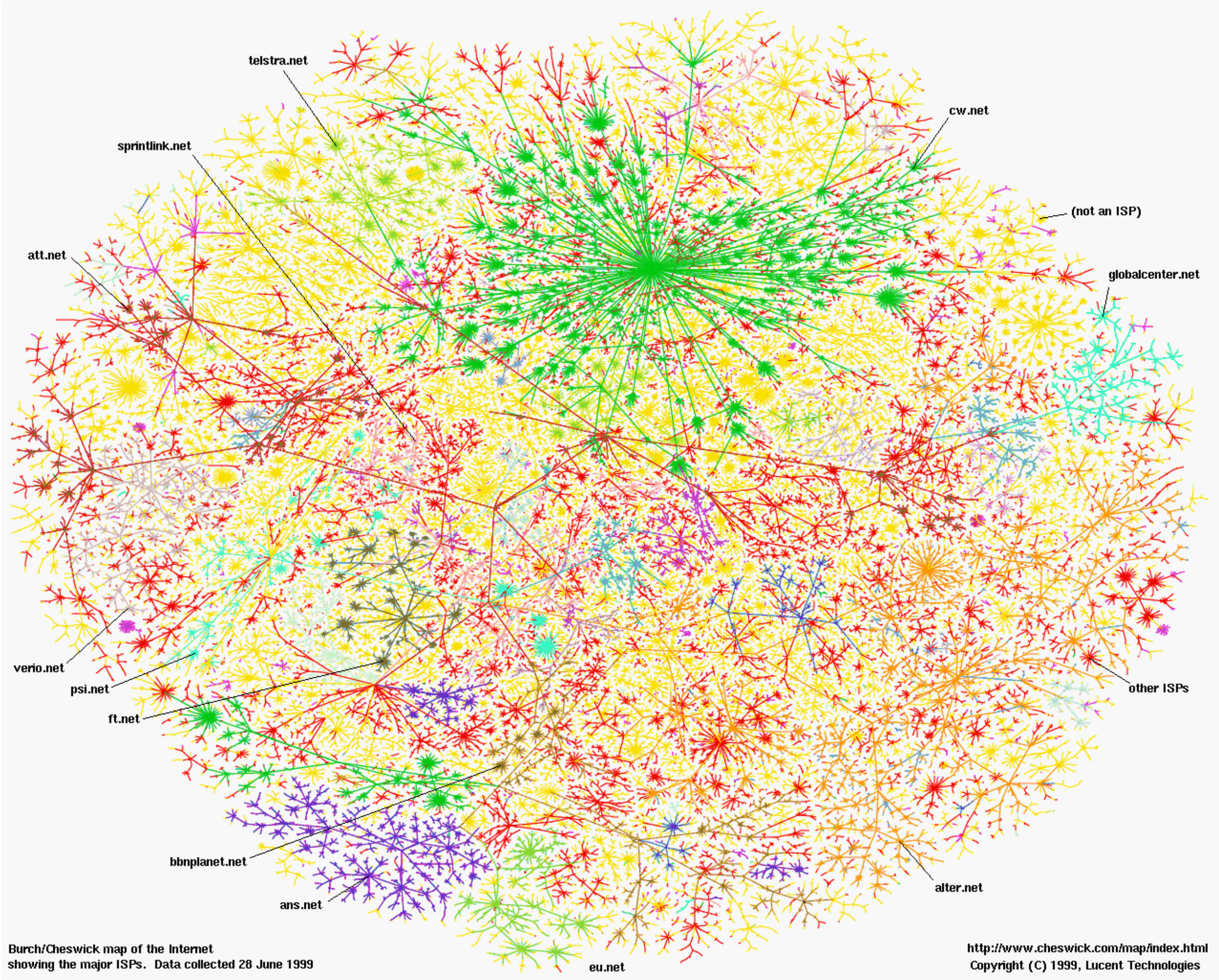
2000 km of fiber optic cable on the seafloor, connecting thousands of chemical, physical, and biological sensors



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



Point-of-sale terminals

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

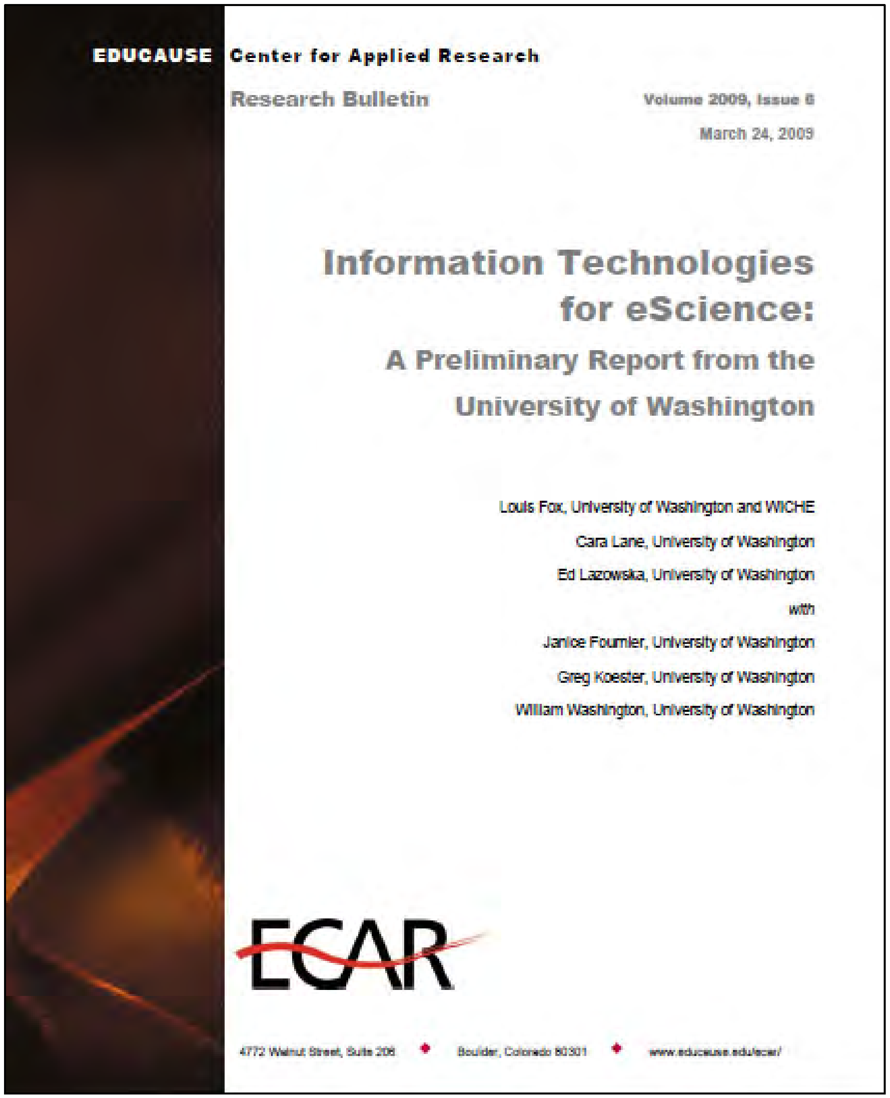
The technologies of eScience

- Sensors and sensor networks
- Databases
- Data mining
- Machine learning
- Data visualization

eScience will be pervasive

- Computational science 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

Top faculty across all disciplines understand the coming data tsunami



EDUCAUSE Center for Applied Research

Research Bulletin

Volume 2009, Issue 6

March 24, 2009

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/

eScience Institute

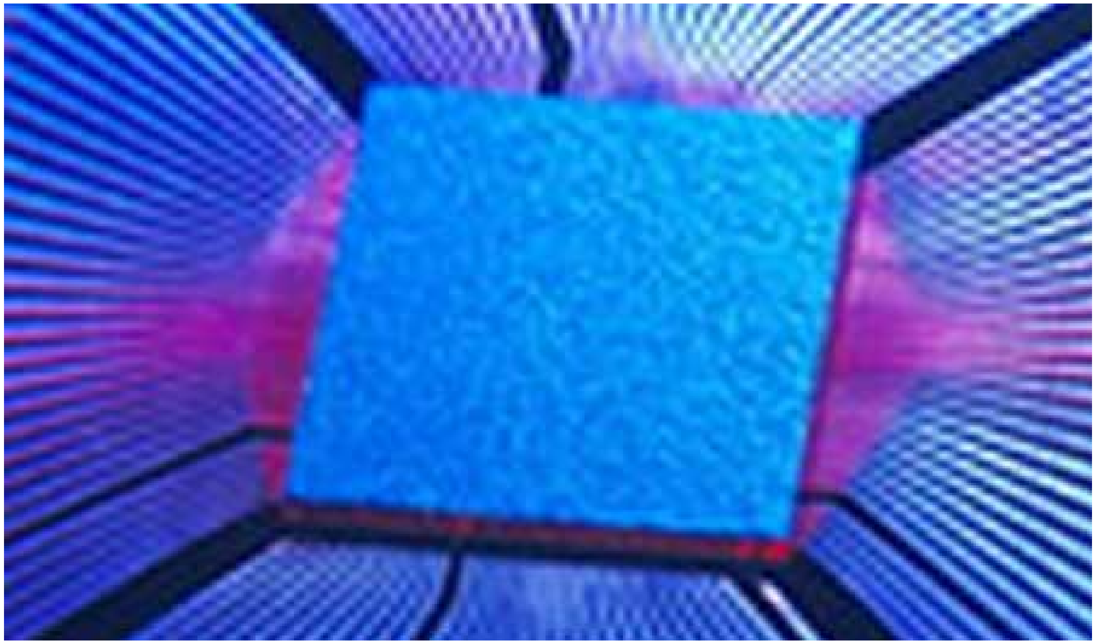
Questions for you …

- 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

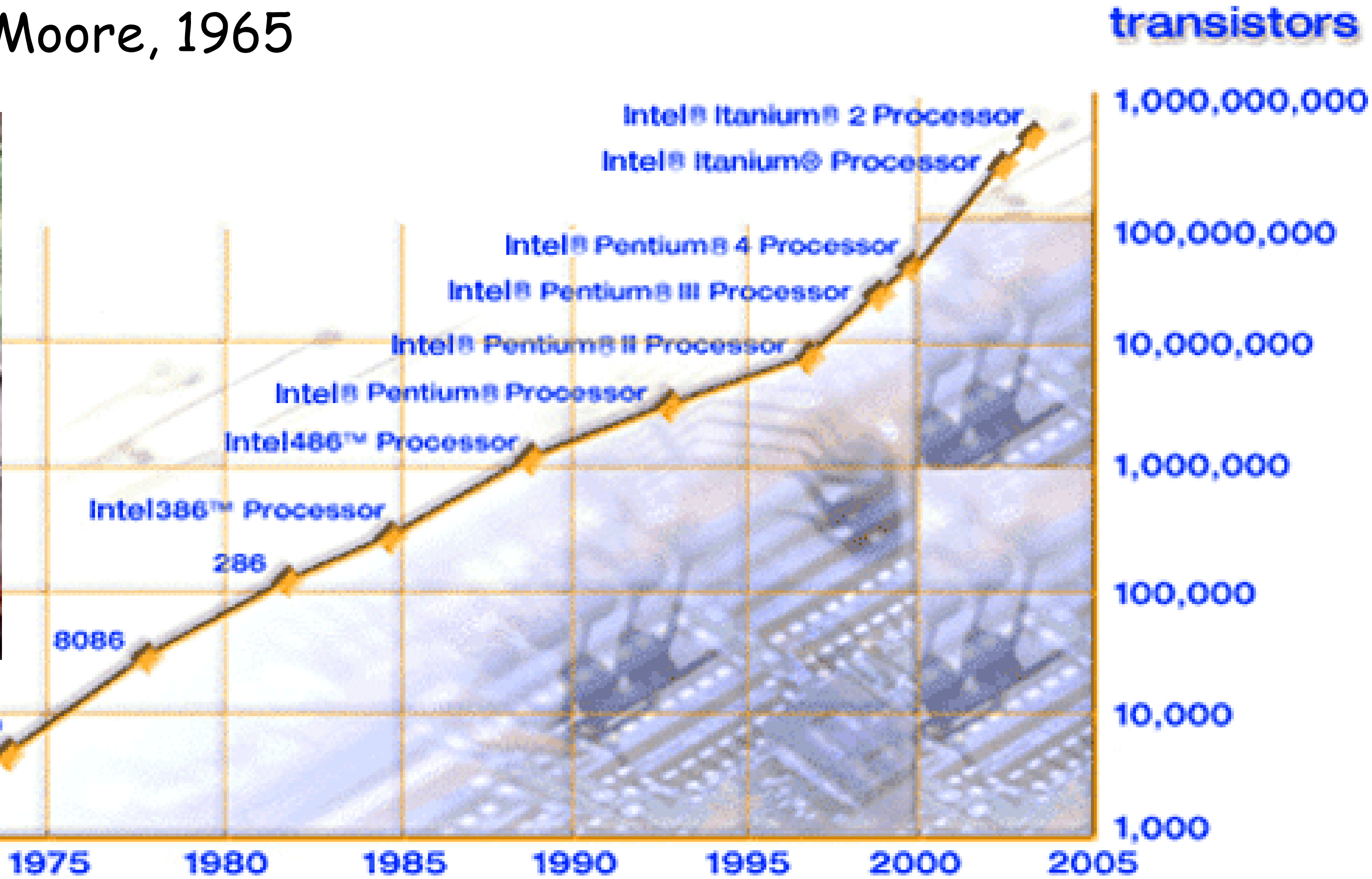
- Ten quintillion: $10*10^{18}$
  - The number of grains of rice harvested in 2004
  - The number of transistors fabricated in 2004



- 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

- **Moore's Law**
  - Gordon Moore, 1965

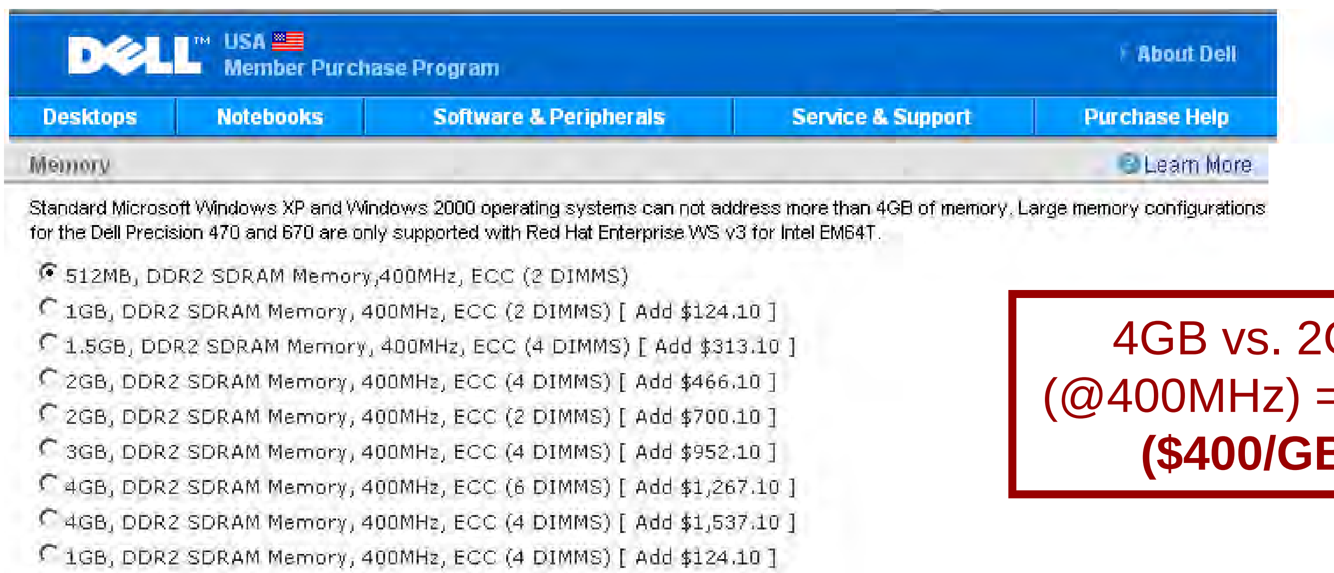



UNIVAC


UNIVAC

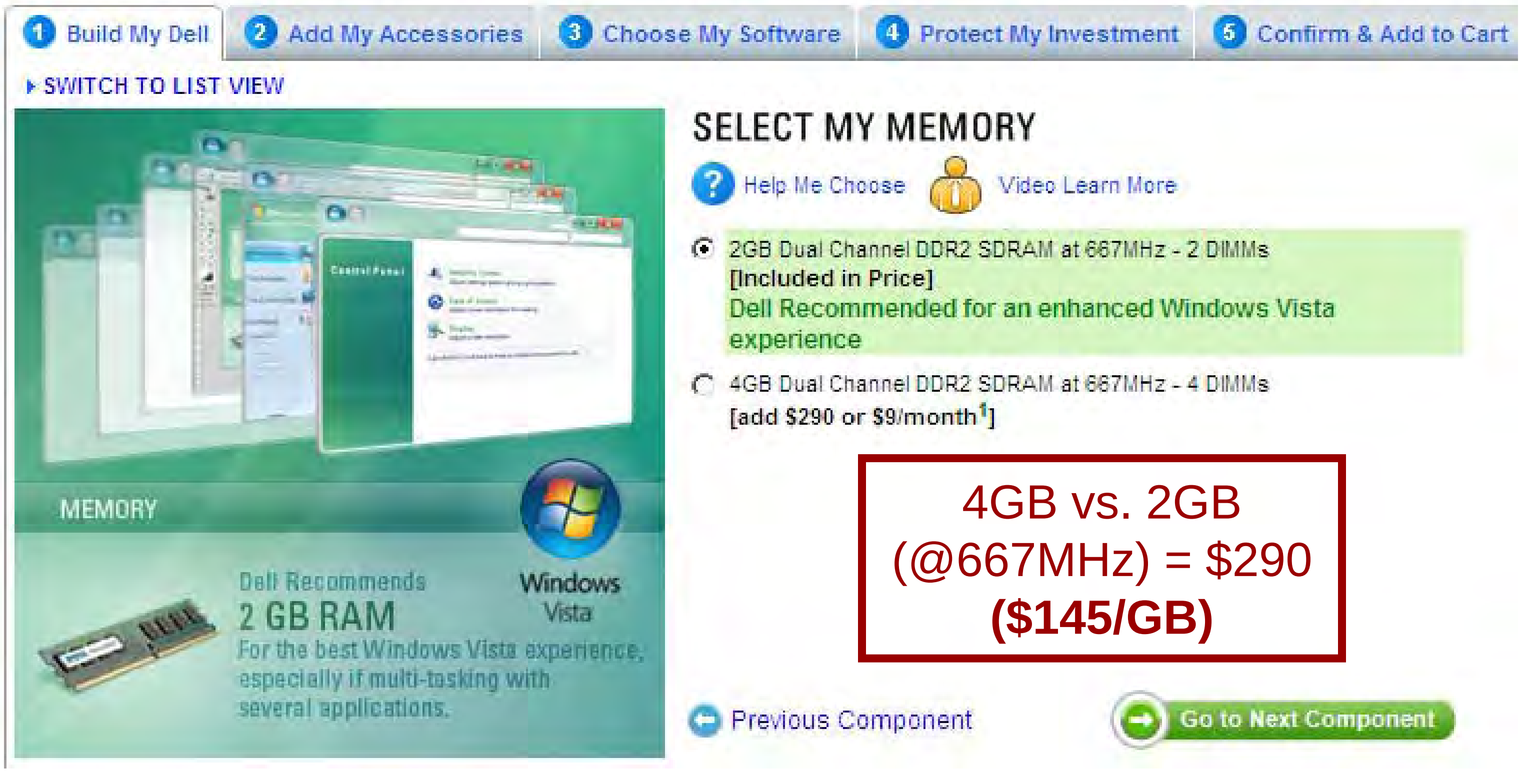
- Processing power, historically
  - 1980: 1 MHz Apple II+, $2,000
    - 1980 also 1 MIPS VAX-11/780, $120,000
  - 2006: 2.4 GHz Pentium D, $800
    - A factor of 6000
- Processing power, recently
  - Additional transistors => more cores of the same speed, rather than higher speed
  - 2008: Intel Core 2 Quad-Core 2.4 GHz, $800 (4x the capability, same price)
  - 2009: Intel Core 2 Quad-Core 2.5 GHz, $183 (same capability, 1/4 the price)

- Primary memory – same story, same reason (but no multicore fiasco)
  - 1972: 1MB, $1,000,000
  - 1982: 1MB, $60,000
  - 2005: $400/GB (1MB, $0.40)



4GB vs. 2GB (@400MHz) = $800 **($400/GB)**

- 2007: $145/GB (1MB, $0.15)



4GB vs. 2GB
(@667MHz) = $290
($145/GB)

- 2008: $49/GB (1MB, $0.05)

- 2009: $31/GB (1MB, $0.03)

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Dell recommends Windows Vista® Home Premium.

You are here: USA > Home & Home Office

To compare multiple configurations, click the review and continue tab below then click 'Add to Wish List'.

1 Customize | 2 Software & Accessories | 3 Services | 4 Review

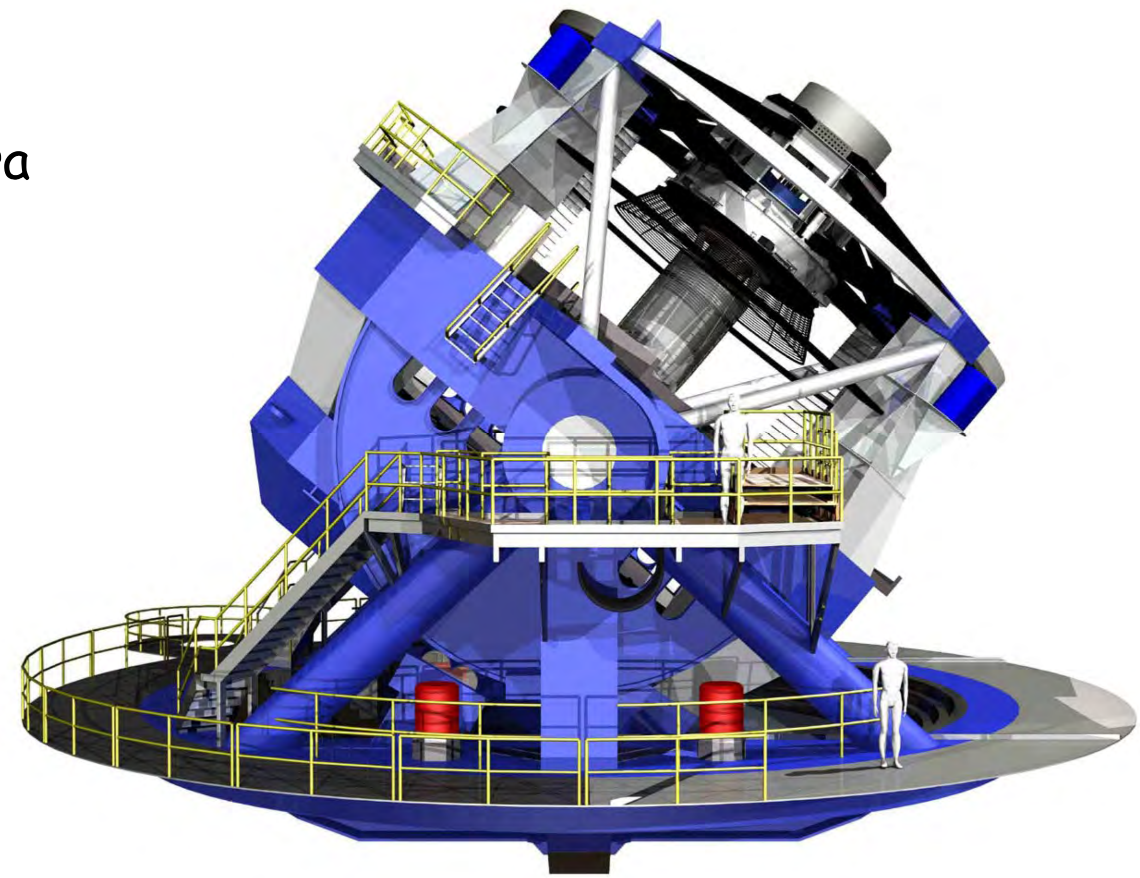
▸ SWITCH TO LIST VIEW

SELECT MY MEMORY

- ◉ 4GB Dual Channel DDR2 SDRAM at 800MHz- 4DIMMs [Included in Price]
- ○ 6GB Dual Channel DDR2 SDRAM at 800MHz - 4 DIMMs [add $75 or $3/month[1]]
- ○ 8GB Dual Channel DDR2 SDRAM at 800MHz - 4 DIMMs [add $125 or $4/month[1]]

8GB vs. 4GB (@800MHz) = $125 **($31/GB)**

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



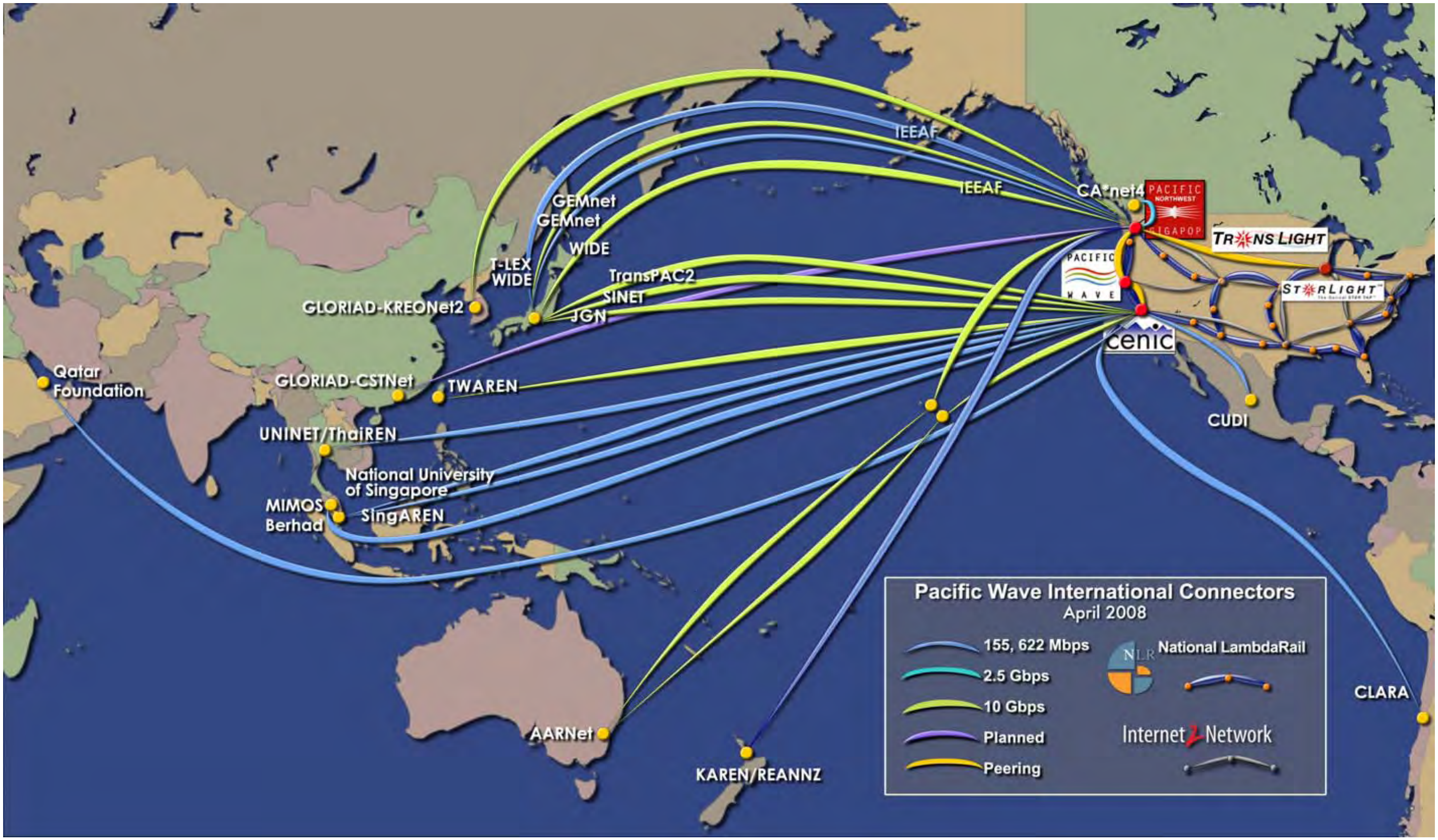
- Disk capacity, 1975-1989
  - doubled every 3+ years
  - 25% improvement each year
  - factor of 10 every decade
  - Still exponential, but far less rapid than processor performance
- Disk capacity since 1990
  - doubling every 12 months
  - 100% improvement each year
  - factor of 1000 every decade
  - 10x as fast as processor performance

- Only a few years ago, we purchased disks by the megabyte (and it hurt!)
- Current cost of 1 GB (a billion bytes) from Dell
  - 2005: $1.00
  - 2006: $0.50
  - 2008: $0.25
- Purchase increment
  - 2005: 40GB
  - 2006: 80GB
  - 2008: 250GB

- Optical bandwidth today
  - Doubling every 9 months
  - 150% improvement each year
  - Factor of 10,000 every decade
  - 10x as fast as disk capacity
  - 100x as fast as processor performance

A connected region – then

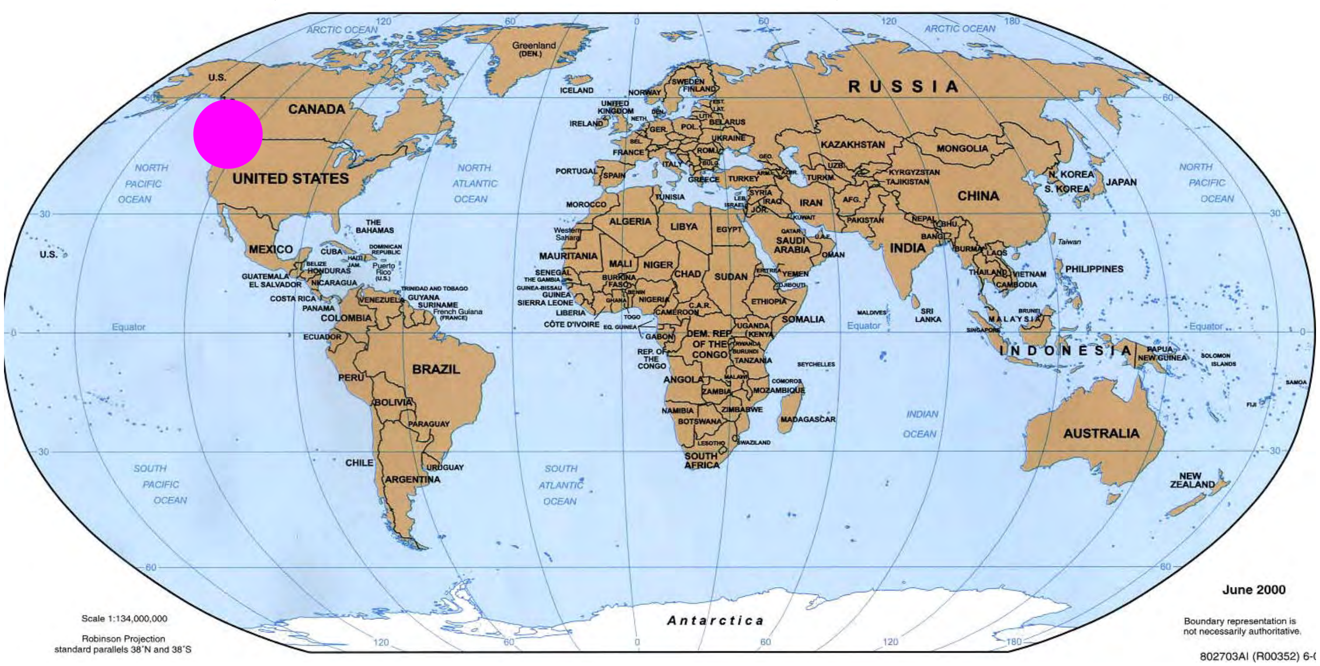
A connected region - now



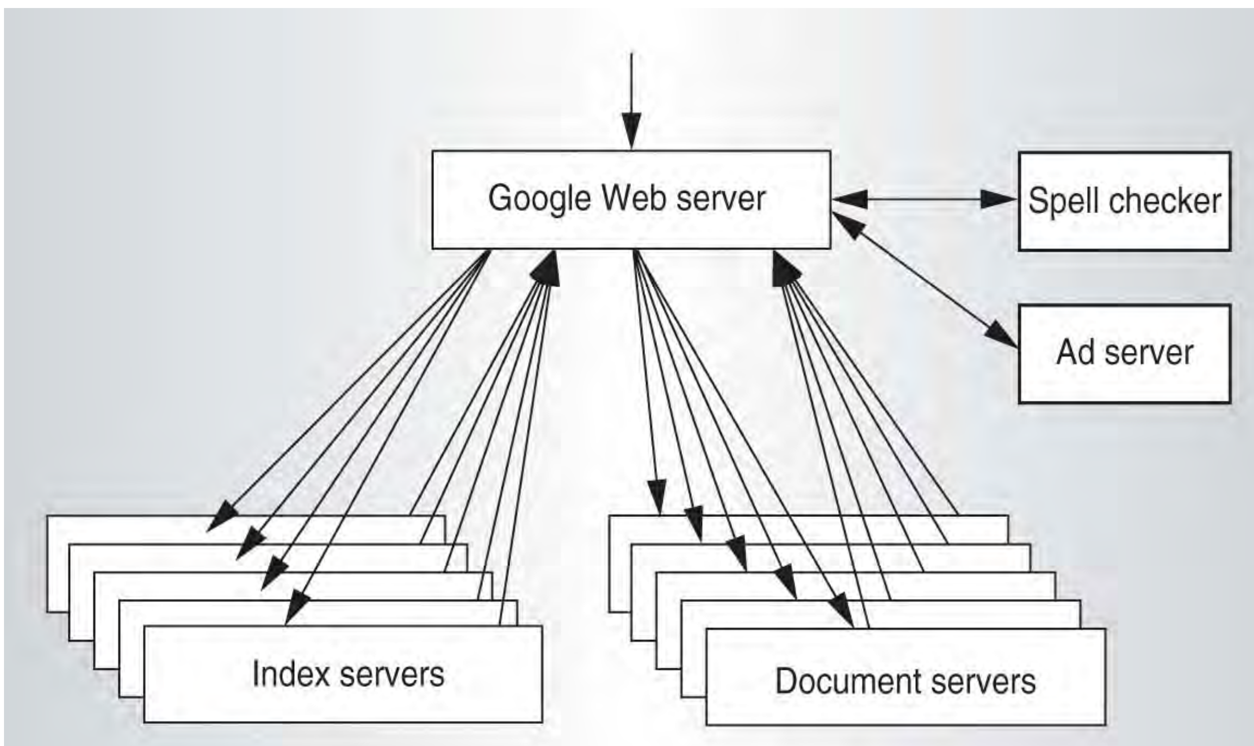
But eScience is equally enabled by *software* for *scalability* and for *discovery*

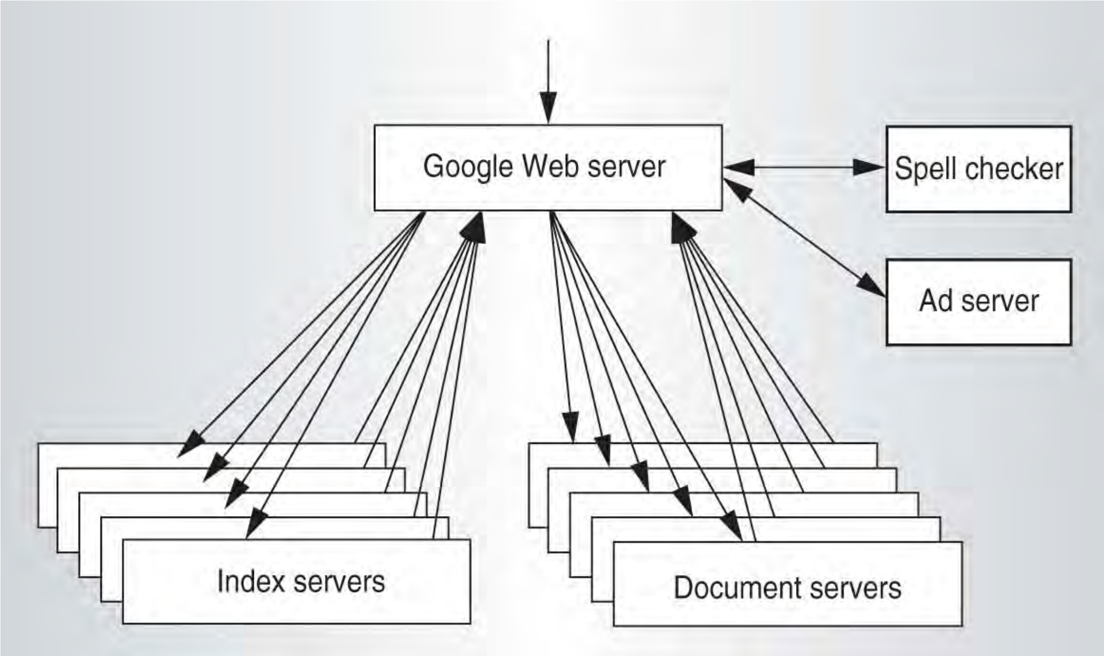
- It's likely that Google has several million machines
  - But let's be conservative – 1,000,000 machines
  - A rack holds 176 CPUs (88 1U dual-processor boards), so that's about 6,000 racks
  - A rack requires about 50 square feet (given datacenter cooling capabilities), so that's about 300,000 square 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

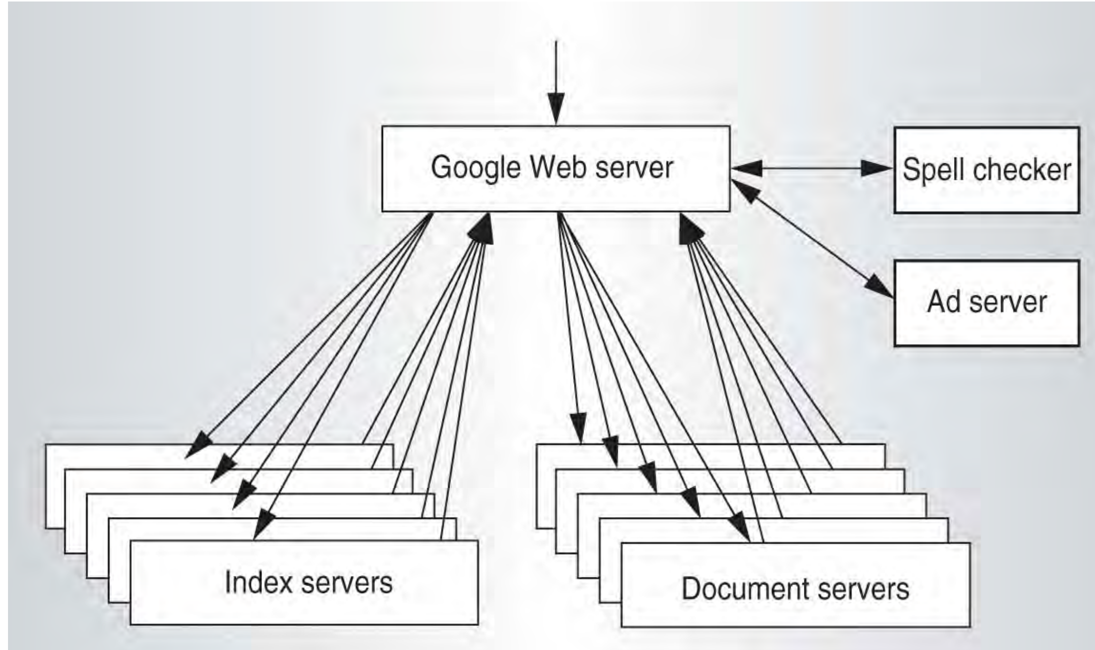


- A cluster consists of Google Web Servers, Index Servers, Doc Servers, and various other servers (ads, spell checking, etc.)
- These are cheap standalone computers, rack-mounted, connected by commodity networking gear

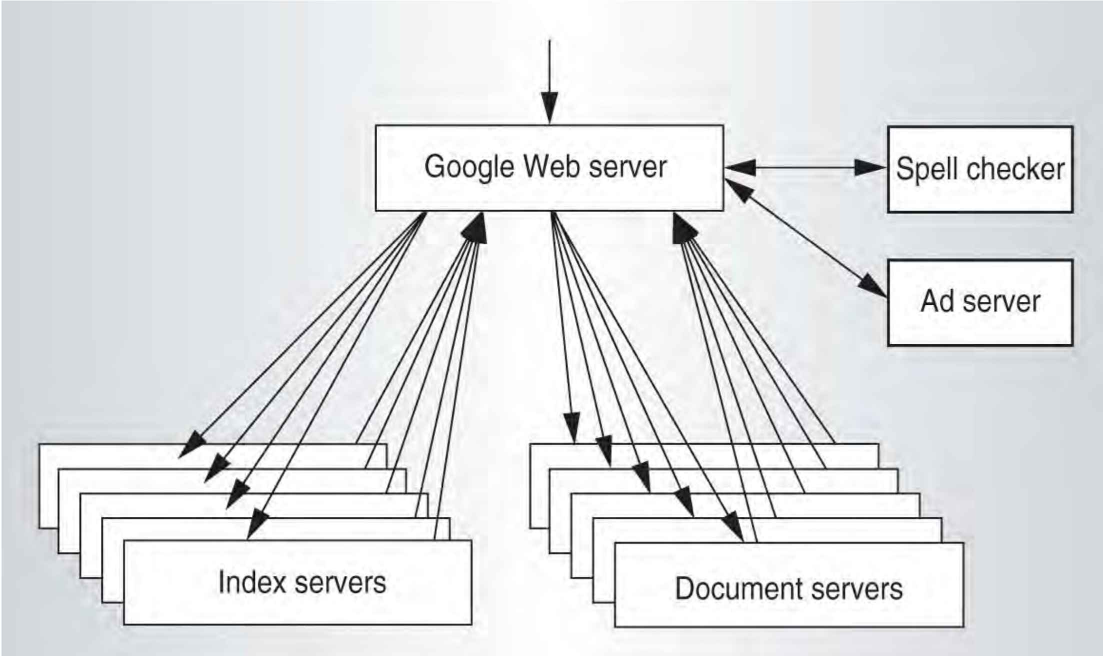




- Within the cluster, load-balancing routes your search to a lightly-loaded Google Web Server (GWS), which will coordinate the search and response
- The index is partitioned into "shards." Each shard indexes a subset of the docs (web pages). Each shard is replicated, and can be searched by multiple computers – "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.

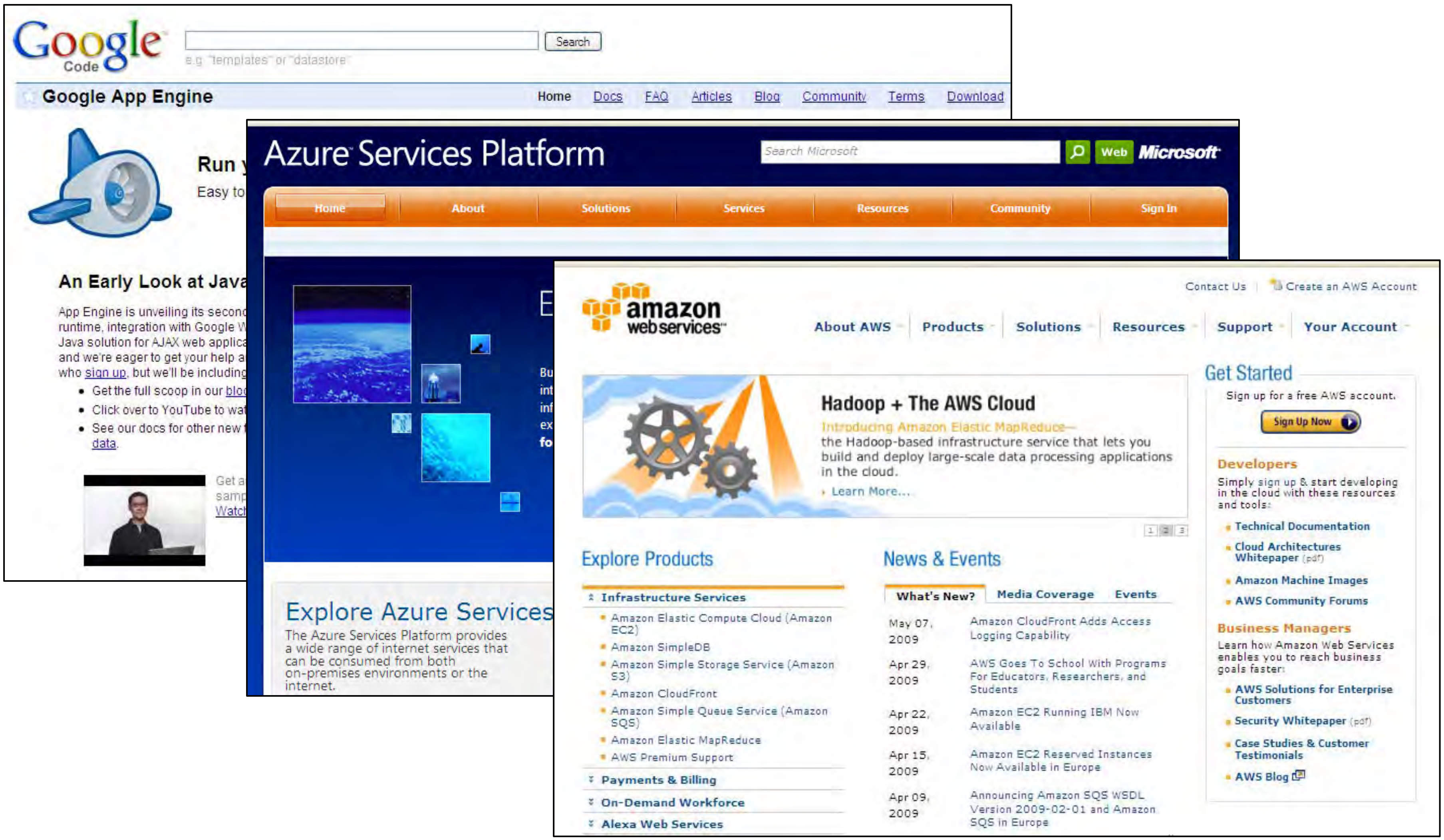
- Enormous volumes of data
- Extreme parallelism
- The cheapest imaginable components
  - Failures occur all the time
  - You couldn't afford to prevent this in hardware
- Software makes it
  - Fault-Tolerant
  - Highly Available
  - Recoverable
  - Consistent
  - Scalable
  - Predictable
  - Secure

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

Scalable computing for everyone



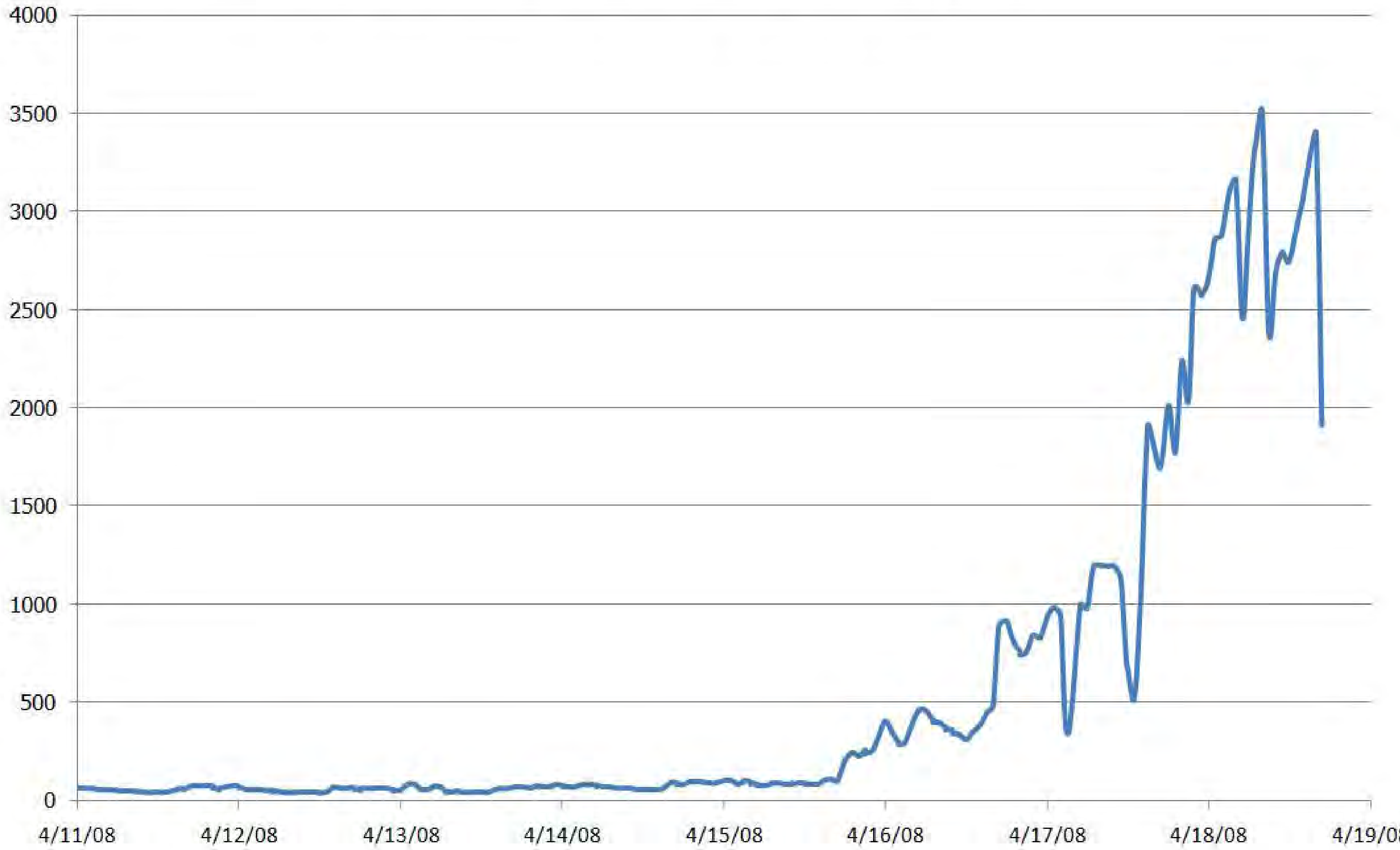
Amazon Elastic Compute Cloud (EC2)

- $0.80 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?
  - $4800

- $0.10 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?
  - $590

- This includes
  - Purchase + replacement
  - Housing
  - Power
  - Operation
  - Reliability
  - Security
  - Instantaneous expansion and contraction

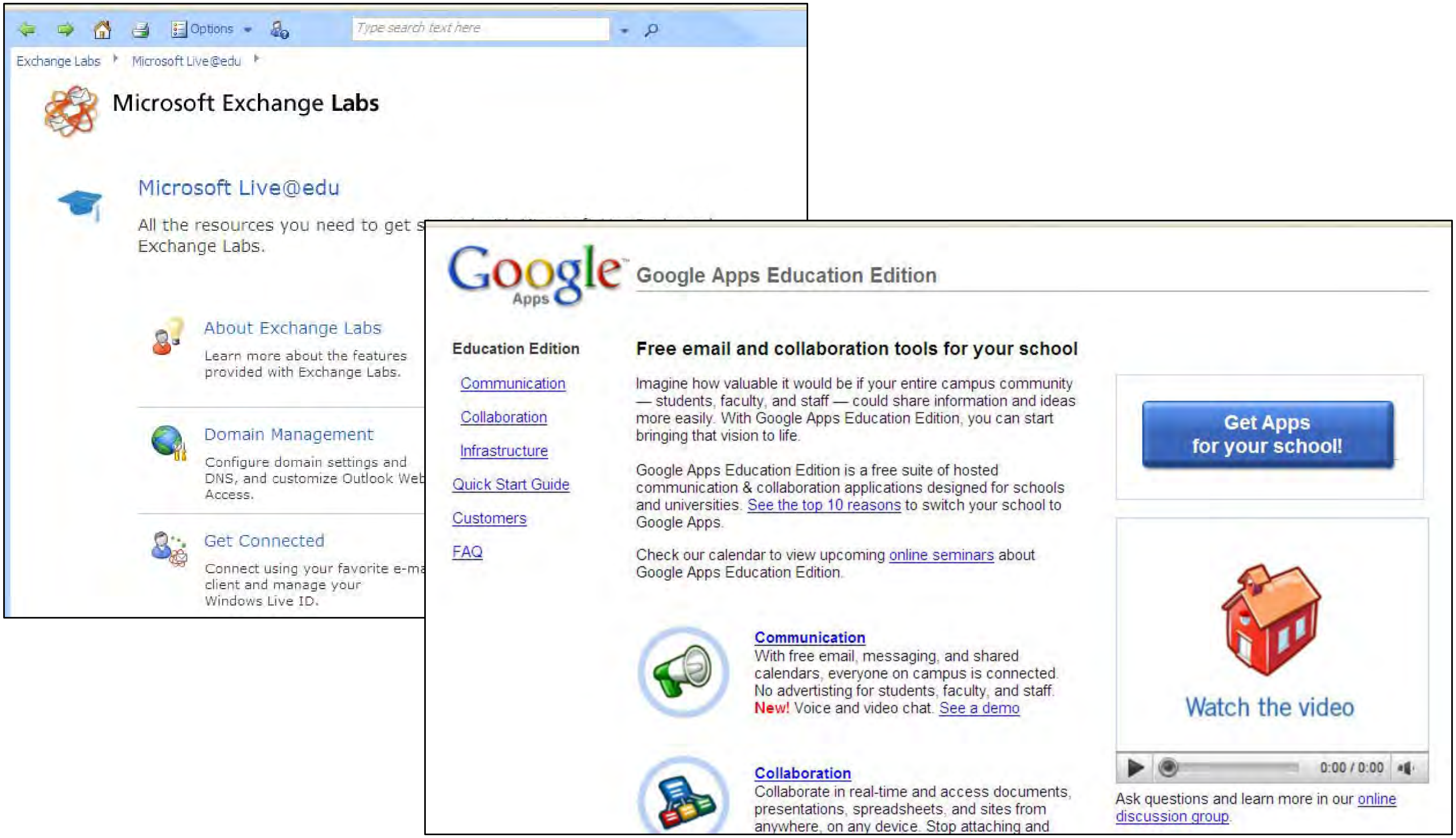
Animoto: EC2 Instance Usage

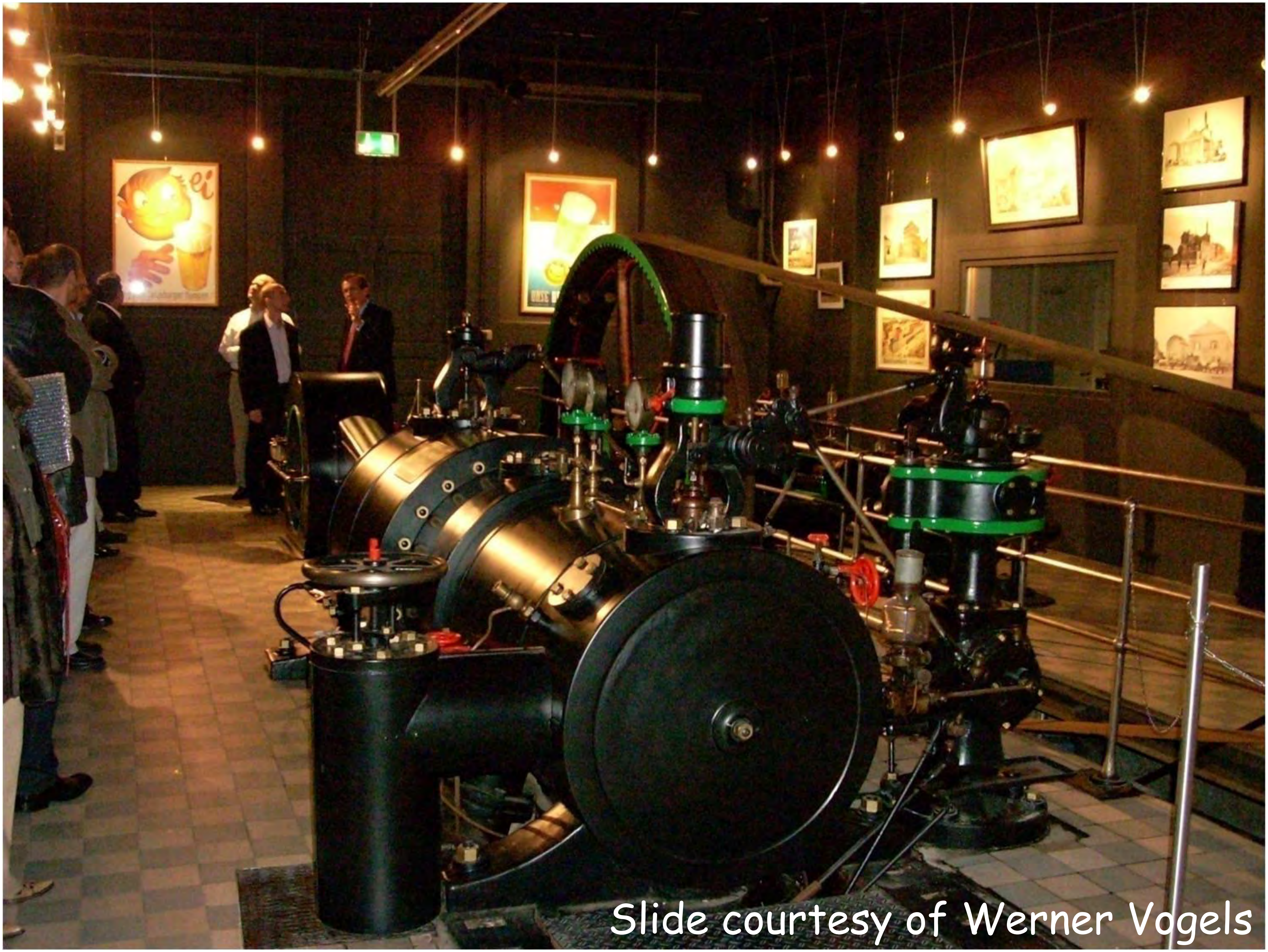


Slide courtesy of Werner Vogels

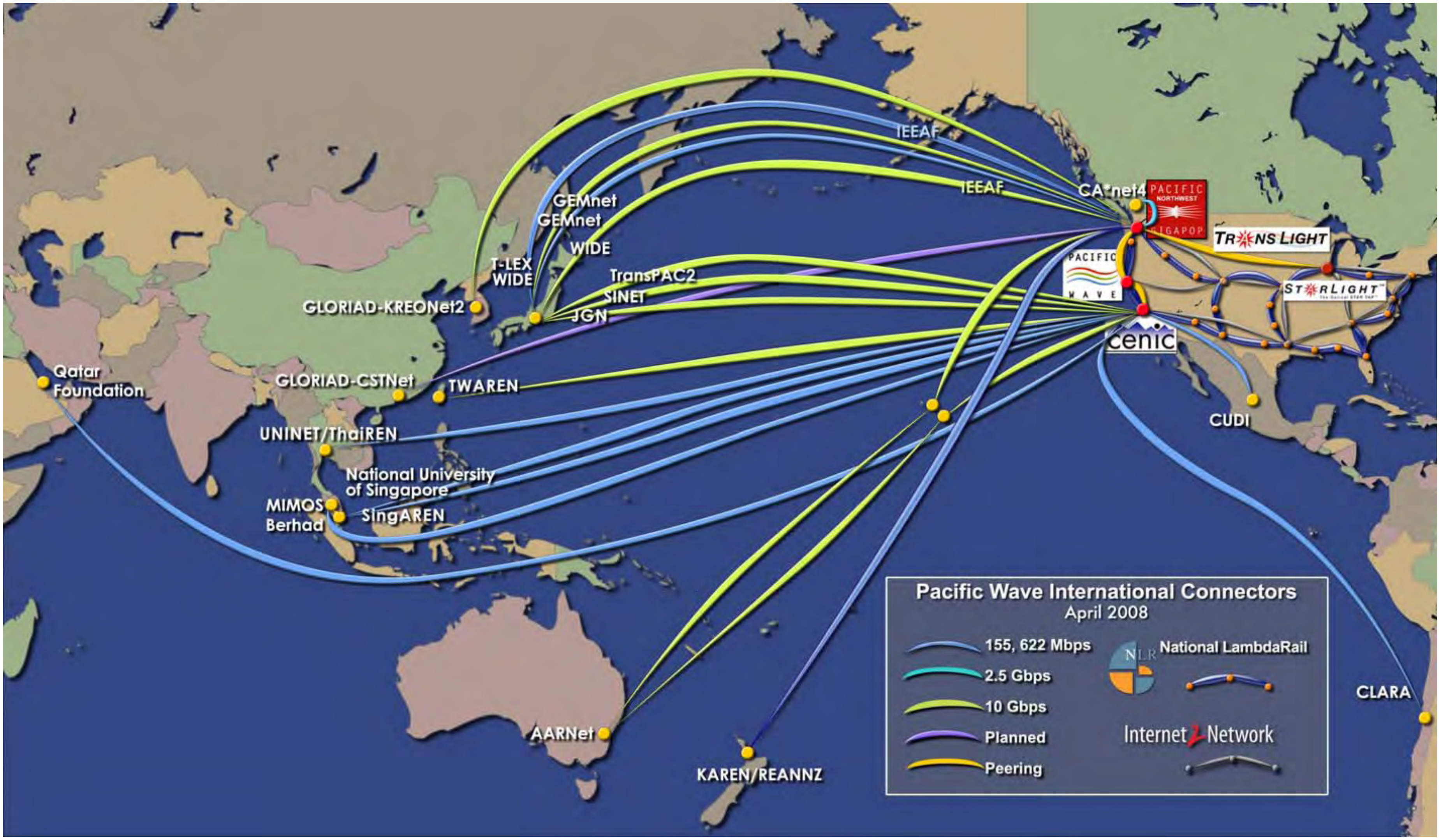
- 1000 processors for 1 hour costs the same as 1 processor for 1000 hours
  - Revolutionary!
- Your application doesn't run decently on this environment?
  - Start figuring out how to change that!

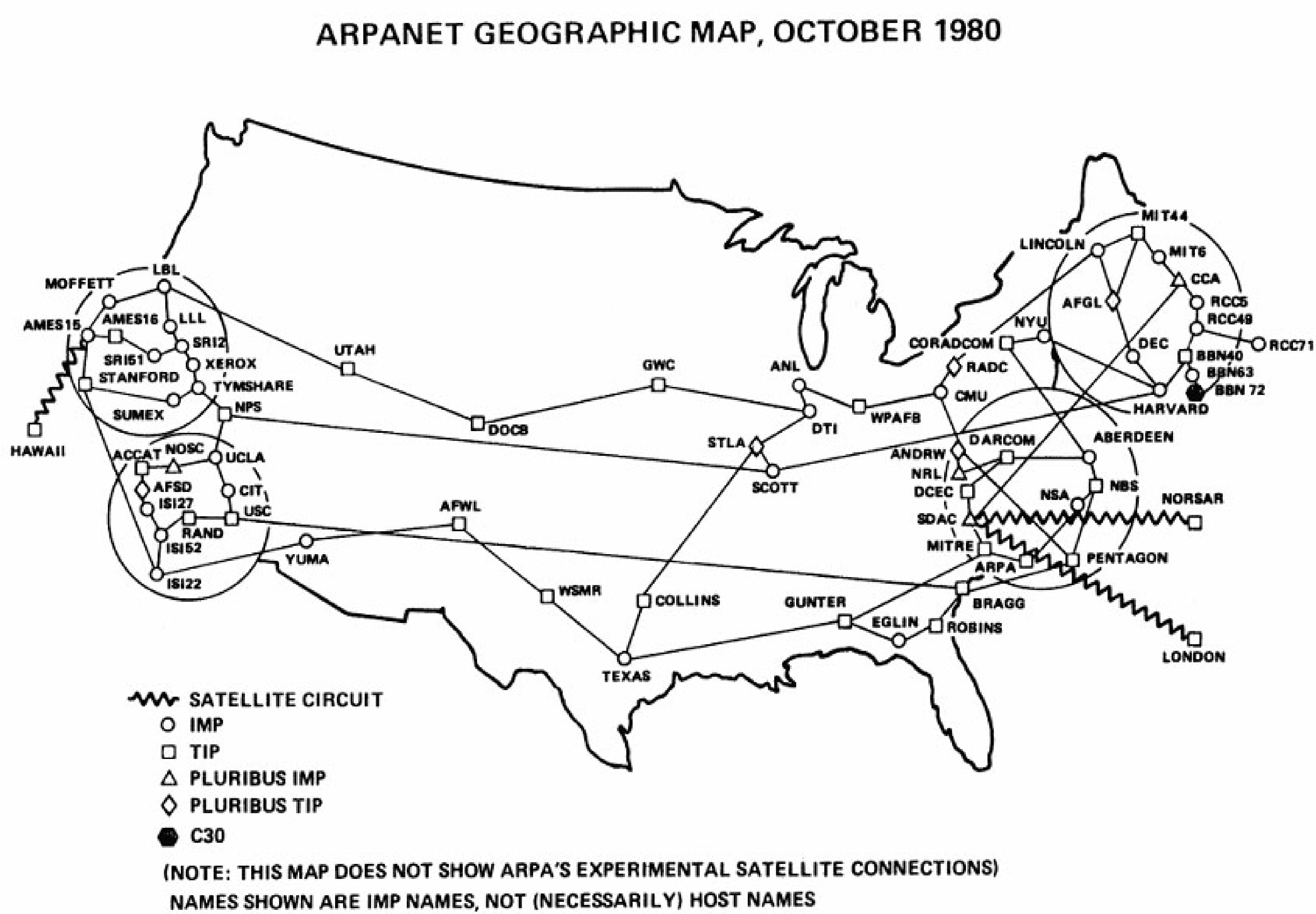
Still running your own email servers?



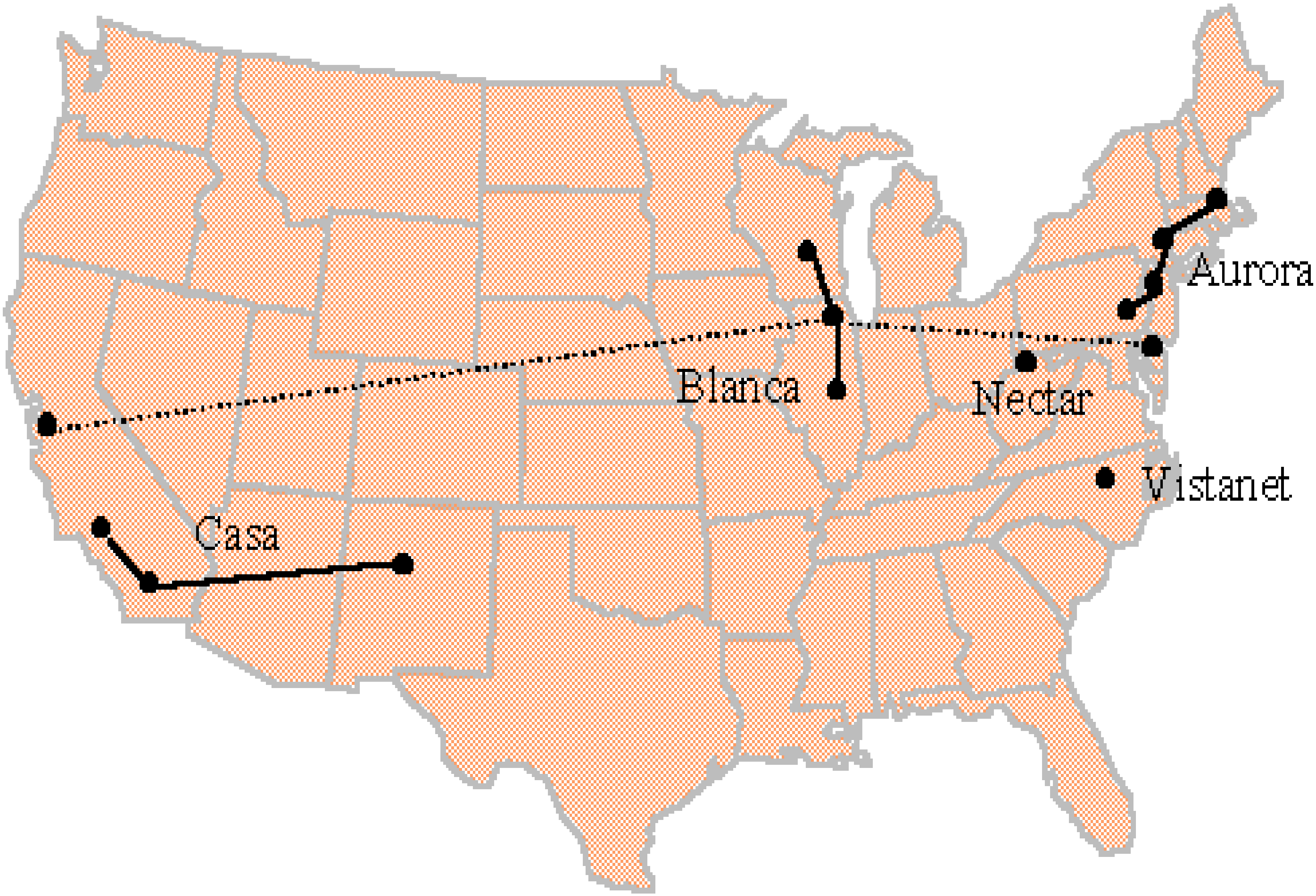

Slide courtesy of Werner Vogels

Networking in the West

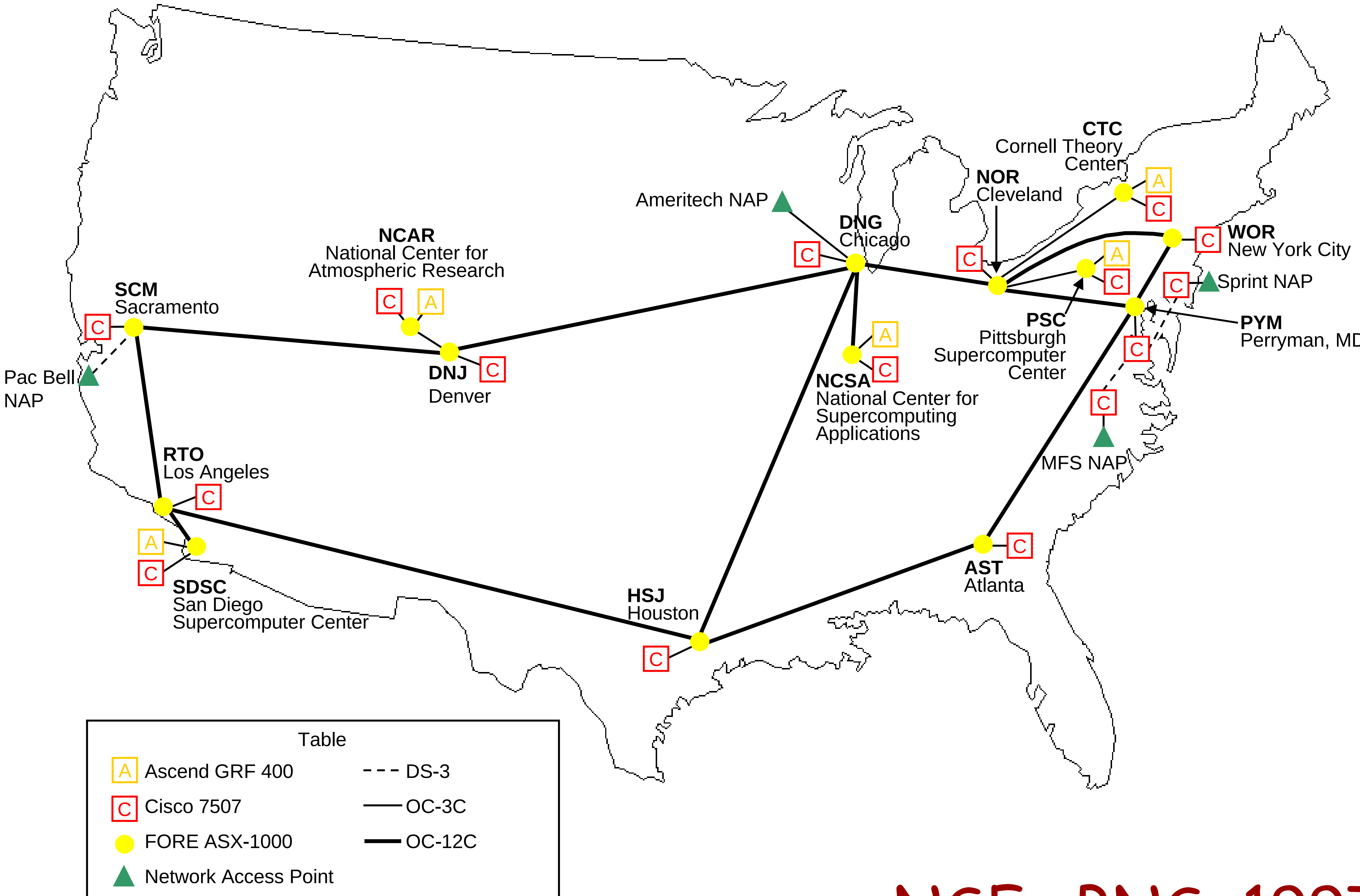




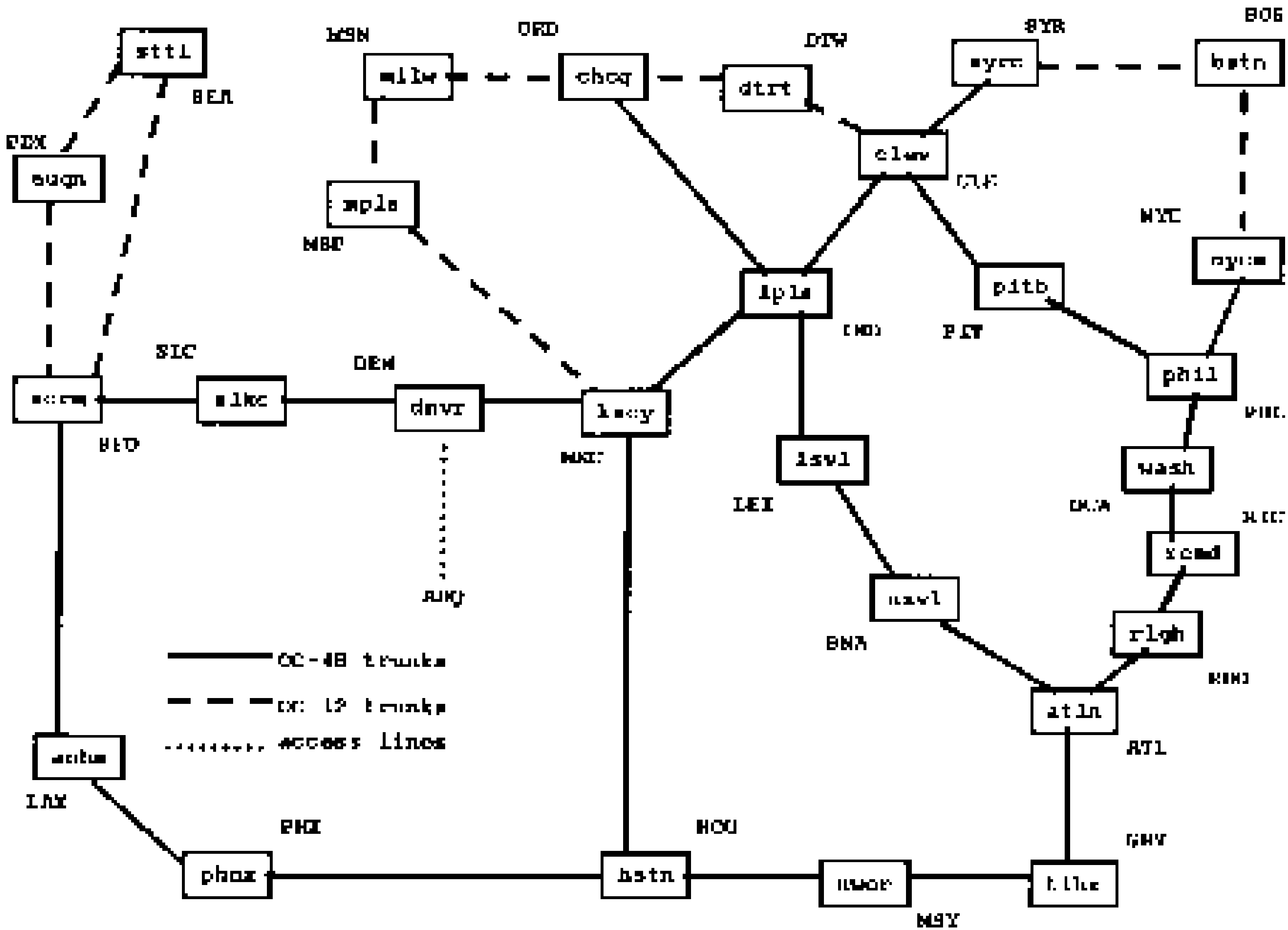
ARPANET, 1980



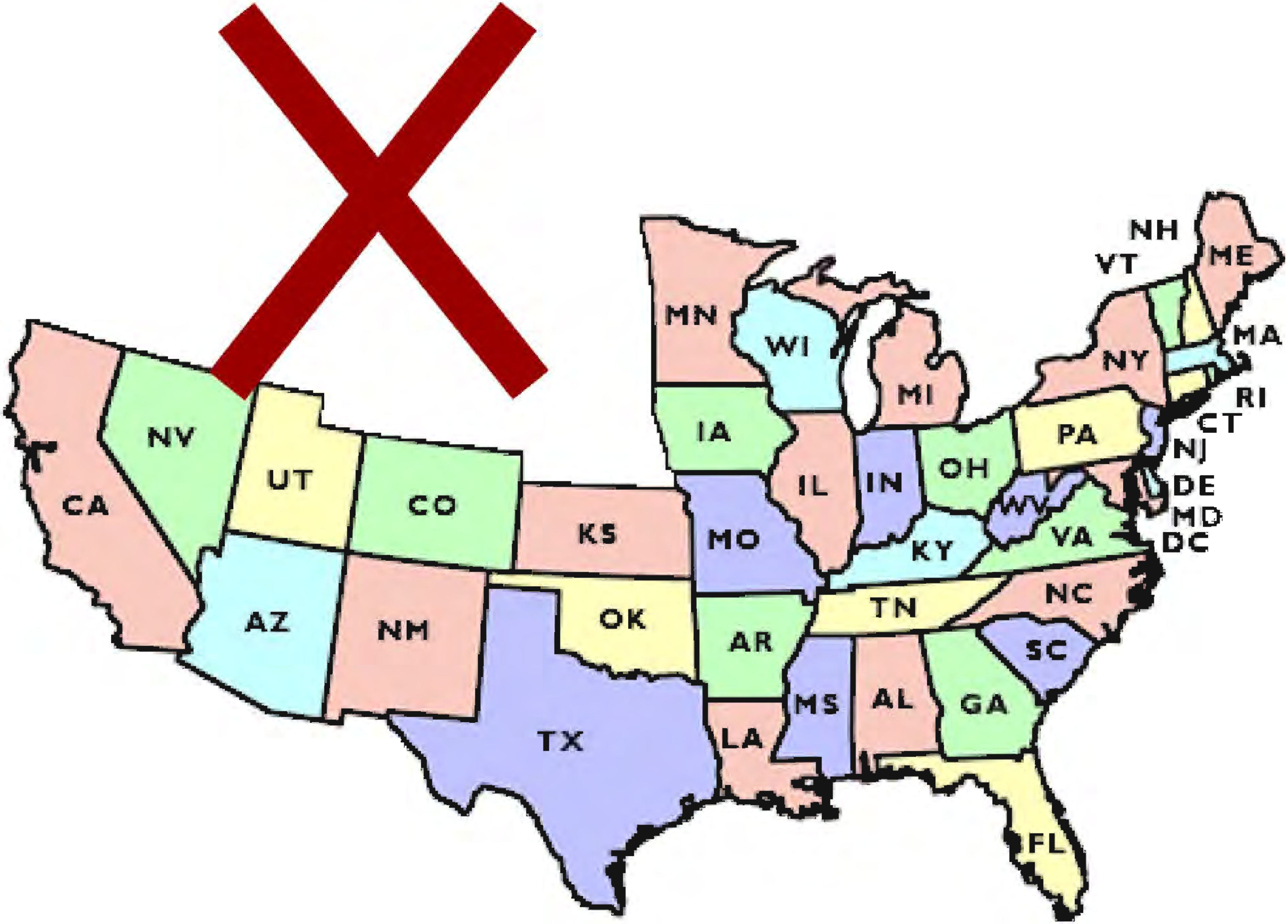
DARPA Gigabit Testbeds, mid-1990's



NSF vBNS, 1997



UCAID Abilene network, 1998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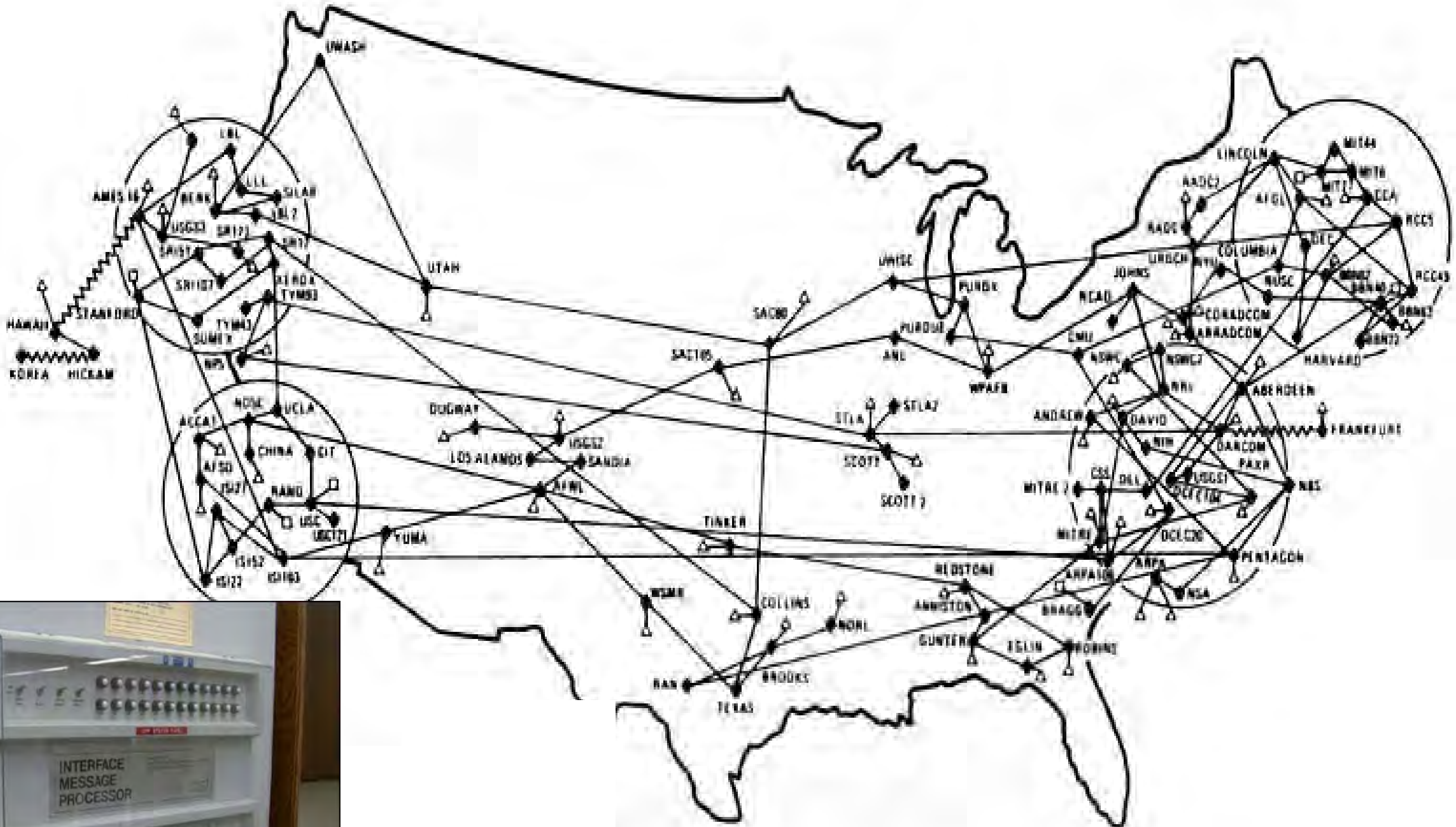
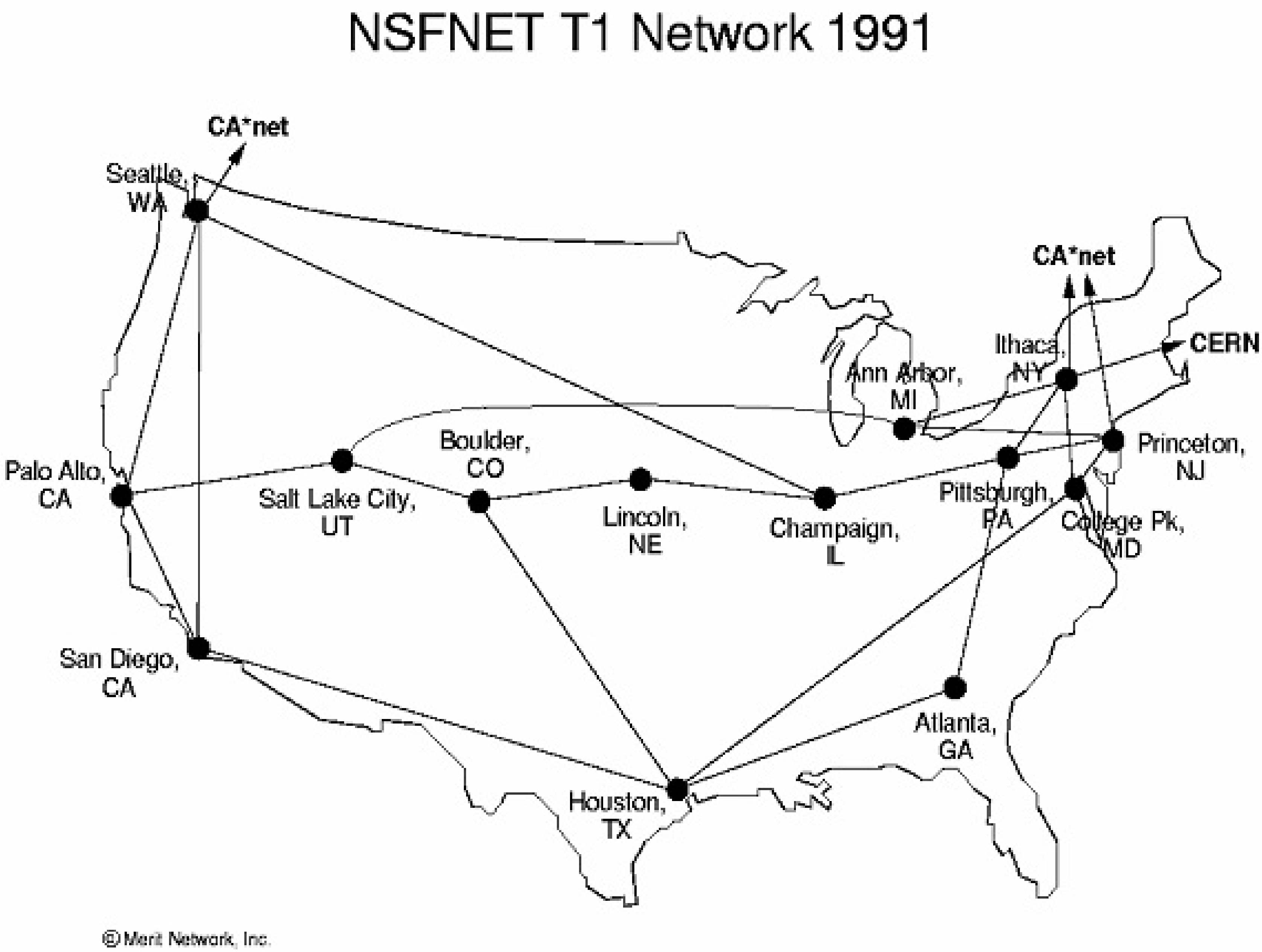


ARPANET, 1983


NSFNET T1 Network 1991
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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
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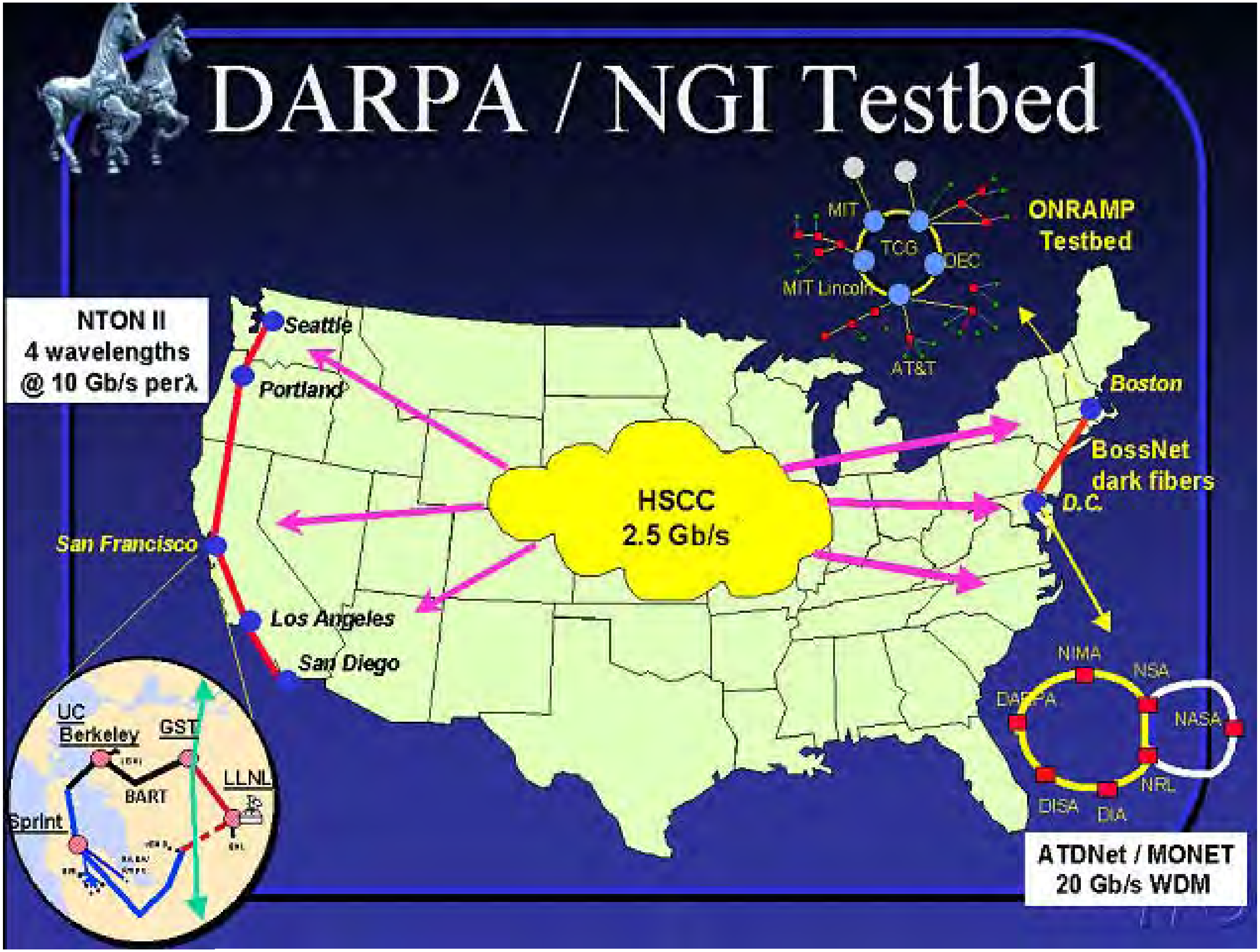
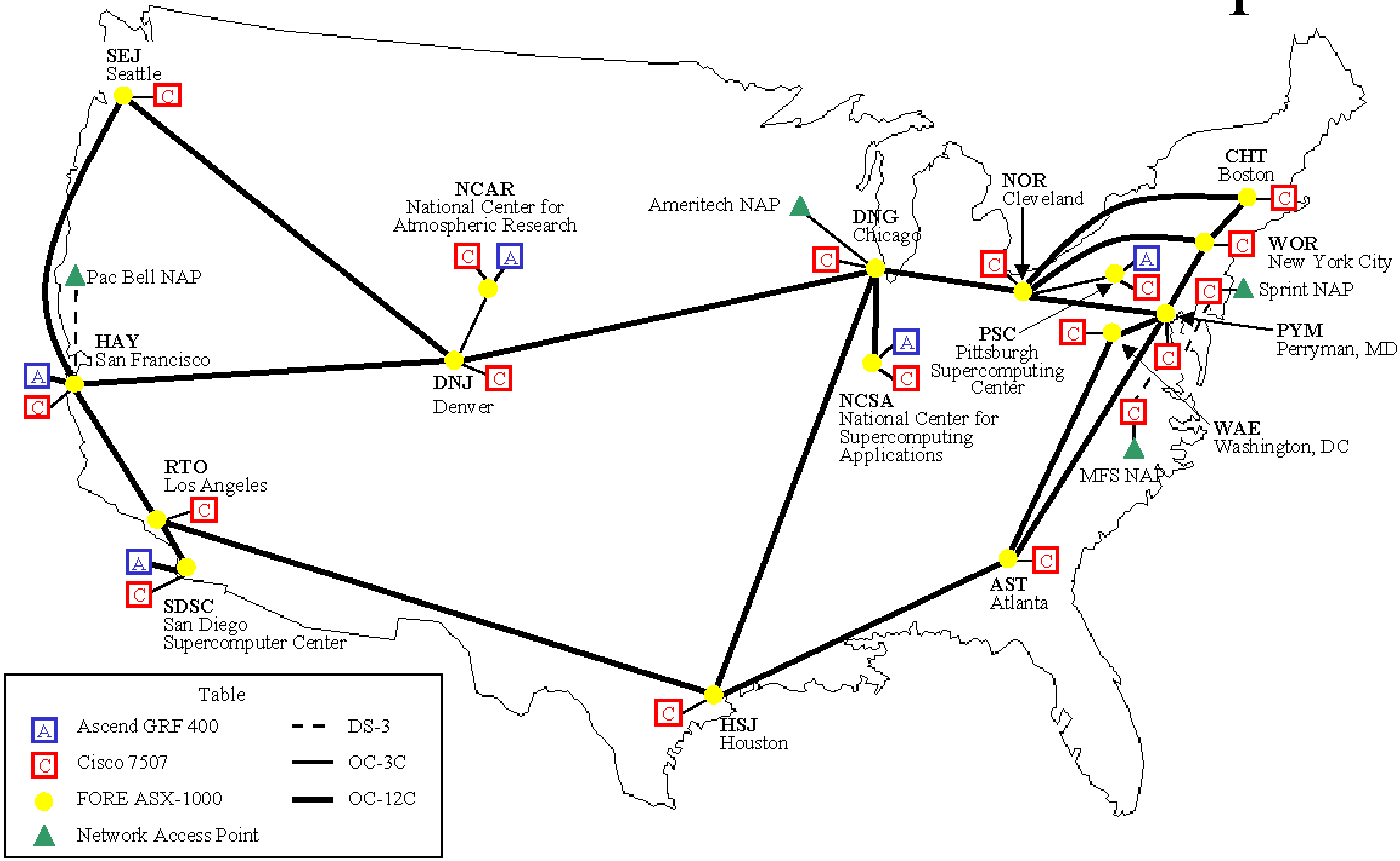
College Pk, MD
San Diego, CA
Atlanta, GA
Houston, TX
© Merit Network, Inc.

NSFNET, 1991

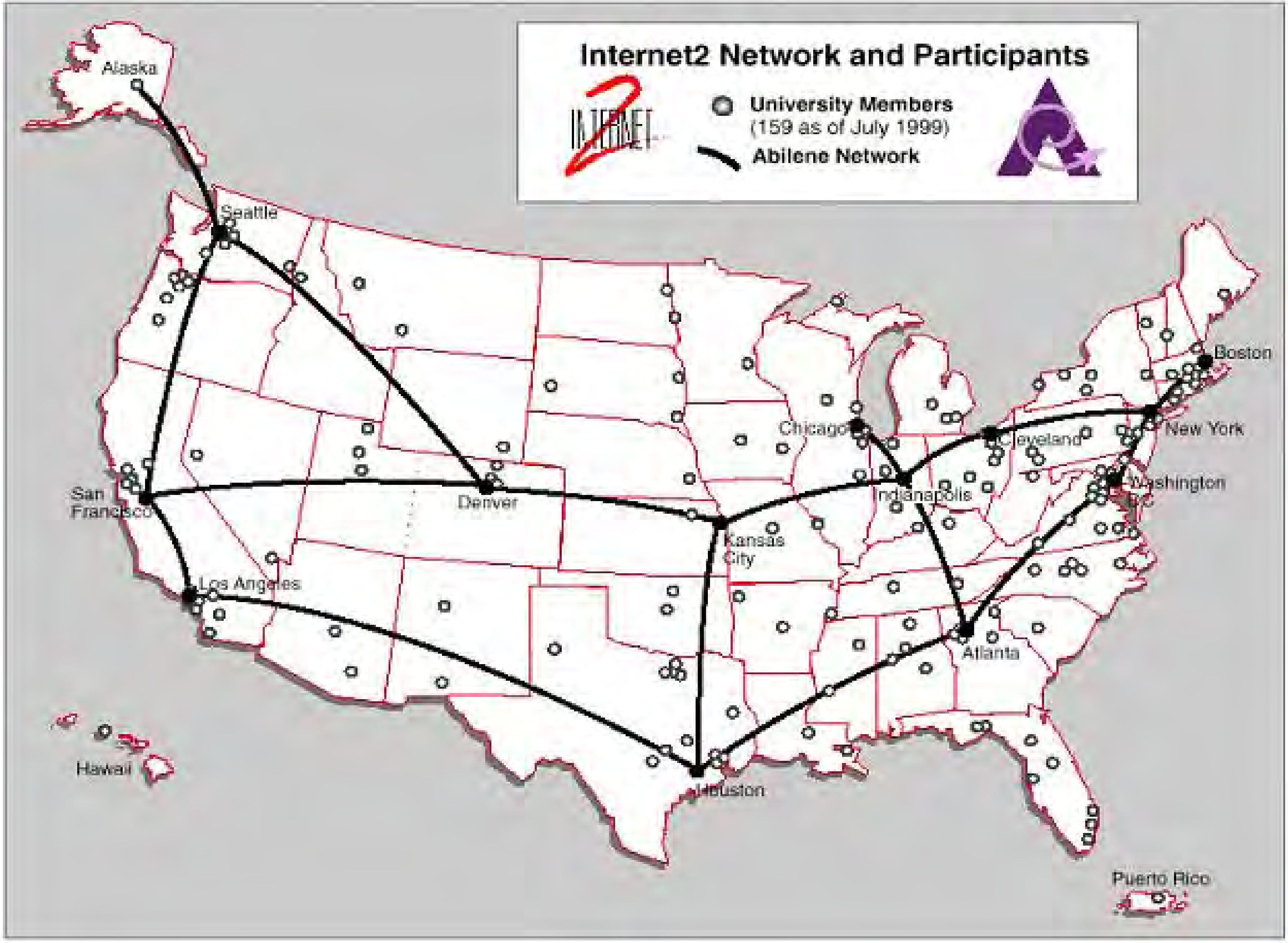


DARPA / NGI Testbed, late 1990's

vBNS Backbone Network Map



NSF vBNS, 1998

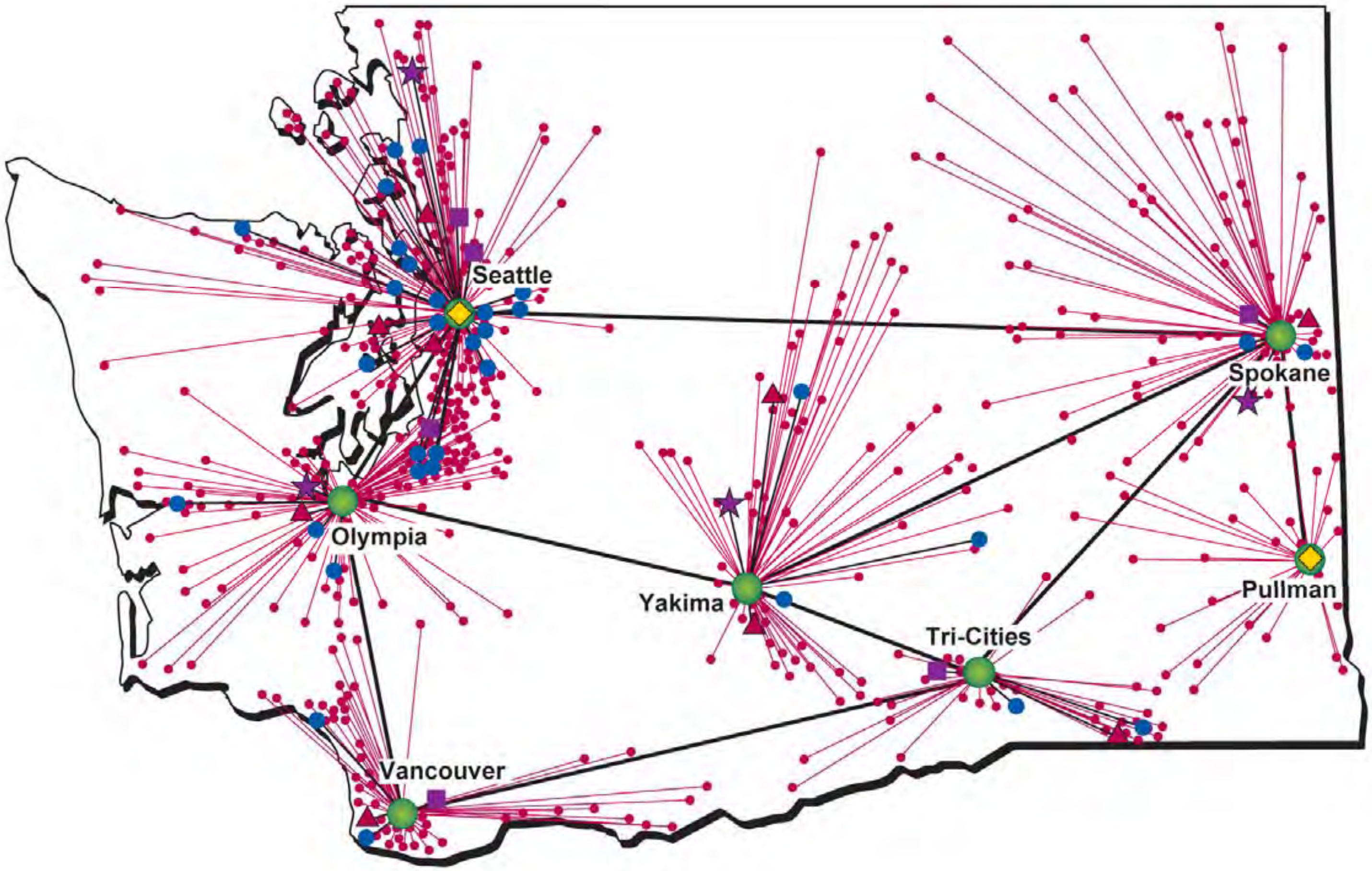


Internet2, 1999

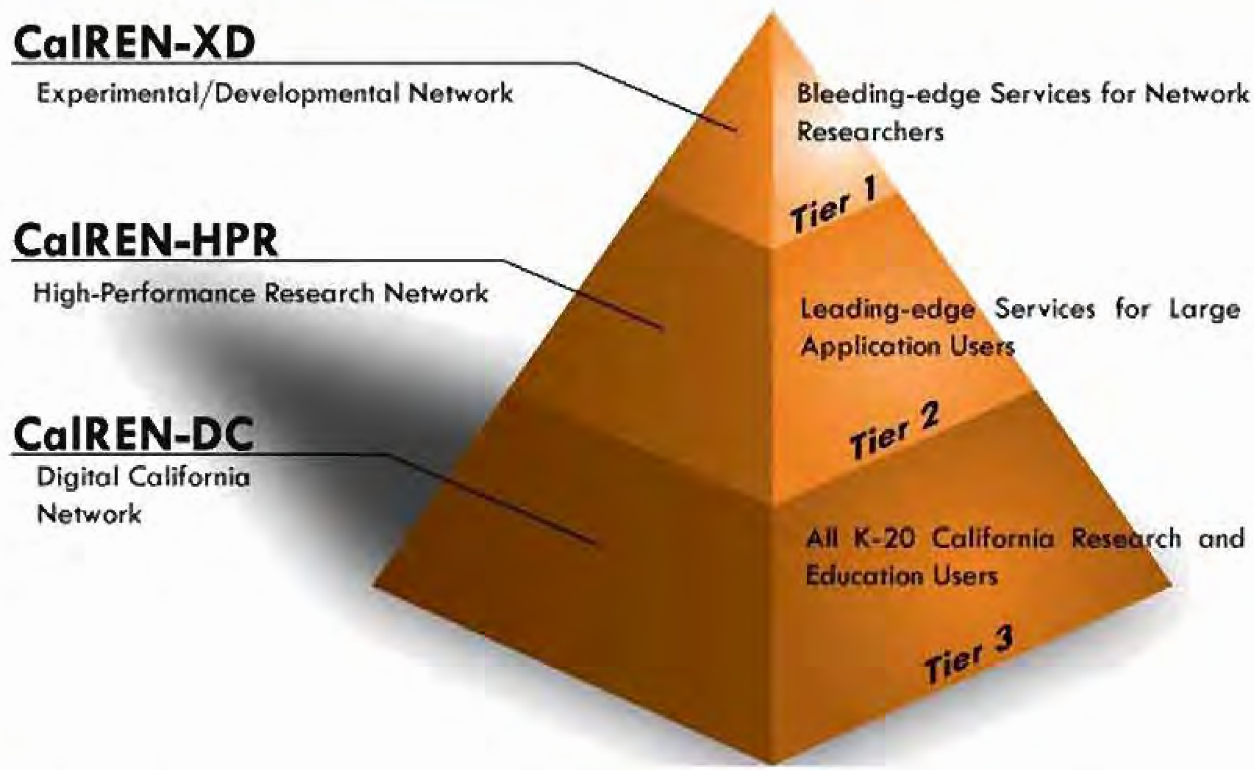
NLR – Optical Infrastructure - Phase 1

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

National Tele

FED

In the matter of

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CONSOLIDATED

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."

. . .

INTERNET2

COMPUTING RESEARCH ASSOCIATION CRA

EPSCoR/IDeA FOUNDATION

EDUCAUSE

NLR

STATENETS America's State Education Networks

THE QUILT

SURA

WICHE

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.

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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.

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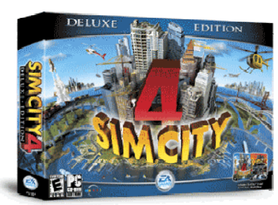
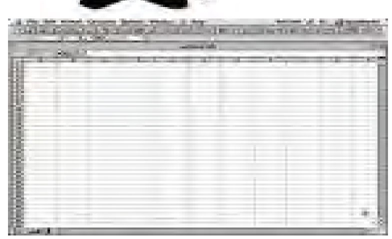
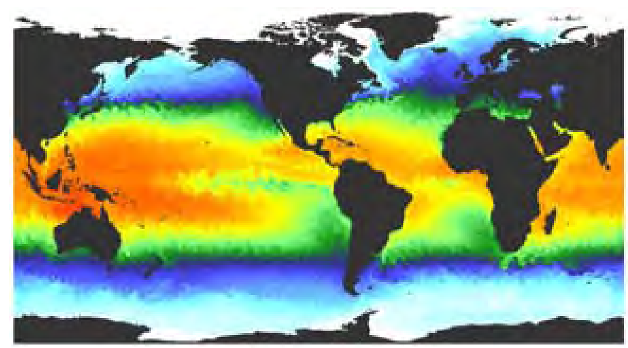
Computer science & engineering: Changing the world

- *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







Business

THE COUNT

Internet, Mobile Phones Named Most Important Inventions

By PHYLLIS KORKKI
Published: March 7, 2009

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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
7. Microprocessors
8. Fiber optics
9. Office software
10. Laser/robotic surgery
11. Open-source software
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

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THE NEW YORK TIMES

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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

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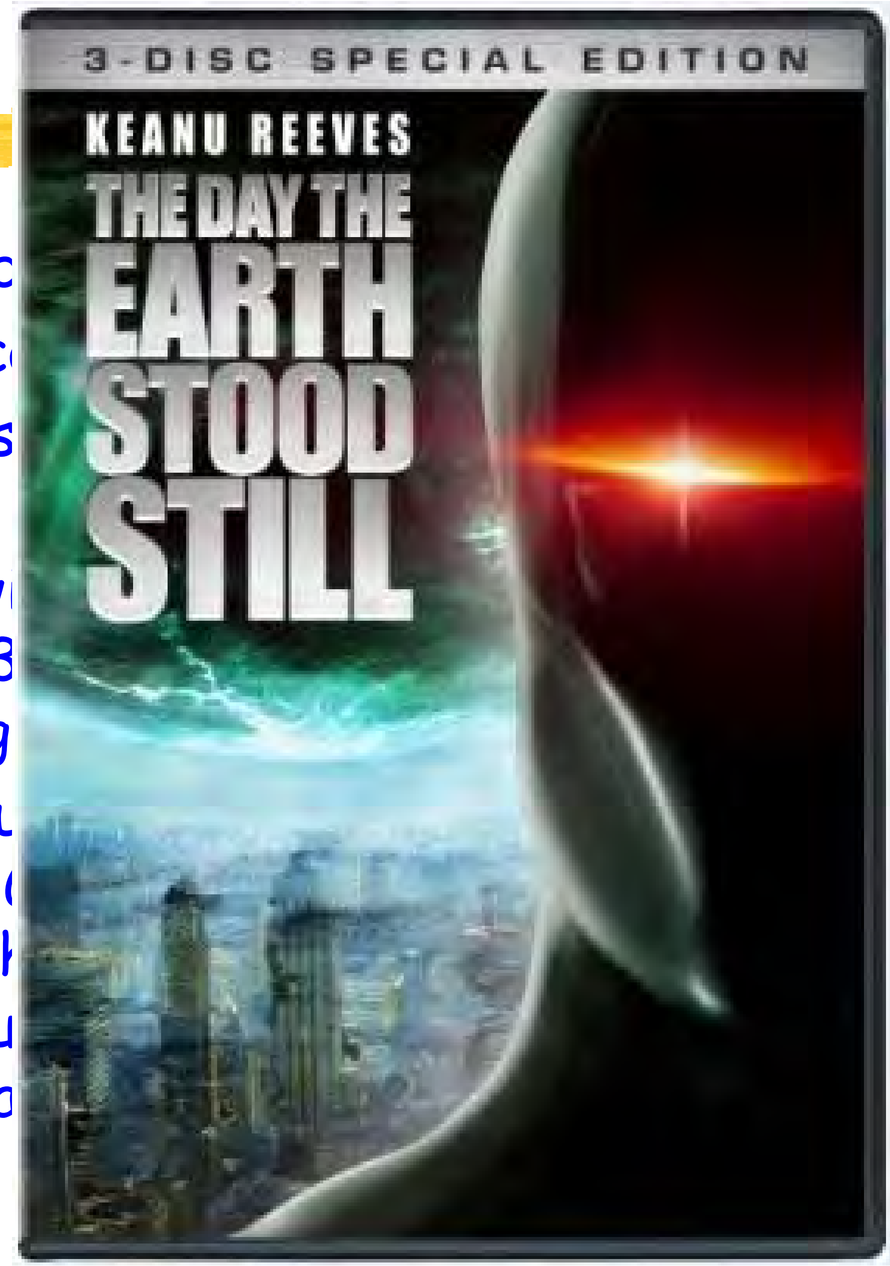
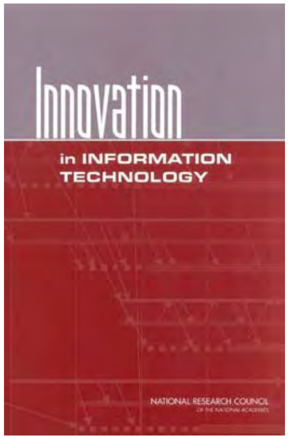
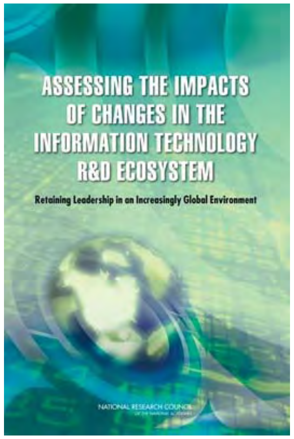
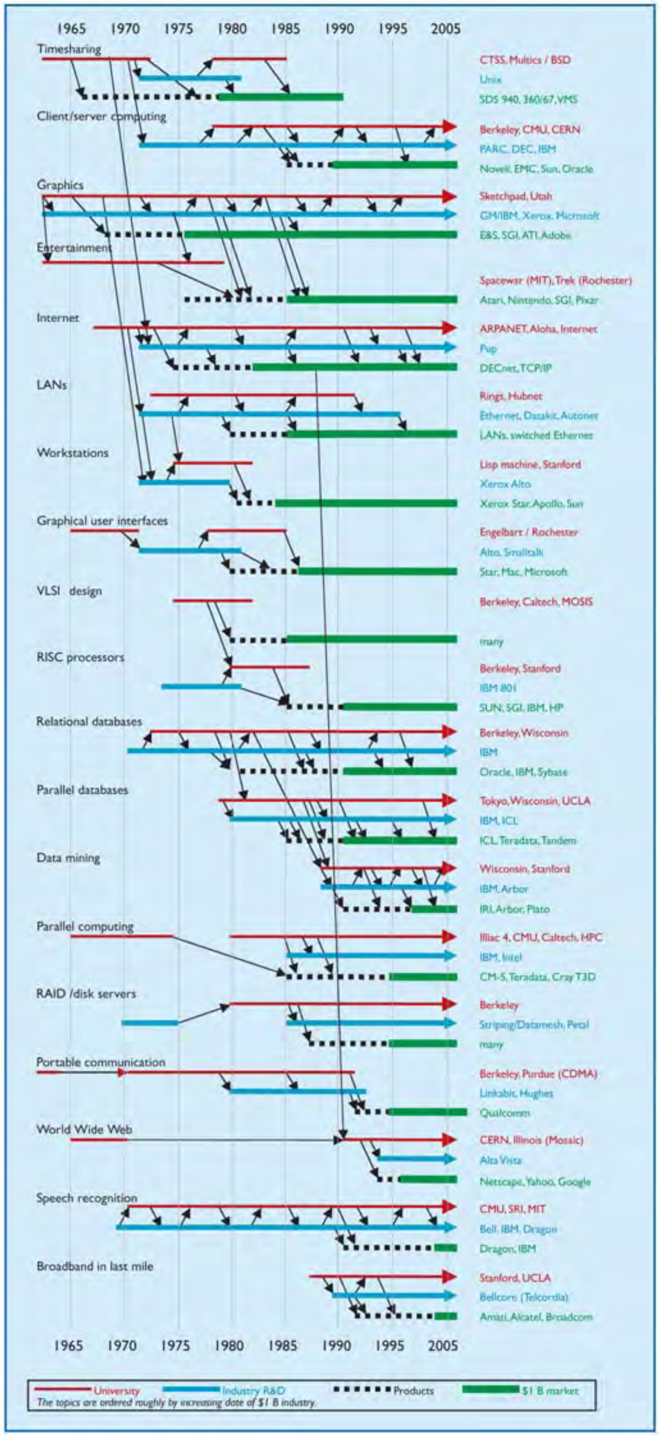


Research has built the foundation

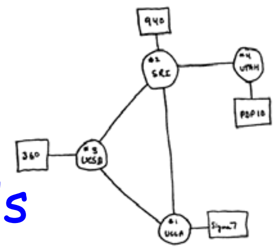


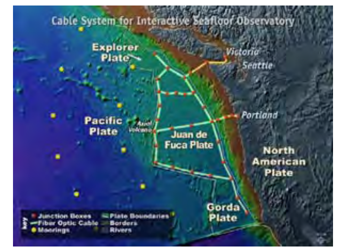


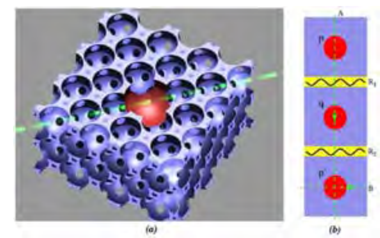


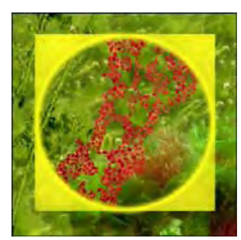
The future is full of opportunity

- 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 of the developing world
- Personalized health monitoring => quality of life
- Neurobotics
- Synthetic biology









Why do students choose the field?

HOME PAGE | TODAY'S PAPER | VIDEO | MOST POPULAR | TIMES TOPICS

The New York Times

Business

WORLD | U.S. | N.Y. / REGION | BUSINESS | TECHNOLOGY | SCIENCE | HEALTH | SPORTS | OPINION | ARTS

Software Jobs Go Begging, Threatening Technology Boom

By AMY HARMON
Published: Tuesday, January 13, 1998

"The pitch I make to high school kids is: Where's the intellectual excitement? Why would you choose civil engineering or mechanical engineering? There's only so much you can do with asphalt.' "

Power to change the world

- People enter the field for a wide variety of aspirational reasons
- http://www.cs.washington.edu/WhyCSE/

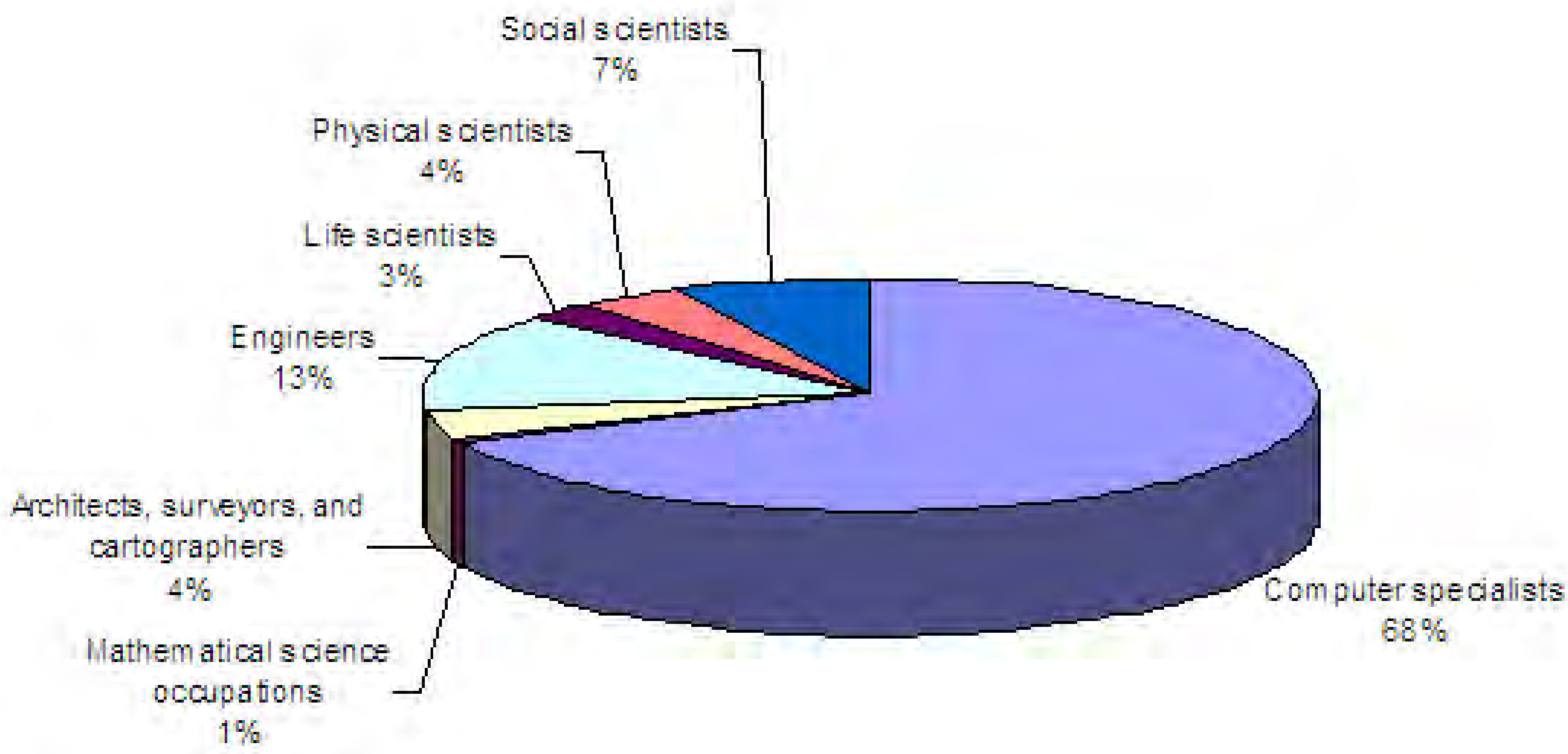
Pathways in computer science

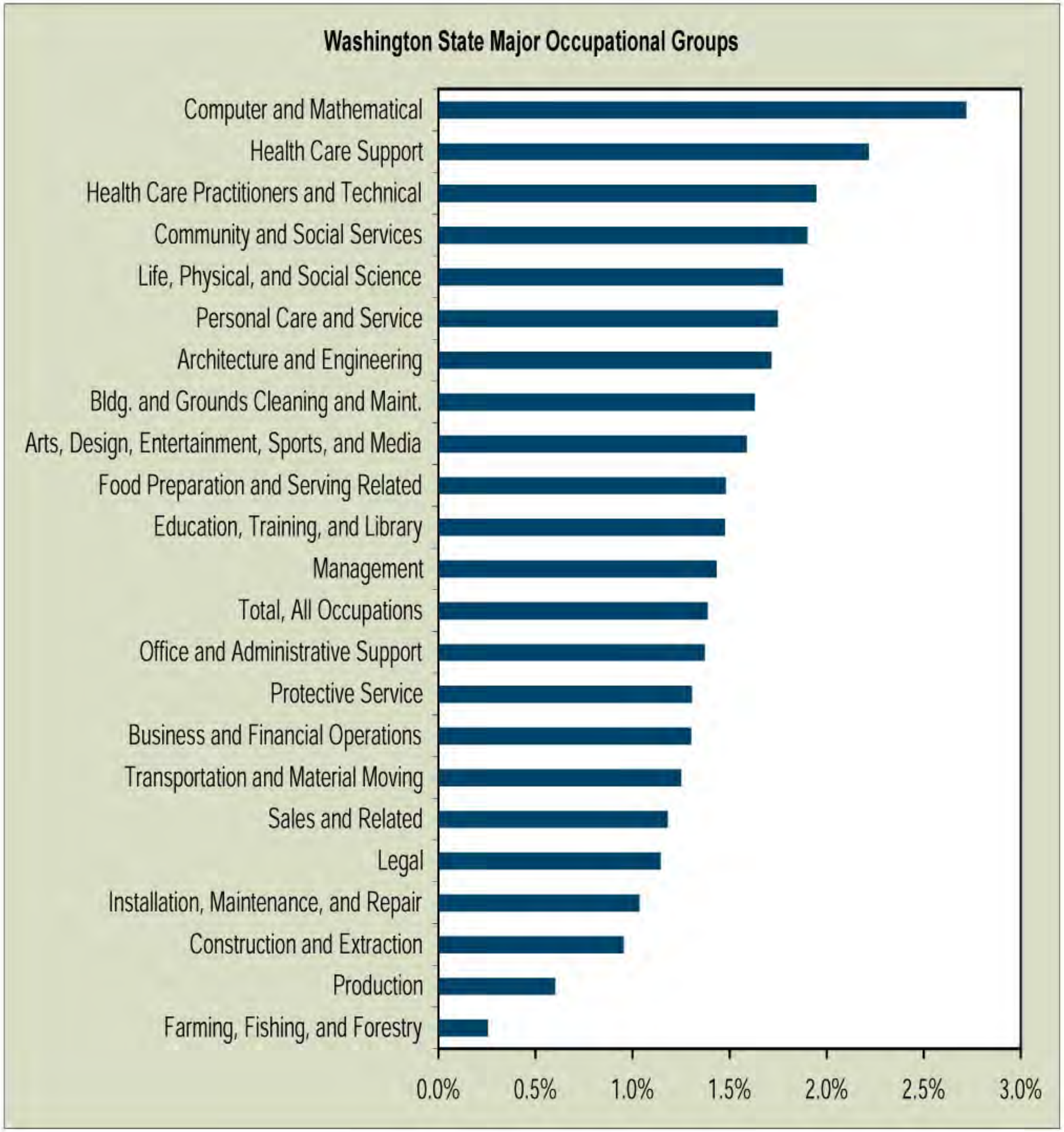
- People pursue diverse careers following their education in computer science
- http://www.cs.washington.edu/WhyCSE/

A day in the life

- Working in the software industry is creative, interactive, empowering
- http://www.cs.washington.edu/WhyCSE/

Science & Engineering Job Growth, 2006-16
(BLS Occupational Employment Projections)

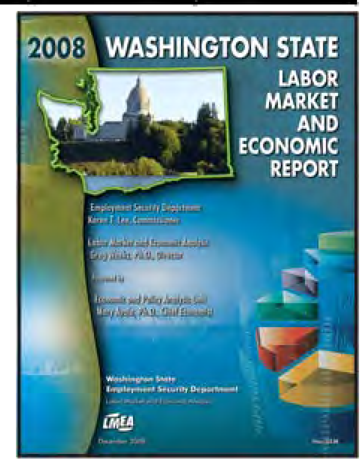




Average annual projected growth rates for all 22 major occupational groups in Washington State, 2006 to 2016

	A	B	C	D	E	F
	Top Ten Occupations for Washington State					
	Occupational Titles	**Preparation Level**	**Estimated Employment 2006**	**Average Annual Growth Rate**	**Average Annual Total Openings**	**Average Wage March 2008**
	Computer Software Engineers, Applications	Bachelor's degree or higher	24,922	2.90%	1,246	$86,829
	Personal and Home Care Aides	Short-term on-the-job training (short demonstration up to one month)	22,909	2.90%	1,199	$22,169
	Computer Software Engineers, Systems Software	Bachelor's degree or higher	13,760	3.40%	779	$92,622
	Computer Programmers	Bachelor's degree or higher	11,134	3.30%	710	$82,798
	Computer Systems Analysts	Bachelor's degree or higher	12,574	2.60%	761	$78,478
	Landscaping and Groundskeeping Workers	Short-term on-the-job training (short demonstration up to one month)	25,577	2.20%	1,000	$27,934
	Multi-Media Artists and Animators	Bachelor's degree or higher	4,608	3.40%	314	$57,515
	Home Health Aides	Short-term on-the-job training (short demonstration up to one month)	10,071	2.70%	418	$21,815
	Medical Secretaries	Moderate on-the-job training (1-12 months)	17,909	2.20%	757	$35,006
	Hairdressers, Hairstylists, and Cosmetologists	AA degree, post-secondary training, or Long-term on the job training	17,658	2.20%	670	$29,753

Occupations are ranked based on the average of two criteria: average annual growth rate for 2006 to 2016 and total number of job openings due to growth and replacement



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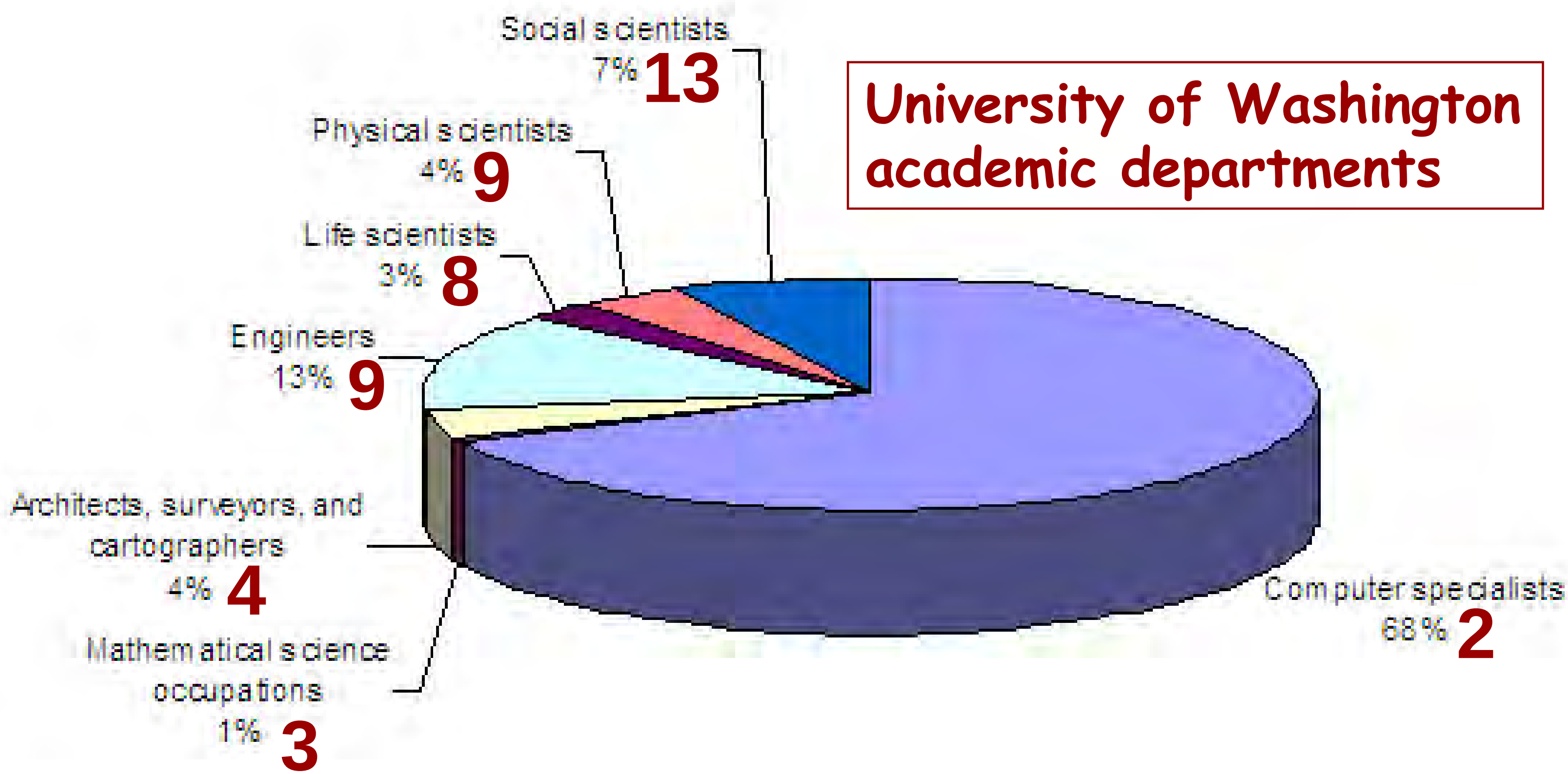
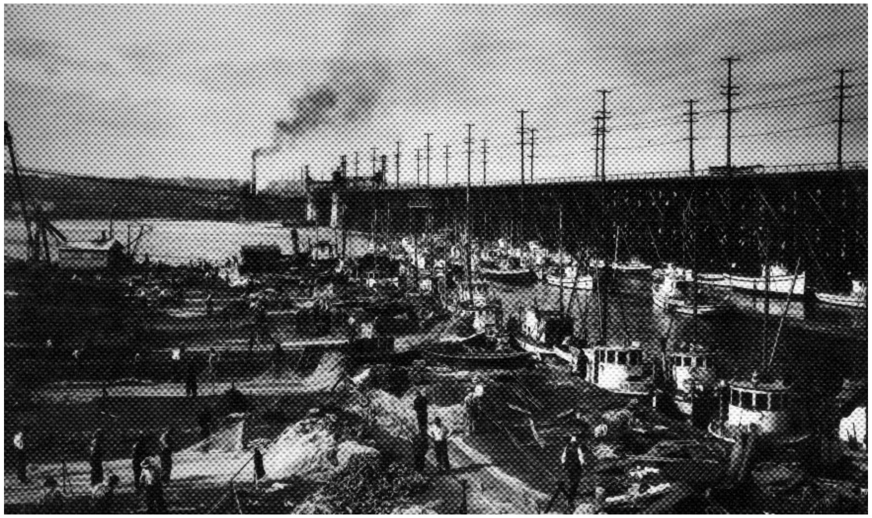
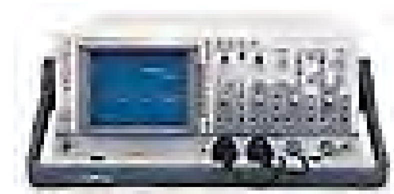


The transformation of our economy, and of educational requirements

- Once upon a time, the "content" of the goods we produced was largely physical

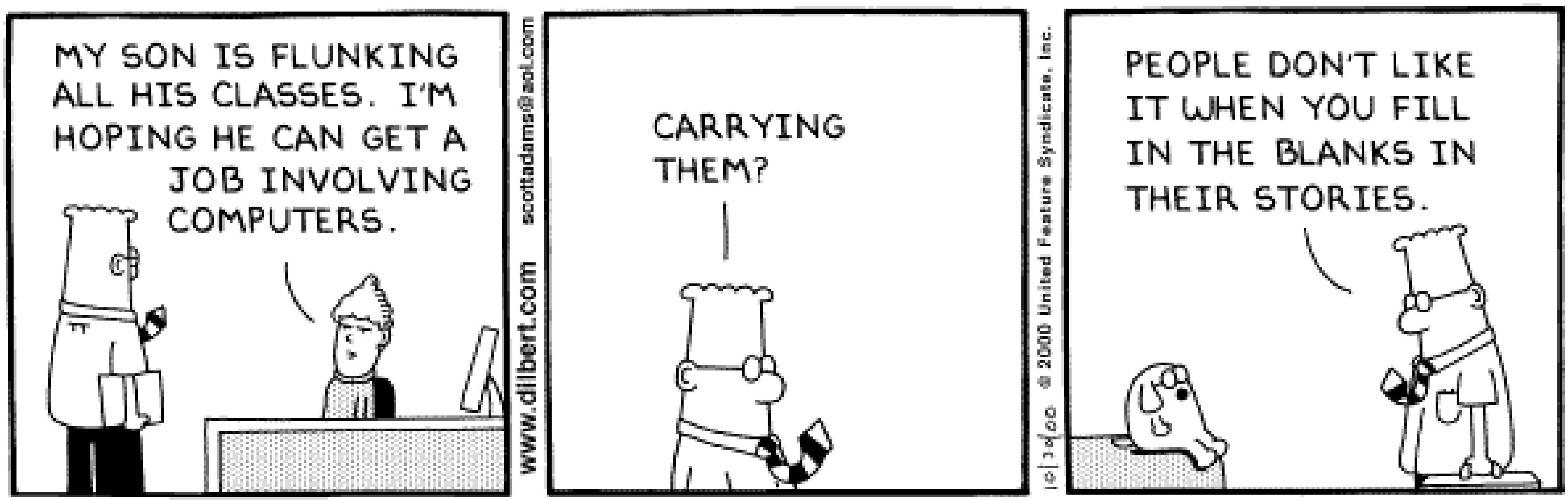


- Then we transitioned to goods whose "content" was a balance of physical and intellectual



- In today's knowledge-based economy, the "content" of goods is almost entirely intellectual rather than physical

- What kind of education is required to produce a good whose content is almost entirely intellectual?



Education in Washington: Where do we stand among the states?

The Nation's S&E Top 5
(Workforce intensity, all S&E occupations, 2006)

1. Virginia
2. Massachusetts
3. Maryland
4. **Washington**
5. Colorado

	ENGINEERS	LIFE/PHYS. SCIENTISTS	COMPUTER SPECIALISTS
PEERS:	2	3	6
NATION:	3	7	8

HIGHER EDUCATION:
(BACHELOR'S PRODUCTION, S&E GRADUATE PARTICIPATION, S&E PhD PRODUCTION)

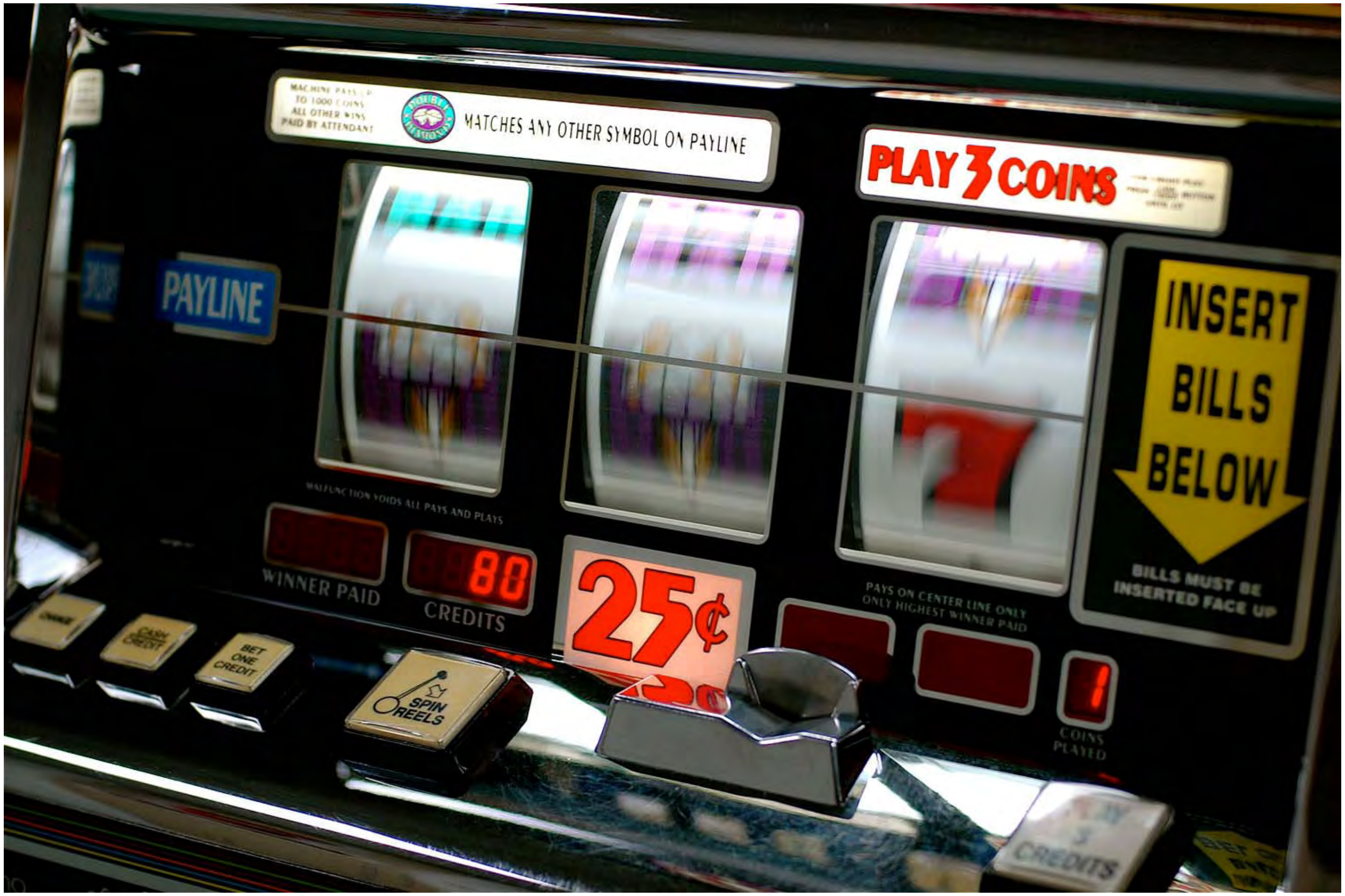
	BACHELOR'S PRODUCTION	S&E DEGREE PRODUCTION	S&E GRADUATE PARTICIPATION	S&E PhDs AWARDED
PEERS:	8	7	10	10
NATION:	36	31	46	27

K-12 ACHIEVEMENT:
(2007 8^{TH} GRADE NAEP & GRADUATION RATE FROM POSTSECONDARY.ORG)

	HIGH SCHOOL GRADUATION
PEERS:	7
NATION:	32

Technology Alliance

Washington State is gambling with its future!



How about you?

This morning

- The nature of eScience
- The advances that enable it
- Scalable computing for everyone
- Networking in the West
- “There’s only so much you can do with asphalt”
- “What happens in Vegas, stays in Vegas” – don’t gamble with the future of your region and of the kids who grow up there

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