
Economies of Scale
HPC into the Next Millennium
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SMABY GROUP


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Game Plan

Supercomputing

- ✓'What It Was Ain't What It Is'
- ✓Fifty Years of Evolution
- ✓Mainstreaming HPC
- ✓2001 and Beyond
- ✓Q & A

Conference on High Speed Computing - April 23, 1998
Salishan Lodge

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What *Was* a Supercomputer?

The world's fastest computer
. . .at any given point in time.

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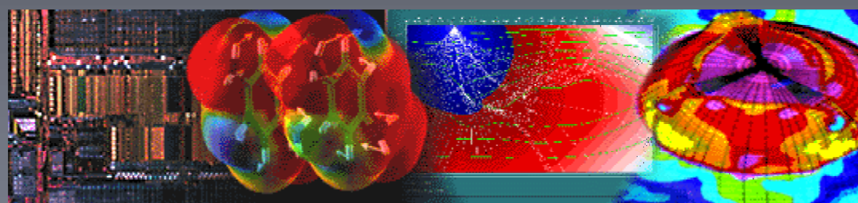
Today's Supercomputer

A platform-independent computational visualization tool for the imagination . . . . a time machine for simulating natural phenomena.



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Original Apps

- ✓Calculate trajectories
- ✓Crack codes
- ✓Design weapons

(German V-2)

(Colossus)

(Manhattan Project)

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The Evolution of Supercomputing The Forties

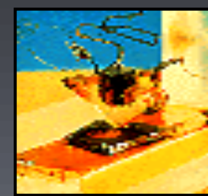
von Neumann defines first stored-program computer . . .

Grace Hopper discovers the first computer bug - a moth stuck between relays

1945

ENIAC - first digital computer fills 30x50 room, weighs 30 tons, 18,000 vacuum tubes, 1000 memory bits, 7500 ops

1946



Semiconductor revolution begins - transistor soon supplant vacuum tube

1947

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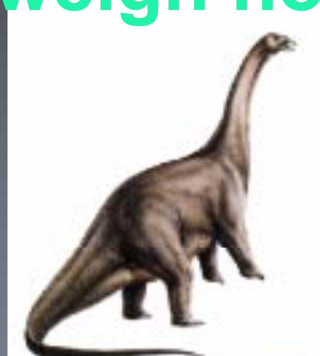
"Computers in the future may weigh no more than one-and-a-half tons."



Popular Mechanics (1949)

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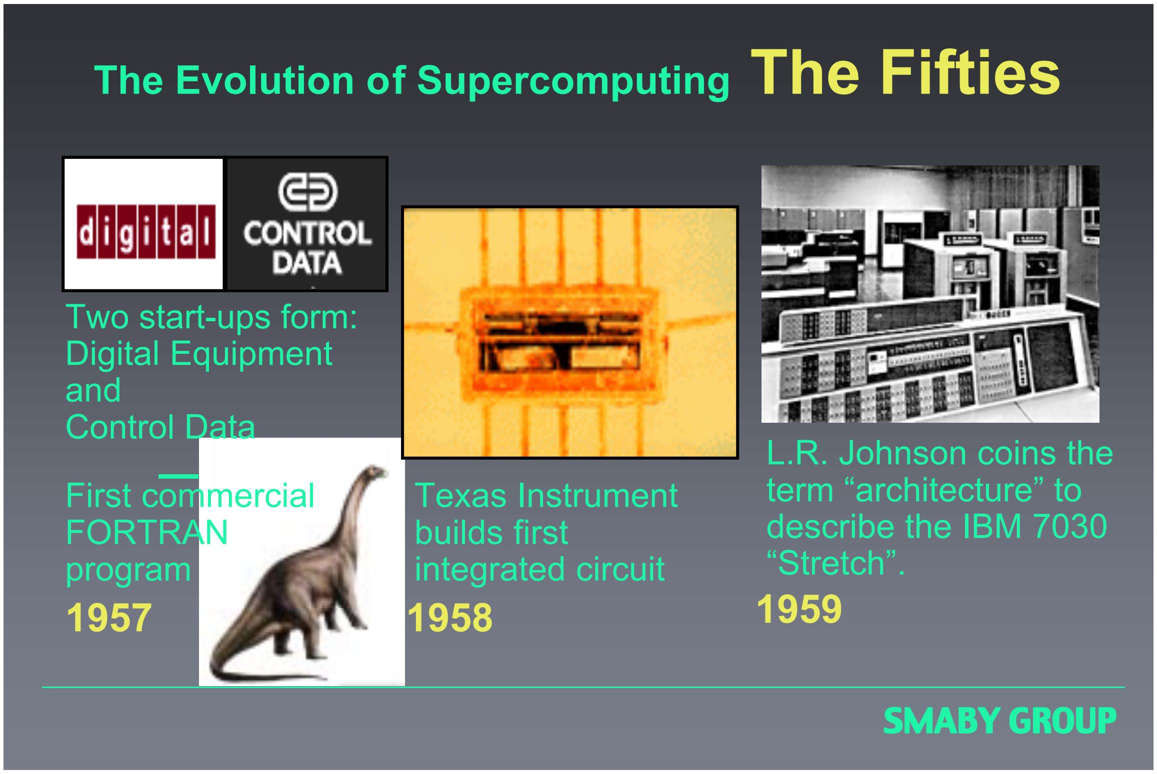
The Evolution of Supercomputing The Fifties
digital
CONTROL DATA
Two start-ups form:
Digital Equipment
and
Control Data
First commercial
FORTRAN
program
1957
Texas Instrument
builds first
integrated circuit
1958
L.R. Johnson coins the
term “architecture” to
describe the IBM 7030
“Stretch”.
1959
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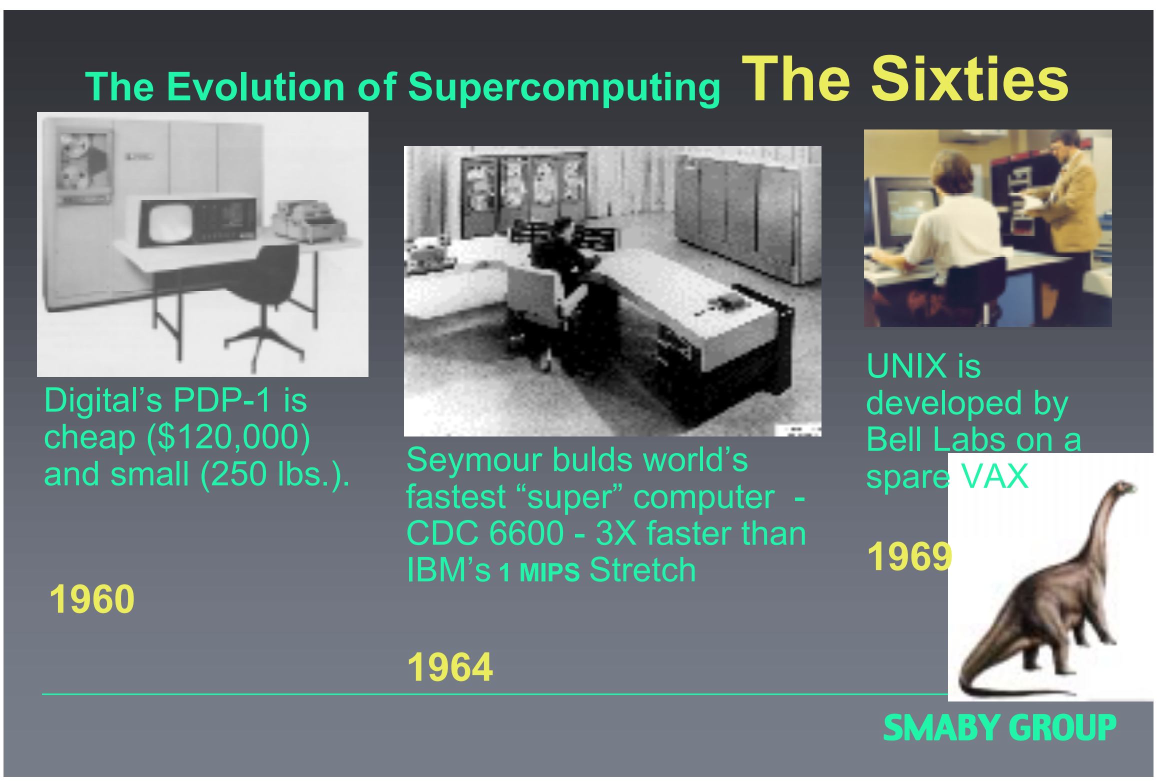
The Evolution of Supercomputing The Sixties
Digital’s PDP-1 is
cheap ($120,000)
and small (250 lbs.).
1960
Seymour bulds world’s
fastest “super” computer -
CDC 6600 - 3X faster than
IBM’s 1 MIPS Stretch
1964
UNIX is
developed by
Bell Labs on a
spare VAX
1969
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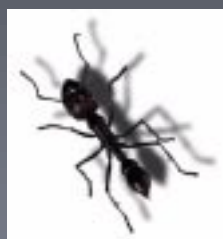
"But what the hell is it good for?"

Anonymous IBM Engineer
Commenting on the computer chip (1968)



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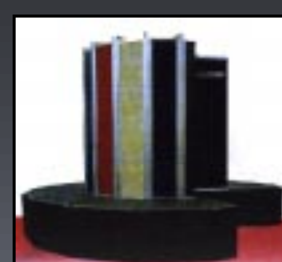
The Evolution of Supercomputing The Seventies

Seymour Cray leaves Control Data to start Cray Research. . .

1972



Cray-1 debuts. . . all R&D costs recovered in first sale to Los Alamos

1976

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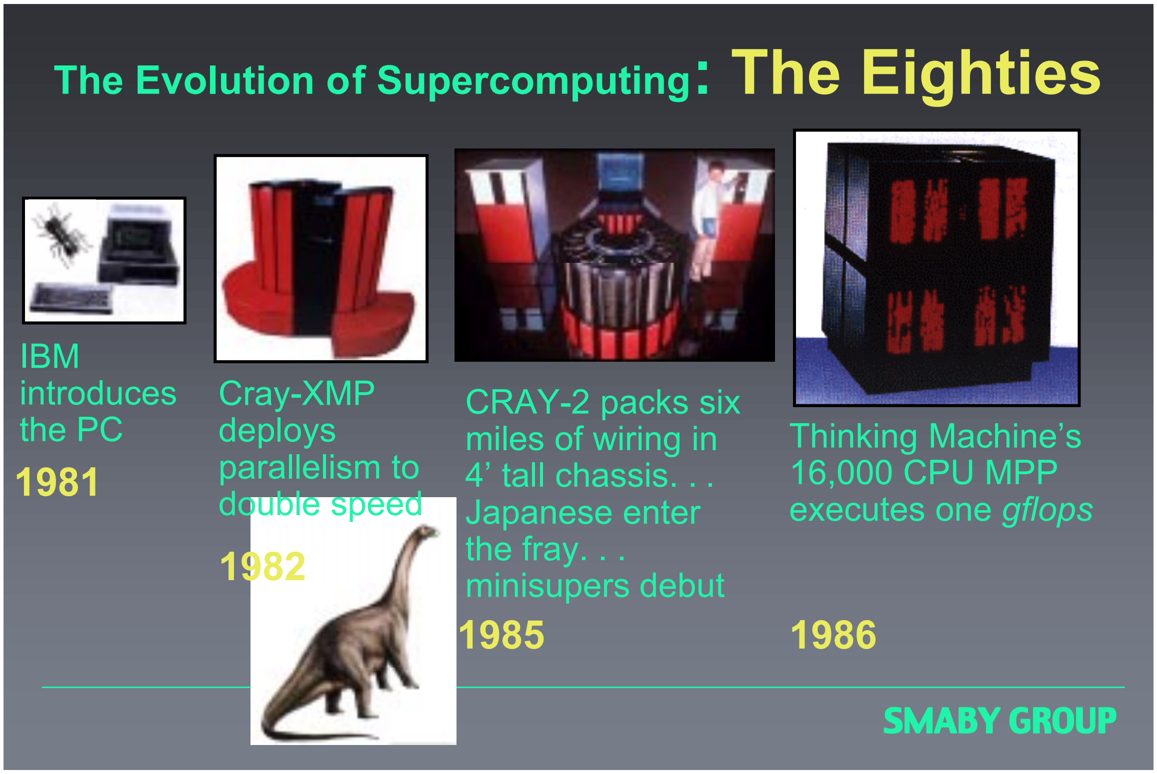
The Evolution of Supercomputing: The Eighties
IBM introduces the PC
1981
Cray-XMP deploys parallelism to double speed
1982
CRAY-2 packs six miles of wiring in 4' tall chassis. . . Japanese enter the fray. . . minisupers debut
1985
Thinking Machine's 16,000 CPU MPP executes one gflops
1986
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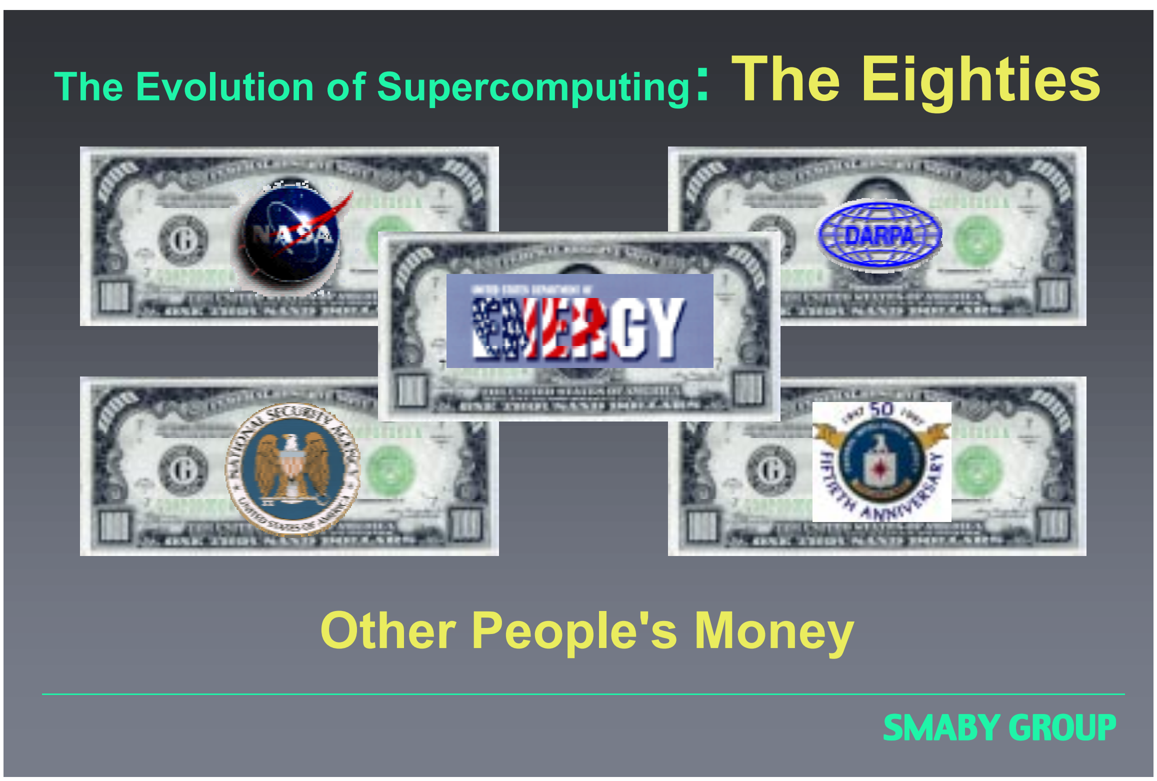
The Evolution of Supercomputing: The Eighties
NASA
DARPA
ENERGY
Other People's Money
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Collapse
of the
Evil Empire
The Evolution of Supercomputing
The Eighties
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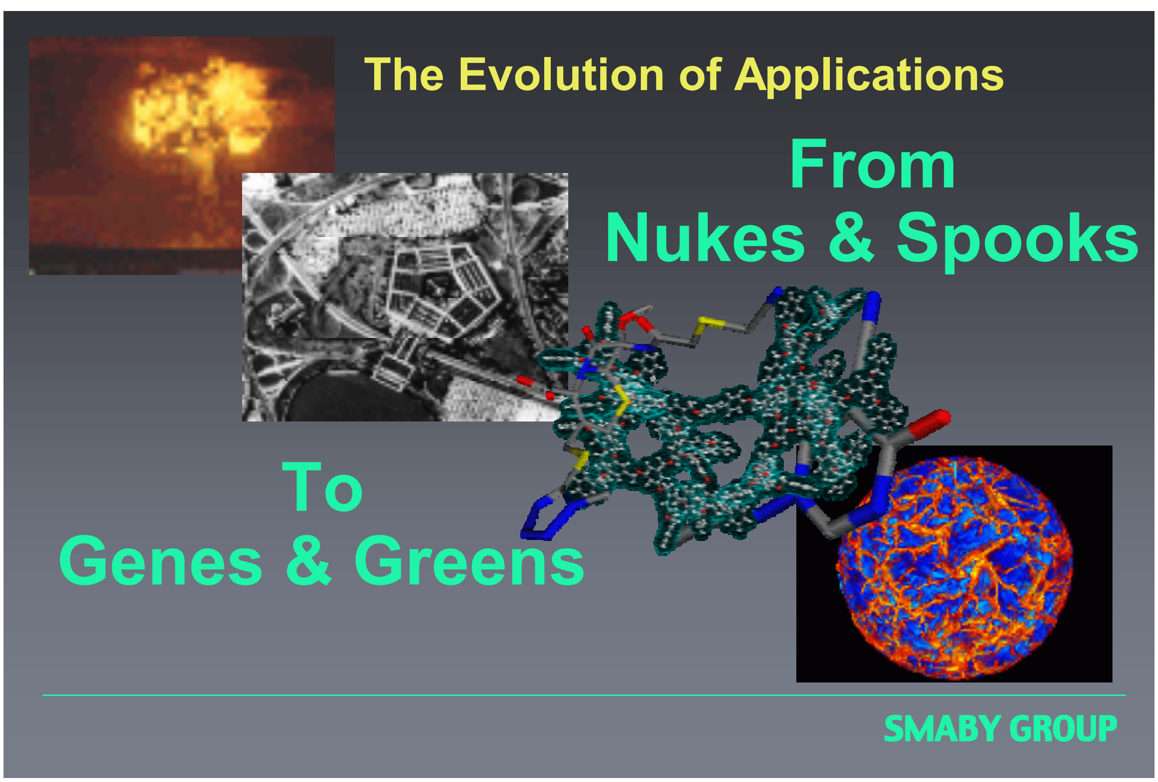
The Evolution of Applications
From
Nukes & Spooks
To
Genes & Greens
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From Nukes and Spooks . . .
SPIRE
Spatial Paradigm for Information Retrieval and Exploration
FIFTIETH ANNIVERSARY
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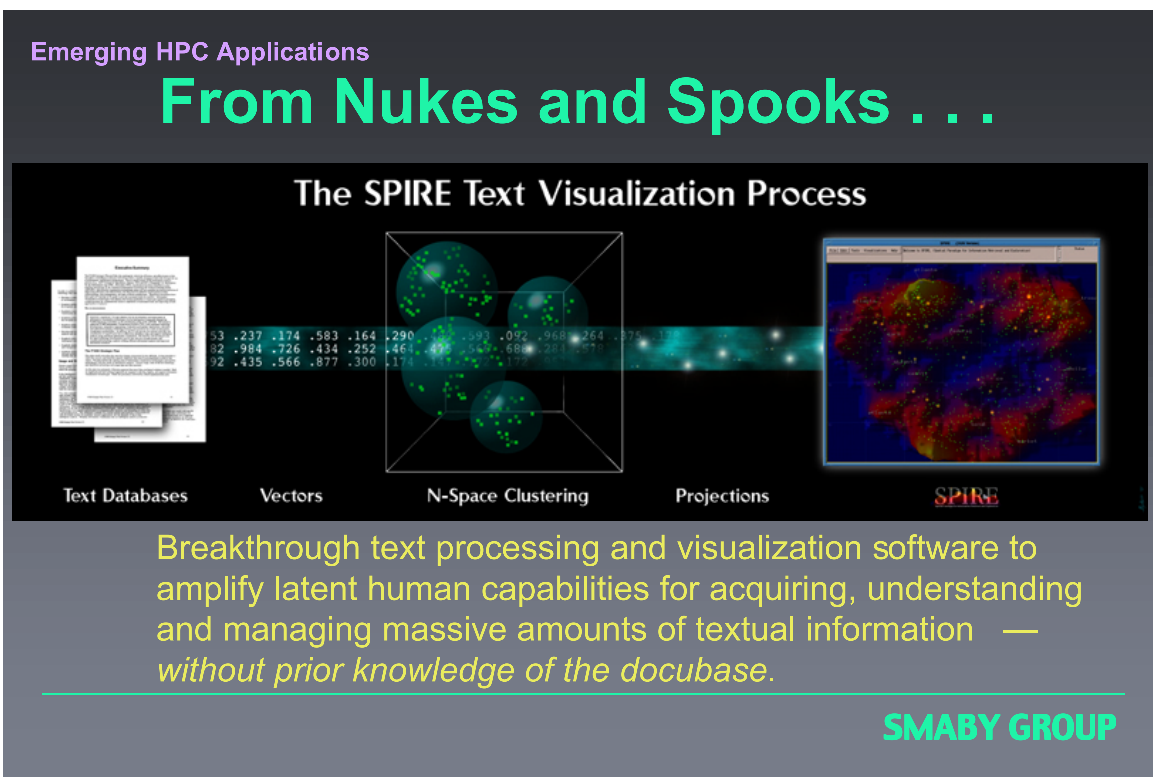
Emerging HPC Applications
From Nukes and Spooks . . .
The SPIRE Text Visualization Process
Text Databases
Vectors
N-Space Clustering
Projections
SPIRE
Breakthrough text processing and visualization software to amplify latent human capabilities for acquiring, understanding and managing massive amounts of textual information — *without prior knowledge of the docubase.*
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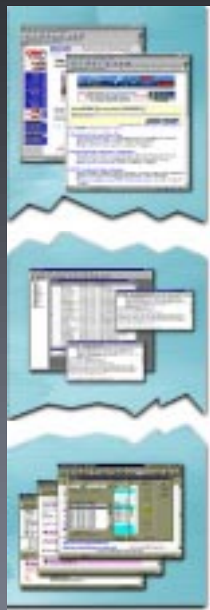
Emerging HPC Applications

Competitive Intelligence



A systematic business methodology for gathering and analyzing information about your competitors, customers, suppliers, and markets to further your own company goals.

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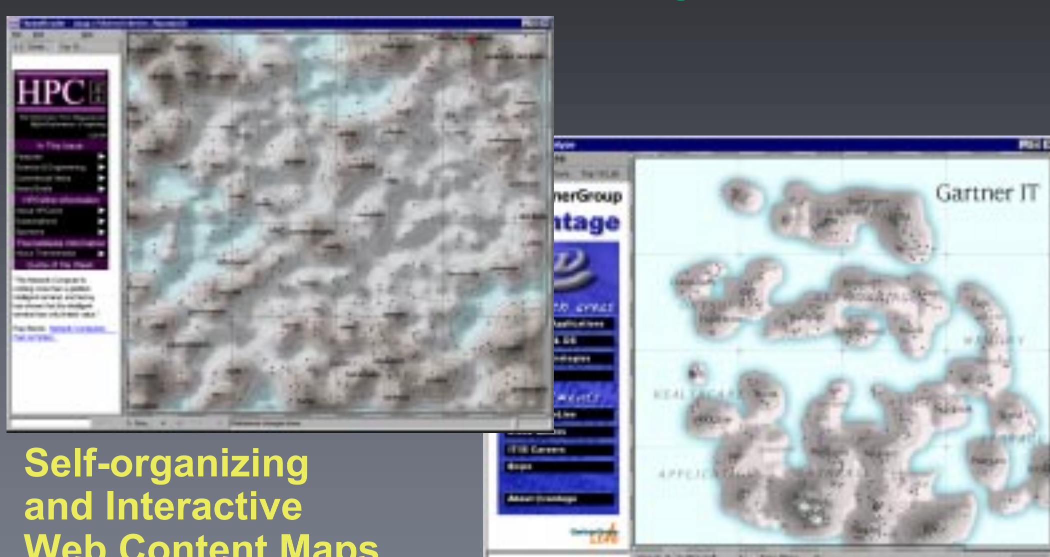
ForeKnowledge™



Self-organizing and Interactive Web Content Maps

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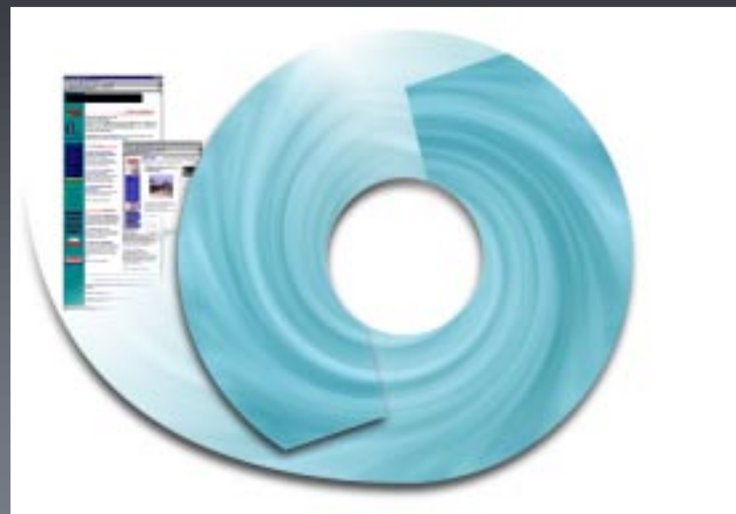
Common Knowledge™

A self-organizing knowledge reservoir that dynamically receives and maps intellectual corporate assets sent to it via email.



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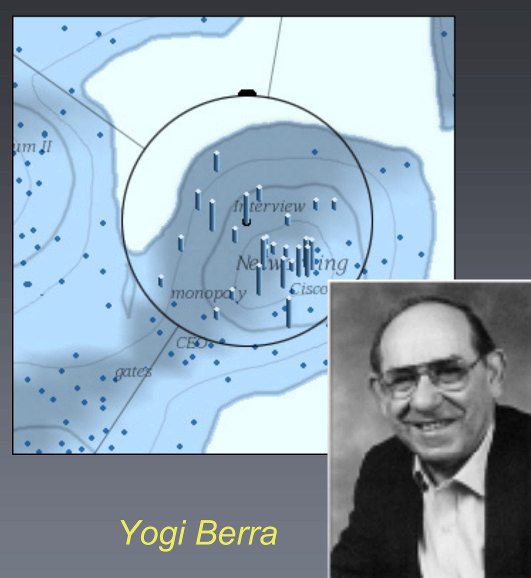
Emerging HPC Applications

Competitive Intelligence

"You can see alot by watching."

Yogi Berra



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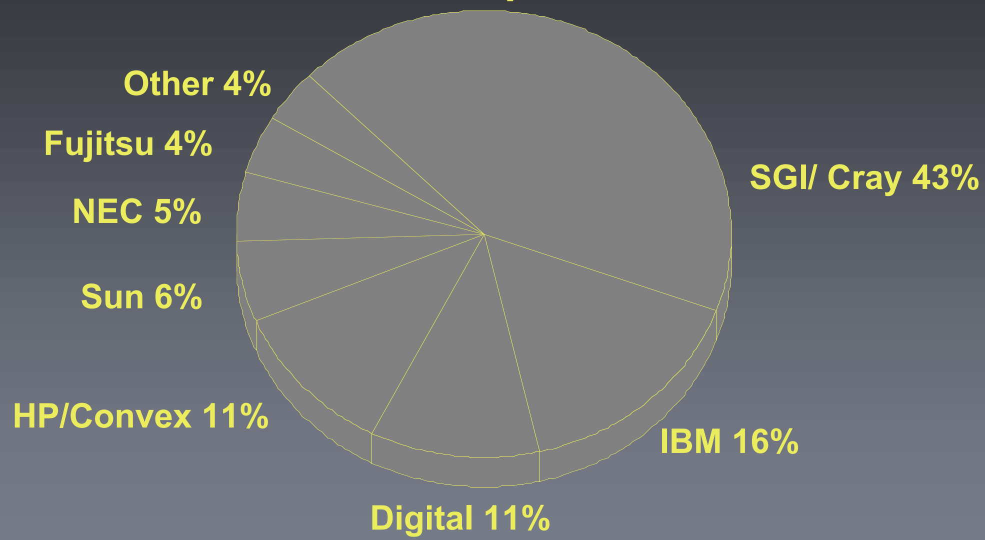
Market Scale
1997 - $2.18B



Scientific/Engineering/Technical HPC Market Size - Worldwide

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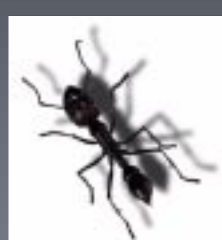
The Evolution of Supercomputing
Predictions: 2001 and Beyond

1) The Ants Prevail



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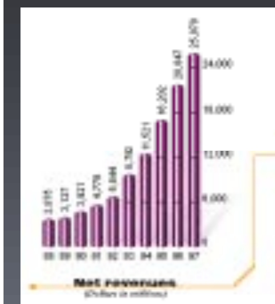
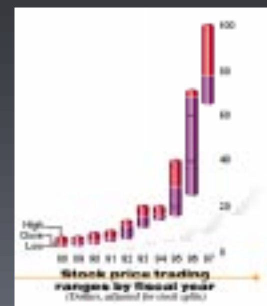
Economies of Scale





Merced Chip (P7)

Debuts in 1999 at 600 Mhz
SPECfp95 > 100
8 Instructions @ Cycle
Scales 1Ghz to 4Ghz
Design/Fab Cost >$2.5B
Cost to Produce ~$100
Intel Market Cap ~$125B

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The Evolution of Supercomputing

Predictions: 2001 and Beyond

2) Cray Makes Like Harley

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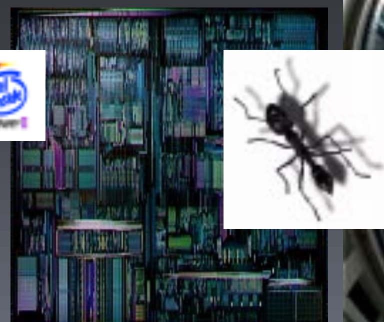
The Evolution of Supercomputing: Today

Cray's Origin2000 scalable system stacks processors like LEGO blocks to achieve increased performance



Emergence of Intel's off-the-shelf Pentium and IA-64 processors

Sandia links 9072 Intel Pentium Pro chips to top one *teraflops*

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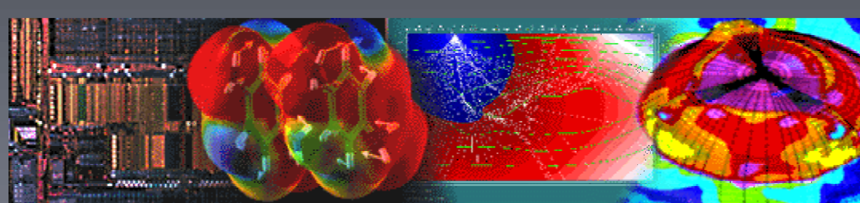
The Evolution of Supercomputing
Predictions: 2001 and Beyond

3) Apps Rule



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Hot HPC Apps

- ✓Model new drugs
- ✓Design exotic securities
- ✓Map the human genome
- ✓Create Hollywood special effects
- ✓Web-based knowledge management
- ✓Designing stuff (cars, airplanes,golf clubs)

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The Evolution of Supercomputing

Predictions: 2001 and Beyond

4) Money Still Talks

"The real limitations come from money, not physics."

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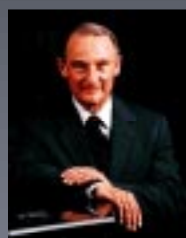
PETAFLOP COMPUTING?



"We don't have too far to go (with circuit technology) until we get to the size of biological molecules . . . I think we'll be coming face-to-face with the life force."

Seymour Cray (5/30/96)

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The Evolution of Supercomputing
2001 and Beyond

"The future isn't what it used to be."

Arthur C. Clarke

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Q & A
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Conference Presentation by William Trimmer
The Other Side of Computing by William Trimmer Belle Mead Research, Inc.

Phone 908 359 0012, Fax 908 359 2094 58 Riverview, Belle Mead, NJ 08502 USA

Web trimmer.net, Email W.Trimmer@IEEE.org

Abstract

Computation takes us to a world of its own. An intangible world where incantations create, modify, destroy, and build castles in the sky. In this world huge power can be generated, information neatly trimmed for a purpose, and couriers sent to other castles at nearly the speed of light.

What computation and software can not do is interact with the real world. Interaction with the tangible takes forces and photons and electromagnetic fields and sensors.

Information and computational ability is intriguing and of great utility, but it can not tie your shoe, or fry an egg.

The original ingenious and intelligent computing systems were mechanical, things such as clocks that chimed and displayed dancing figures on the hour. Moving electrons in micro computers are now doing a superb job of providing the intelligence. Complex calculations and decisions are inexpensive. It is now the mechanical devices needed to interface electronics to the world that are expensive.

But things are about to change. This talk discusses the proliferation of micro mechanical devices. A complete gear syste
m, or a motor, or a chemical sensor can be made that is 1/1000 the size and cost of a CPU or memory chip. A revolution in our ability to interface computing power to the real world is about to begin.

Computation is to micro mechanical devices as Yin is to Yang. One is soft and intangible, the other active and tangible. The real promise is in their combination.

Prelude

There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy. [Ref 1]

Alessandro Volta, an Italian Physicist (1745 to 1827), experimented with dissimilar metals in aqueous solutions, and found a weak source of current. Andre Marie Ampere, a French Physicist (1775 to 1836), passed currents through wires and discovered the relationship between currents and magnetic fields. Imagine now, if you can, these gentlemen walking through your house. What wonders we take for granted. Did their genius prepare them to comprehend the computer on your desk?

The world of science and engineering is still unfolding wonders. One recent development is the ability to make micro mechanical devices. Motors the diameter of a human hair and sensors the size of a grain of salt are enabling inexpensive systems that can interact with our world on a new scale.

Surprisingly, the time scale from conception to utilization has been collapsing. Nikola Tesla and Thomas Alva Edison developed practical electric motors in the 1880's, about a hundred years after Volta and Ampere's work. The micro comb drive motor was described in 1989, and is currently being used in automobiles as an airbag sensor. This micro development took less than a dozen years from conception to full scale implementation.

There are several reasons for the rapid advances of micro devices (also called MicroElectroMechanical Systems, MEMS, micromechanics, Micro System Technologies, mst, and Micro Machines). One, manufacturers of these micro devices are using well established technologies. The electronics industry provides sophisticated process chambers for making micro comb drive motors and a host of other micromachined devices. The machine tool industry has developed micro Electro Discharge Machining, EDM, techniques and single point diamond machining tools that can fabricate minuscule mechanical devices. The plating and molding communities have enabled LIGA and other replication processes that can replicate extremely fine structures. Two, there are a number of people skilled in these base technologies who are looking for new challenges. And three, established companies and the investment community recognize the potential of new technologies. The micro technologies are exploding forth using a well established infrastructure.

Volta and Ampere worked quietly in their labs. Edison worked with a small group of researchers. Currently I estimate there are 10,000 people working on micro-mechanical projects. Much of this current effort is developing products.

While there are more things in the universe that one can imagine, we can push the boundaries. Your help exploring the applications and engineering and science of micro devices is welcome.

Introduction

Micromechanics is an extremely broad field, a field that will touch most aspects of our grandchildren's lives. This field encompasses all of the current technologies -- only it is concerned with a smaller dimensional scale. And micromechanics promises applications in all disciplines. Richard Feynman well conveyed the excitement of our new discipline:

"I imagine experimental physicists must often look with envy at men like Kamerlingh Onnes, who discovered a field like low temperature, which seems to be bottomless, and in which one can go down and down. Such a man is then a leader and has some temporary monopoly in a scientific adventure. Percy Bridgman, in designing a way to obtain high pressures, opened up another new field and was able to move into it and lead us all along. The development of ever higher vacuum was a continuing development of the same kind.

"I would like to describe a field, in which little has been done, but in which an enormous amount can be done in principle. This field is not quite the same as the others in that it will not tell us much of fundamental physics (in the sense of, "what are the strange particles?" but it is more like solid-state physics in the sense that it might tell us much of great interest about the strange phenomena that occur in complex situations. Furthermore, a point that is most important is that it would have an enormous number of technical applications.

"What I want to talk about is the problem of manipulating and controlling things on a small scale." [Ref2]

Below is discussed the earlier perceptions that hindered the development of small mechanisms, our current field and needs, and a look at our future.

The Genesis

Perhaps things normally start small, and grow. Man's habitats have grown from houses, to buildings, to skyscrapers. Our ability to travel has increased from a few miles on foot, to horses, to trains, and now we can encircle the world in a few days. Individually we work to make large accomplishments in hopes of enormous success. We are enthralled with the big and sign)ficant and substantial.

The insignificant, insubstantial, and minuscule is usually beneath our concern.

And yet.

A dozen years ago, I was trying to persuade a machinist to build a very small structure. He listened patiently for awhile and then said, “Why do you want something small, a toy? I can make you something that is big and good.” In his mind, most people’s minds, small things were cheap and no more than a toy. When H. A. Rowland (1848 to 1901, professor of physics at the Johns Hopkins University, Baltimore) went to make very small and accurate grooves for diffraction gratings, he used large machines and buried them in even larger vaults for thermal stability. Ten years ago an eminent colleague at Bell Laboratories looked me in the eye, and said, “Your micro things will never amount to anything. Large objects will always do a better job at a lower cost. “ This was very strongly the feeling at this time.

Even Feynman responded with good natured jesting to critics of small machines. In his famous talk There’s Plenty of Room at the Bottom, given at the American Physical Society meeting in 1959 he says “What would be the utility of such machines? Who knows? Of course, a small automobile would only be useful for the mites to drive around in, and I suppose our Christian interests don’t go that far.” [Ref 3] And in his 1983 talk, Infinitesimal Machinery, at the Jet Propulsion Laboratory he says, “I also talked in the 1960 lecture about small machinery and was able to suggest no particular use for the small machines. You will see there has been no progress in that respect. “ [Ref 4]

Originally, the ingenious and intelligent systems were mechanical, things such as clocks that chimed and displayed dancing figures on the hour. Electronics is now doing a superb job of providing this intelligence. Complex calculations and decisions have now become inexpensive. Presently, it is the mechanical devices required to interface electronics to the world that are expensive. Fortunately the new micromechanical devices integrate well with electronics: one providing the intelligence and one providing the hands.

Electronics has led much of the recent development of micromechanical devices by providing many of the tools and techniques, making the rapid advances possible. This partnership is to great advantage.

Surprisingly, mechanical systems can now be smaller and less expensive than electrical systems.

There is an increasing breadth of microfabrication techniques enriching our capabilities. Examples include LIGA, EDM, precision machining, plating, and molding. To ignore the wide range of fabrication techniques available is to limit oneself.

Yet how did things insignificant in size gain a purpose?

Perhaps Johann Gutenberg gave an indication of the usefulness of small mechanical devices. Gutenberg means good mountain, and indeed, in 1456 he set in motion a mountain of small mechanical devices (individual movable type) for the good of mankind. One interesting aspect of his work is the interchangeability - a few standardized units are made that can be combined to meet most needs. This concept may be useful for our micro devices.

Ideas, excellent ideas, often seem to gain a life of their own. Like grass growing through the pavement, they seem to search for fertile minds and the correct opportunities. Often key ideas are invented in several different places. For example, Pi Sheng of China made movable type of Chinese characters from clay in 1040. And Korea molded metal type in sand in 1361. Gutenberg was just one of several who expressed the idea of moveable type. If you have a good idea, I encourage you to develop it now; there is a high probability others share your idea.

Until recently, minute mechanical systems have developed at a stately pace. For years the watch makers' art has represented the limits of our micro excursion. And the practitioners ofthe watch industry have succeeded admirably. For example, the motor in a wrist watch has high efficiency, runs for years (even after being dropped), and costs less than a cup of coffee. Yet, when I was talking with a gentleman who had designed many of the watches we wear, he said, "I have spent my life trying to make smaller mechanisms, and when you show me something really smaller, I do not know what to do with it." This was a common response to motors the diameter of a human hair.

The Present

The rapid race to more clever micro machines has just begun.

The earlier disdain for the small and insignificant is gone. Now there is a growing excitement about the micro.

Gone are my fears that the micro field would grow on 'isn't that neat' and then die when no purpose was found. Enough people now recognize the importance of micro science and engineering and product development to ensure the field.

Things insignificant in size do have a grand purpose.

Yet it is difficult to realize the breadth of this field of micro mechanical devices.

Most advances represent a specific technology. The Scanning Tunneling Microscope for example, gives us the ability to detect and perhaps manipulate atoms. High temperature superconductors hold the promise of efficient power transmission and novel electronic

circuits. The diesel engine gives us a source of mechanical power. Each of these is an important advance of a single thing.

The field we are contemplating here today is vast beyond our normal concerns. It is the science and engineering and development and commercialization of a whole new realm of human enterprise.

I defy you to think of a large scale, macro discipline in science or engineering that does not have a small scale, micro equivalent. Your challenge, should you decide to accept it, is helping to image the macro into the micro.

The Future

What will the field of micro mechanical devices be like in a thousand years?

The first thing to do after such a question is to recover from the shock of being asked.

Yet, it is useful to ponder the potential.

To stir the debate, several predictions are given below.

One, micromechanical devices will become omnipresent. They will fill the niches of our lives. Can you find fundamental limitations that will keep microdevices from becoming inexpensive and readily available? If not, why not their proliferation?

Clayton Teague of the National Institute of Standards and Technology in the U.S. gave an interesting presentation [Ref 5] on Feynman's tiny hands. Feynman proposed small hands manufacturing smaller hands, which in turn manufacture even smaller hands. This ever smaller procession of tiny hands can then be used to manufacture large numbers of useful micro devices. In this talk, Clayton Teague also discussed John von Neumann's conjecture on the self replication of complex systems. [Ref 6] At what point can our micro devices start to self replicate themselves? A self replicating micro system needs careful consideration.

Two, unless there is a need for something to be large, it will be small. There are many reasons for this. Material costs are less for small systems. The systems use less space, and small systems can perform functions more rapidly. Because of the small size and low cost, multiple systems can be used for one function, increasing the robustness and reliability. Because of their size, these microsystems can be dispersed; instead of the large devices used now, many micro devices can be used to give a finer "rained sensing and manipulation of our world. Very few things need to be large. But hopefully in the year 3000, dinner will still be large.

Three, the worlds of the micro (millimeter to micron) and the nano (micron to Angstrom), electronics, and genetic engineering will evolve into closely interrelated fields. Already micro devices are helping to image and handle molecules, and nano technology is making small tubes and balls that hold the promise of mechanical structures.

Conclusion

As micro electronics has made possible much of the micro mechanical revolution, so now micro mechanical devices will extend the reach of electronics, and carry electronics into new places.

Micro computers & computation are to micro mechanical sensors & actuators as Yin is to Yang. One is soft and intangible, the other active and tangible. The real promise is in their combination.

Please join us in this great adventure.

William Trimmer

References

1. William Shakespeare, Hamlet, Prince of Denmark Act I, Scene V.

2. “There’s Plenty of Room at the Bottom,” by R. Feynman, Caltech’s Engineering & Science magazine, February, 1960. (Reprinted in Micromechanics and MEMS: Classic and Seminal Papers to 1990, Edited by W. Trimmer, the IEEE Press PC4390-QCL, ISBN 0-7803-1085-3, January 1997, page 3.)

3. “There’s Plenty of Room at the Bottom,” by R. Feynman, Caltech’s Engineering & Science magazine, February, 1960. (Reprinted in Micromechanics and MEMS: Classic and Seminal Papers to 1990, Edited by W. Trimmer, the IEEE Press PC4390-QCL, ISBN 0-7803-1085-3, January 1997, page 7.)

4. “Infinitesimal Machinery, “ by Richard Feynman, Journal of Microelectromechanical Systems, Volume 2, Number 1, March 1993. (Reprinted in Micromechanics and MEMS: Classic and Seminal Papers to 1990, Edited by W. Trimmer, the IEEE Press PC4390-QCL, ISBN 0-7803-1085-3, January 1997, page 11.)

5. “1/N Feynman Machines as a Path to Ultraminiaturization?” by E. Clayton Teague, SPIE Conference on Microelectronic Manufacturing, Austin, Texas, October 23 to 24, 1995.

6. “Theory of Self-Reproducing Automata,” Edited by John von Neumann and completed by Arthur W. Burks, University of Illinois Press, Urbana, IL, 1966.

Portions of this talk are adaptations from the following sources:

a. “Grand in Purpose, Insignificant in Size,” by William Trimmer, given at the Tenth Annual International Workshop on Micro Electro Mechanical Systems, Nagoya, Japan, January 26 to 30, 1997, please see page 9 of the proceedings.

b. “Large Prospects for Small Systems Using Microelectromechanics,” by William Trimmer, given at GOMAC ’98, March 16 to 19, 1998, Arlington, Virginia, USA.

c. Editorial by William Trimmer in the Journal of Microelectromechanical Systems, Volume 6, Number 4, December 1997, pages 290 to 293.

Reference Sources

Micromechanics and MEMS, Classic and Seminal Papers to 1990, Edited by William S. Trimmer, IEEE, Piscataway, New Jersey, ISBN 0-7803-1085-3, IEEE Number PC4390, 1997. For a well written introduction to this field see the papers in Chapter 1.

The Journal of Microelectromechanical Systems, an IEEE / ASME Publication on Microstructures,

Microactuators, Microsensors, and Microsystems.

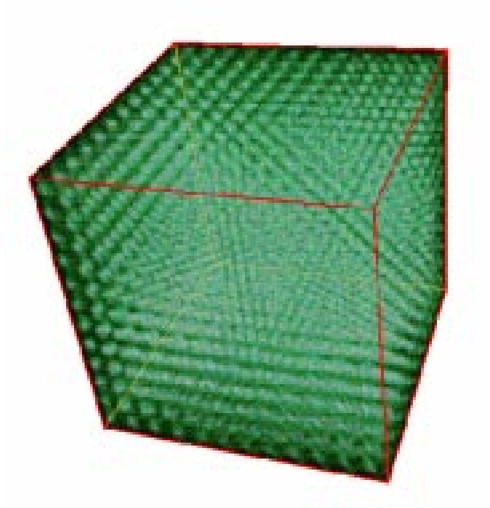
The Journal of Micromechanics and Microengineering, an Institute of Physics Publication on Structures, Devices and Systems.

Sensors and Actuators A, an Elsevier Sequoia Publication on solid-state devices for transducing physical signals.

For list of web sites, conferences, and other sources of information on Micromechanics and MEMS please see the web site: http://www. trimmer. net

"The Other Side of Computing" - Paper for the Conference on High Speed Computing Salishan Lodge, Gleneden Beach, Oregon, April 20 to 23, 1998, Presentation by William Trimmer

Crystalline Computation



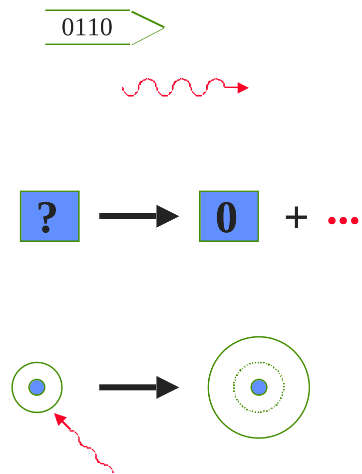
Norman Margolus
BU CCS, MIT AI Lab

Plan of the talk

- Fundamental Constraints $\Longrightarrow$ computers will imitate physics
- Uniform Crystal: general purpose, practical, scalable
- Crystalline Algorithms: what changes?
- Near Term: 3D bit-mapped computations
- Conclusions

Fundamental physical constraints

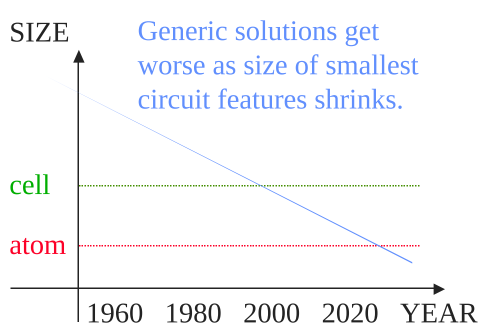
- Locality: no information can travel faster than light
- Invertibility: no information is ever erased from the world
- QM: the laws of physics act differently at small scales



Fundamental physical constraints

Handled in hardware:

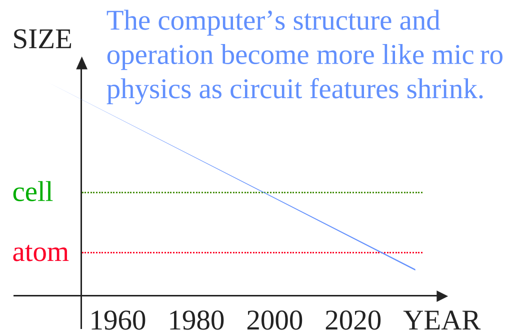
- Locality: use fast/short wires (gets harder)
- Invertibility: throw away info as heat (~ density)
- QM: space and time averaging (stats get bad)



Fundamental physical constraints

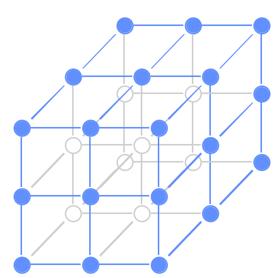
Incorporate constraints:

- Locality: mesh architecture (--> no wires)
- Invertibility: reversible logic (--> no heat)
- QM: exploit digital character (--> no stats)



Why a simple uniform crystal?

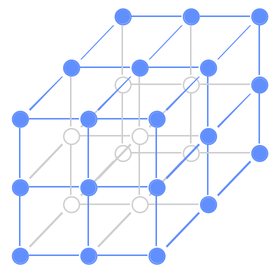
- Practical: easier to design, build, test and control
- Scalable: just make more -- as asymptotically good as anything
- Fast: high processing density and fast cycle time
- Fair: doesn't try to favor any class of (classical) computations



Why a simple uniform crystal?

Why not a ...

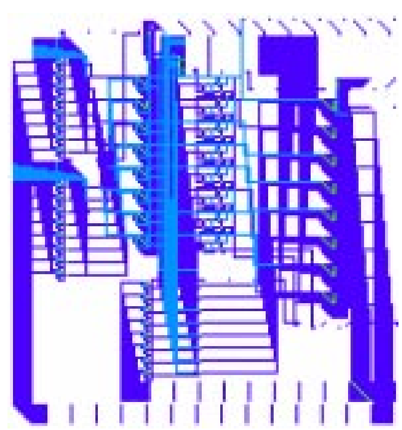
- Coherent quantum computer: too much overhead for general purpose computing
- Amorphous computer: we gain computing power from predictability



Crystalline algorithms

SPACE:

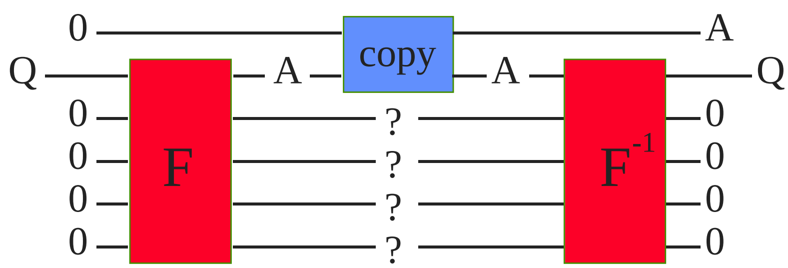
- The computer designer just provides a large-scale digital spatial medium: a 3D FPGA
- Assigning which positions will perform which operations is much like building hardware
- Traditional architectural ideas for mapping computation into space remain interesting



Crystalline algorithms

REVERSIBLE FUNCTIONS:

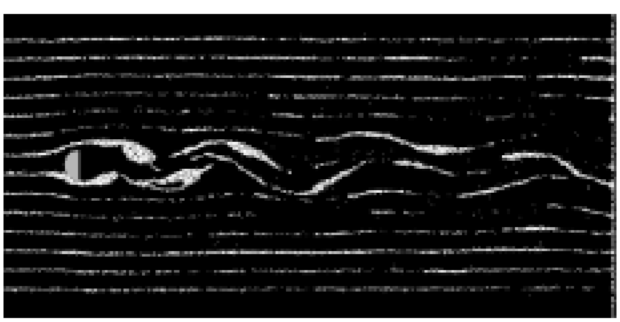
We can avoid the need to throw away information by "uncomputing" partial results.

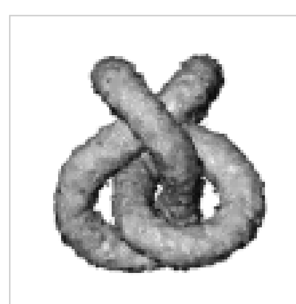


Crystalline algorithms

MACROSCOPIC SCALING:

Large scale combinatorial computations become practical.



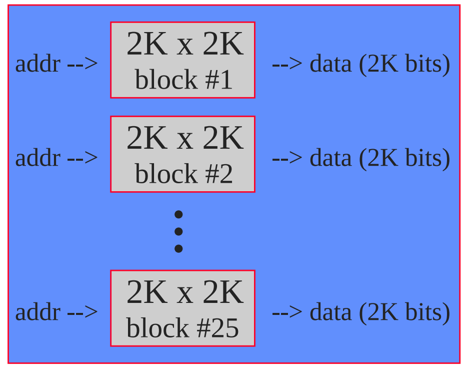


Crystalline computers today

- Mainstream make crystalline look hard

Possible today:

- Terabits/sec/chip for large-scale meshes
- Virtual processor SIMD using embedded DRAM

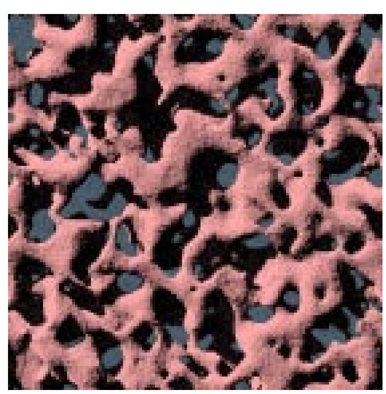


One chip, with 50ns row
of 50Kbits/row = 1 Tbit/

Crystalline computers today

Immediate applications:

- 3D bitmap-based approach to "virtual reality"
- 2D/3D image segmentation, manipulation and rendering
- physics simulations
- cryptography
- levelized logic simulation



Conclusions

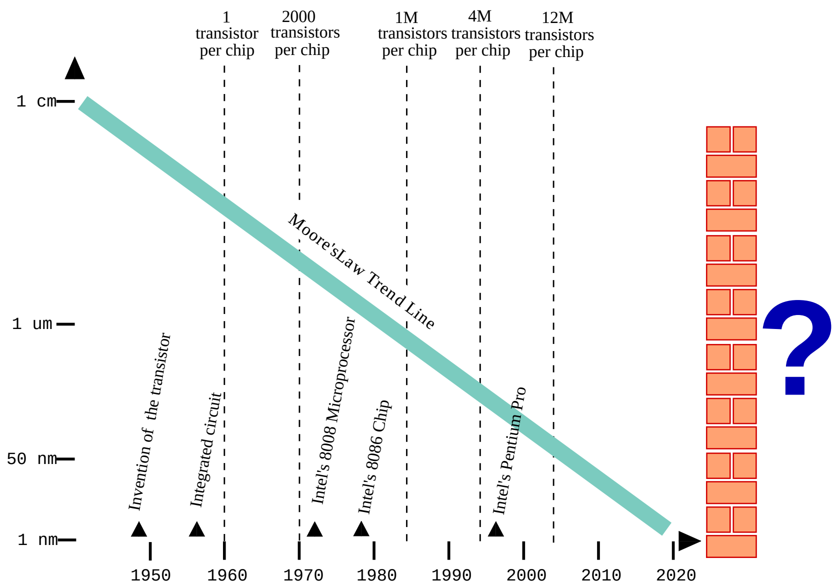
- Algorithms and computers will become more physics-like
- Crystalline computers will be the best possible general purpose computers
- Some of the power of crystalline computations can be harnessed today

Quantum Computing

E. Knill

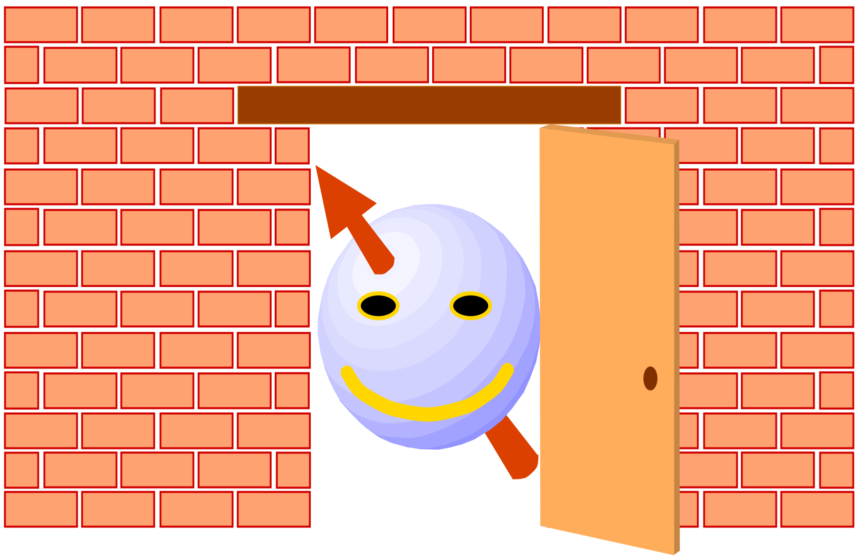
- Quantum computing is inevitable.
- Applications of quantum computers.
- What are quantum computers?
- The power of quantum algorithms.
- Requirements for quantum computing.
- Quantum noise control.
- Proposed quantum computing devices.
- Prospects.

Moore's Law



Moore[27], Montemerlo&*al.*[26]

Behind the Wall?



Lloyd 1996

Quantum Computer Applications

- Long distance quantum cryptography.
- Number theory algorithms: Factoring, discrete logarithm. Shor 1994[31, 34]
- Accelerated combinatorial searching. Grover 1995[12, 13]
- Code breaking: Public key cryptography, DES.
- Physics simulations.

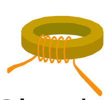
Feynman 1984[10], Lloyd 1996[22], Wiesner 1996[37], Zalka 1996[39]

Specifying a Model of Computation

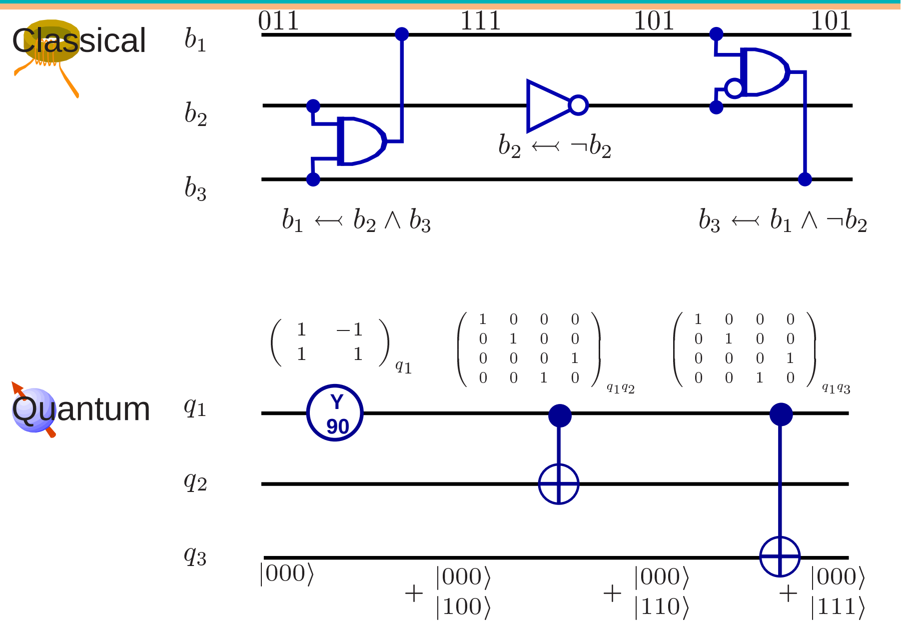
- State space.
- Manipulating states.
- Initial state.
- Read out.

- Quantum computing is an *extension* of classical computing.

State Space

	1 bit	n bits
 Classical	$0, 1$	$000\ldots, 100\ldots,$ $010\ldots, 110\ldots,$ $001\ldots, \ldots$
 Quantum	$\alpha\|0\rangle + \beta\|1\rangle$	$\alpha_{000\ldots}\|000\ldots\rangle +$ $\alpha_{100\ldots}\|100\ldots\rangle +$ $\alpha_{010\ldots}\|010\ldots\rangle +$ $\alpha_{110\ldots}\|110\ldots\rangle +$ $\alpha_{001\ldots}\|001\ldots\rangle + \ldots$

Processing Information



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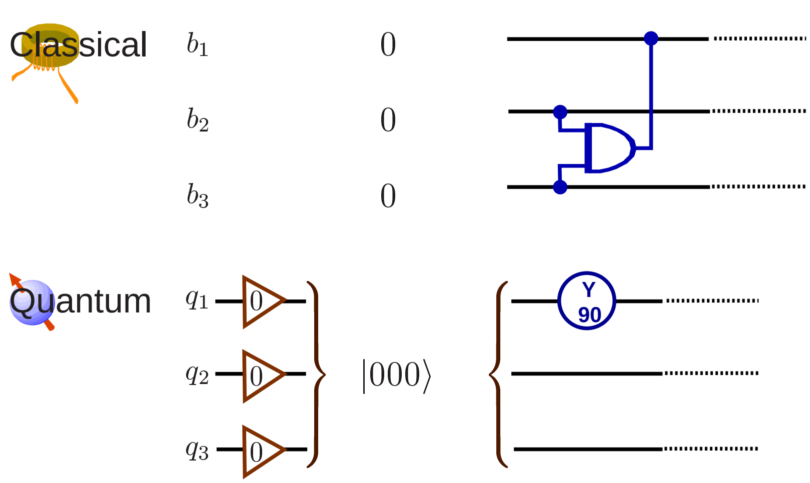
Initial State

prepared state



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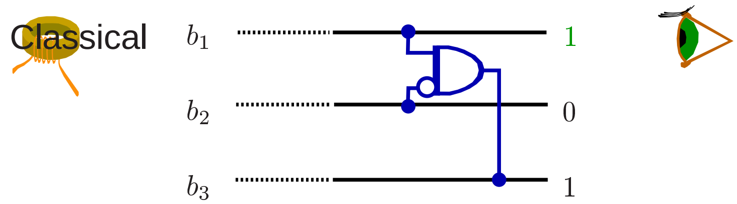
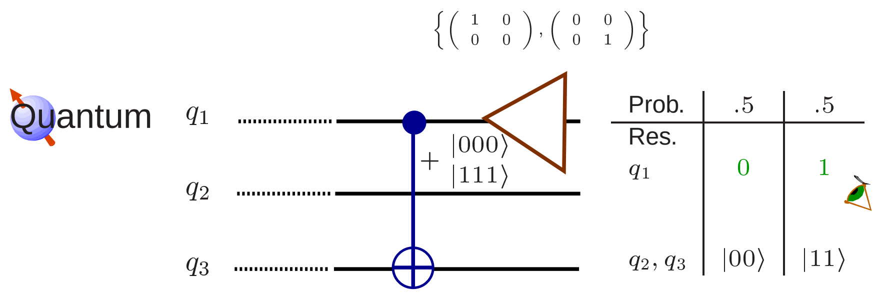
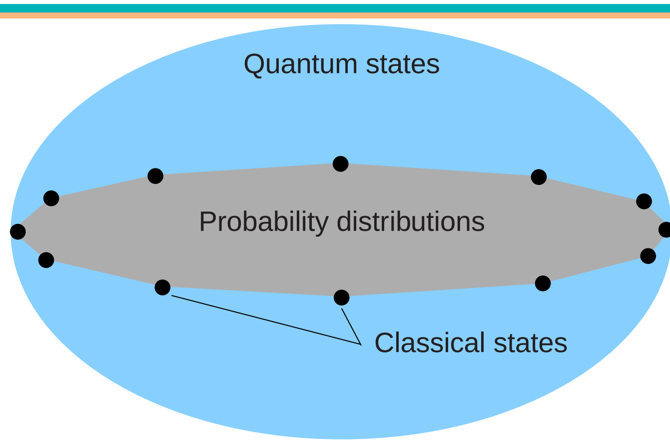
Readout





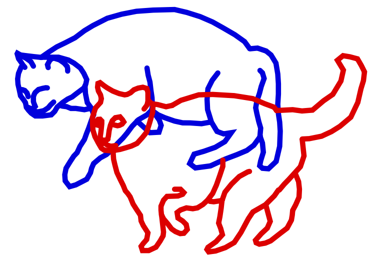
Power of QC†: State Space?



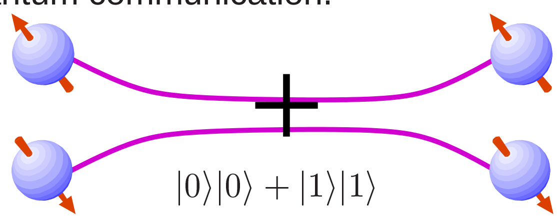
- Exponential dimension in terms of physical resources.
- No feasible classical simulation for > 40 qubits?

† Quantum Computing.

Power of QC[†]: Entanglement?

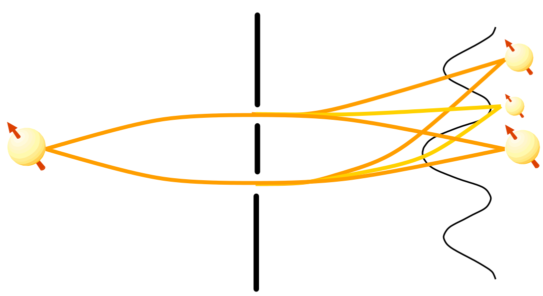


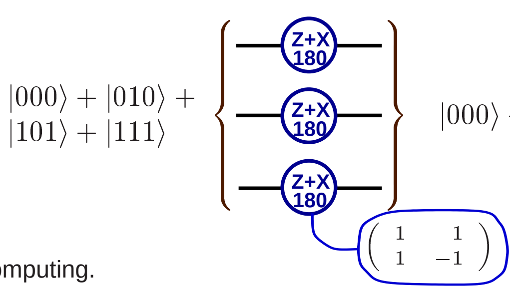
- For quantum communication.



[†] Quantum Computing.

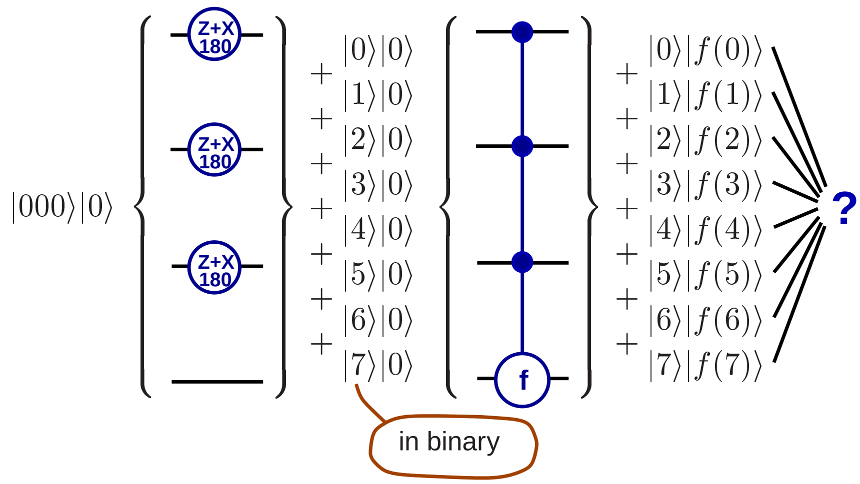
Power of QC[†]: Interference effects?





[†] Quantum Computing.

Power of QC†: Quantum Parallelism?



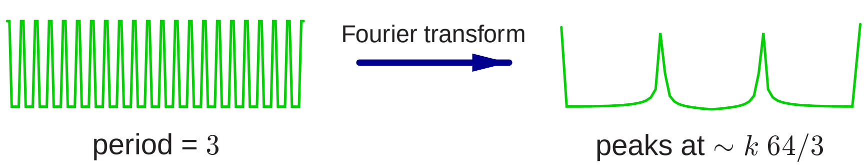
† Quantum Computing.

Period Determination

- f is periodic with period p if for all k, $f(k+p) = f(k)$.

> Example:
> $$f(3k) = 1, \quad f(3k+1) = 0, \quad f(3k+2) = 0$$
> $$k \in \{0, \ldots, 63\}$$

- Problem: Determine the unknown period of a periodic function.



Quantum Fourier Transform

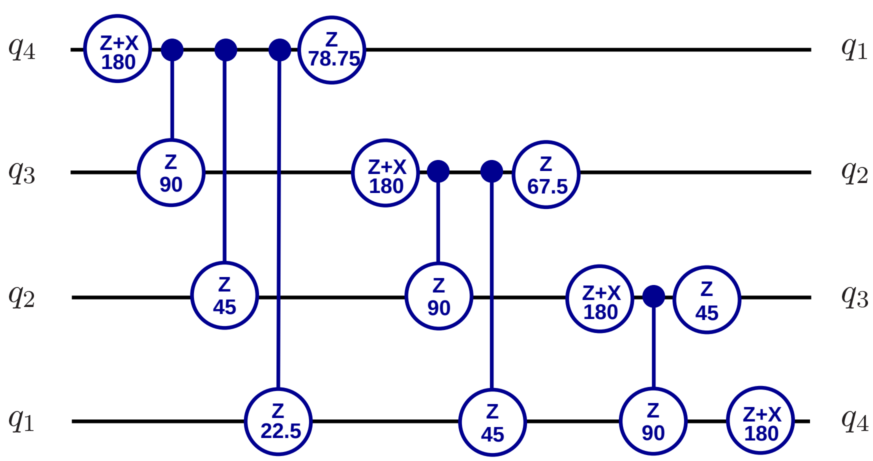
$$\mathcal{F} : \sum_{n=0}^{N} \alpha_n |n\rangle \to \sum_{k=0}^{N} \left(\sum_{n} e^{2\pi nki/N} \alpha_n \right) |k\rangle$$

amplitudes

- Example:

$$\begin{array}{ll} & 1\ |0\rangle \\ + & 0\ |1\rangle \\ + & 1\ |2\rangle \\ + & 0\ |3\rangle \\ + & 1\ |4\rangle \\ + & 0\ |5\rangle \\ + & 1\ |6\rangle \\ + & 0\ |7\rangle \end{array} \longrightarrow \begin{array}{ll} & 1\ |0\rangle \\ + & 0\ |1\rangle \\ + & 0\ |2\rangle \\ + & 0\ |3\rangle \\ + & 1\ |4\rangle \\ + & 0\ |5\rangle \\ + & 0\ |6\rangle \\ + & 0\ |7\rangle \end{array}$$

Network for the QFT[†]



q_4: most significant bit. q_1: least significant bit.

† Quantum Fourier Transform.

Pseudo Code for the QFT†

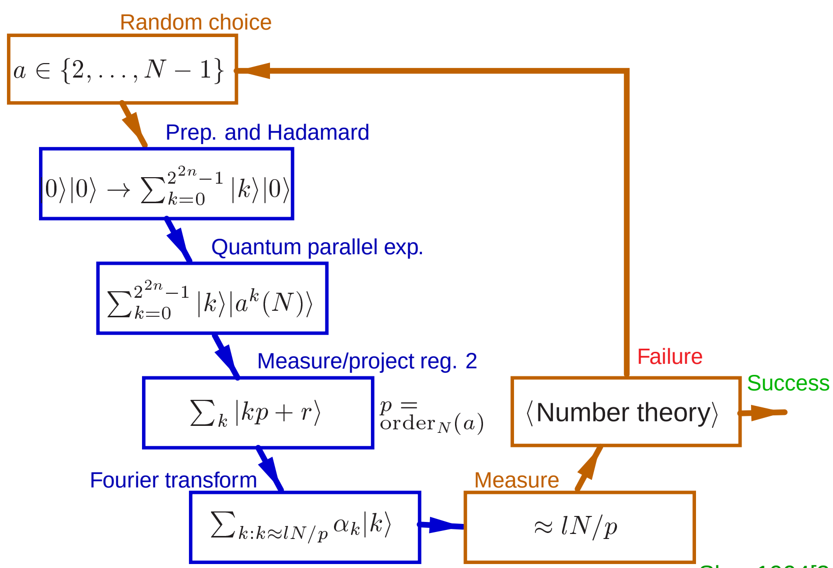
FOURIER($\ulcorner a \urcorner$)
Input: A quantum register $\ulcorner a \urcorner$ with d qubits. The most significant qubit has index $d-1$.
Output: The amplitudes of $\ulcorner a \urcorner$ are Fourier transformed over $\mathbb{Z}_{2^d}$. The most significant bit in the output has index 0, i.e. the ordering is reversed.

$d \leftarrow$ **length** $(\ulcorner a \urcorner)$
$\omega \leftarrow e^{i2\pi/2^d}$
for $i = d-1$ **to** $i = 0$
  for $j = d-1$ **to** $j = i+1$
    if $\ulcorner a_j \urcorner$ **then** $\mathcal{R}_{\omega^{2^{d-i-1+j}}}(\ulcorner a_i \urcorner)$
  end
  $\mathcal{H}(\ulcorner a_i \urcorner)$
end

† Quantum Fourier Transform.

Quantum Factoring

- Factor N, where $2^{n-1} < N \leq 2^n$:



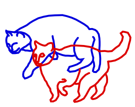
Shor 1994[31, 34]

Requirements for Quantum Computing

- State space:
  - Controlled system space.
  - Scalability.
- State preparation:
  - Fiducial pure initial state.
  - Initial states on demand.
- State control:
  - Single system unitary rotations.
  - Conditional dynamics.
  - Complete set of gates.
- Readout:
  - Reliable projective measurement *or* reliable expectations of system observables.
- Noise:
  - No memory errors *or* high parallelism.
  - Error per operation $<$ threshold.

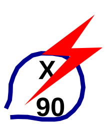
DiVincenzo&Loss 1997[9], Knill&Laflamme 1996[19], Preskill 1997[28]

Noise in Quantum Computing



Memory: Most superpositions are fragile.

- Control vs. environment: Strong interactions for control, but weak interactions with environment.

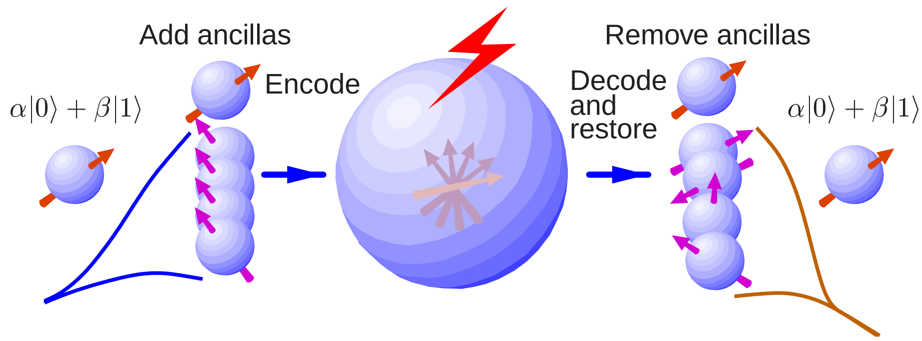


Operations: Gates are inherently “analogue” and hence inaccurate.

- Error space: Continuity of possible errors.

Quantum Error Correction

- Discretize errors.
- Errors are local and independent.



Shor 1995[32], Steane 1995[35]

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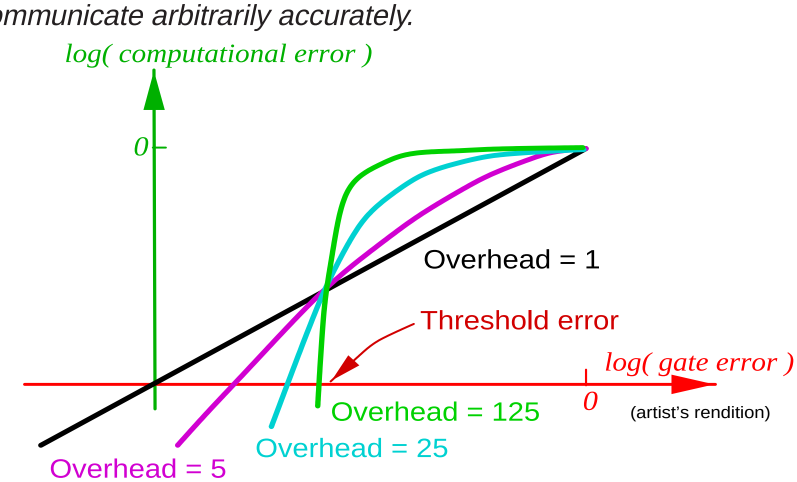
The Accuracy Threshold Theorem

Theorem 1. *If the error amplitude per gate (including "no-op") is less than a threshold, then it is possible to quantum compute and communicate arbitrarily accurately.*



Shor 1996[33]
Knill&*al.* 1996[20], Aharonov&Ben-Or 1996[1], Kitaev 1996[17], Preskill 1997[28]

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Proposed Quantum Computers

- Photonic QC[1]: Photons and nonlinear optics.
  Milburn 1988[24], Yamamoto&*al.* 1988[38]
- Ion trap: Ions in a linear trap, coupling via center of mass mode, control with lasers. Cirac&Zoller 1995[5]
- Cavity QED[2]: Photons in cavities and flying or trapped atoms.
  Turchette&*al.* 1995[36]
- Superconducting Josephson junctions: Superconducting domains, flux or cooper pairs. Bocko&*al.* 1997[2], Shnirman&*al.* 1997[30]
- Quantum dots: Trapped electrons in semiconductor nano-dots.
  Loss&DiVincenzo 1997[23]
- NMR[3]: Nuclear spins in molecules.
  Gershenfeld&Chuang 1996[11], Cory&*al.* 1996[6]
- Solid state NMR[3]: Implanted nuclear spins in silicon at low temperature, coupling via electrons.
  Kane 1997[15], Privman&*al.* 1997[29]
- Others: Optical lattices, crystal NMR[3], . . .

[1] Quantum Computing. [2] Quantum Electro-Dynamics. [3] Nuclear Magnetic Resonance.

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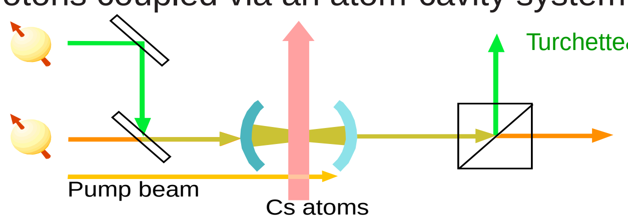
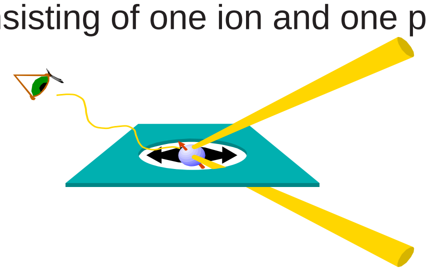
Implemented Quantum Gates I

- Cavity QED: Conditional phase shift between photons coupled via an atom-cavity system.
  Turchette&*al.* 1995[36]



- Ion traps: Conditional dynamics on two bits consisting of one ion and one phonon in a Paul trap.
  Monroe&*al.* 1995[25]



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Requirements for QC†: Ion Traps I

- Initial state, control and readout: Confirmed by experiments using an ion and a phonon.
- Time per operation: $\gtrsim 1\mu s$, depending on phonon frequency.
- Robustness:
  - Achievable: $R \equiv$ operations/error $\lesssim 1000$?
  - Currently: $R \approx 10$.
  - Little parallelism.

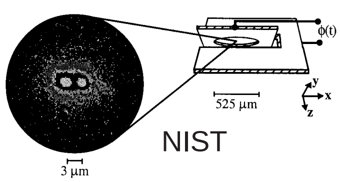
† Quantum Computing.

Requirements for QC: Ion Traps II

- State space and scalability: Single traps are limited to $10\ldots80$ ions in practice.

Elliptical trap:

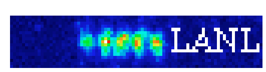
QC ready, in ground state.

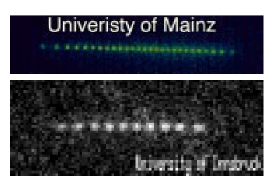


King&*al* 1998[16]

Linear traps:

Crystals, not in ground state





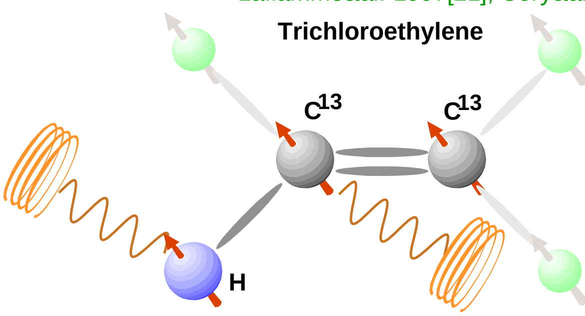
- In theory, parallel, coupled ion traps are possible.

Implemented Quantum Gates II

- Liquid state NMR:

- Two bit algorithms (Pseudo-pure state, EPR, Grover, Deutsch-Josza) in chloroform and cystosine.
  Knill&*al.* 1997[18], Chuang&*al.* 1997[3], 1998[4], Jones&Mosca 1998[14]

- Three bit algorithms (Toffoli gate, GHZ, quantum error correction) in trichloroethylene and alanine.
  Laflamme&*al.* 1997[21], Cory&*al.* 1997[8], 1998 [7]



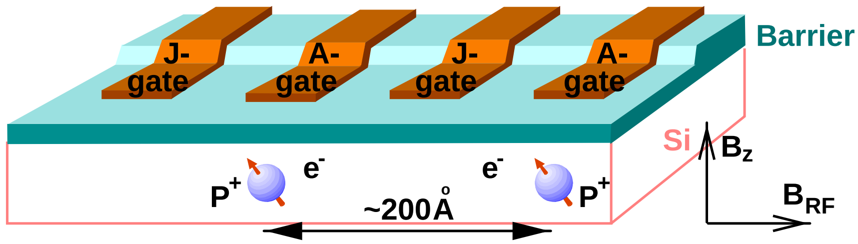
Requirements for QC: Liquid State NMR

- Initial state, control and readout:
  - Experimentally, up to three bits.
  - Exponential loss of signal for state preparation.
- Time per operation: $\gtrsim 10ms$.
- Robustness:
  - Achievable: $R \gtrsim 100$?
  - Currently: $R \approx 20$.
  - But threshold theorem does not apply.
- State space and scalability:
  - State space is scalable, but state preparation is not.
  - Limited to $\lesssim 10$ bits ($\lesssim 100$ for physics simulation?).

Requirements for QC: Solid State NMR

Silicon based quantum computer.

(Theoretical proposal, experiments in progress.)



- Initial state, control and readout: Possible in theory.
- Time per operation: $\gtrsim 2\mu s$.
- Robustness: $R \gg 1000$?
- State space and scalability: Few limitations.

Kane 1997[15]

Quantum Computing Scenarios

- Minimal utilization:
  - Device-level quantum control and error-correction.
  - Long distance quantum cryptography.

$+$ Anticipated utilization: "Quantum coprocessors" for

- "Number theory" calculations.
- Accelerated combinatorial searching.

$++$ Maximal utilization:

- Most computing and communication is fully quantum.

Conclusion

- Quantum computing is inevitable.
  - Needed for atomic scale control and information processing.
- Quantum computing is useful.
  - Quantum communication.
  - Quantum control and error-correction.
  - Optimization and "number theory".
  - Physics simulation.
- Quantum computing is robust.
  - The accuracy threshold theorem.
- Quantum computing "exists".
  - Experiments up to three bits in CQED, ion trap and NMR.

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Quantum Computing [E. Knill, http: / /www. c3 . lam . gov/ ~knill]

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