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DEPARTMENT OF PHYSICS AND ASTRONOMY, VANDERBILT UNIVERSITY

An Introduction to DNA and Quantum Computers

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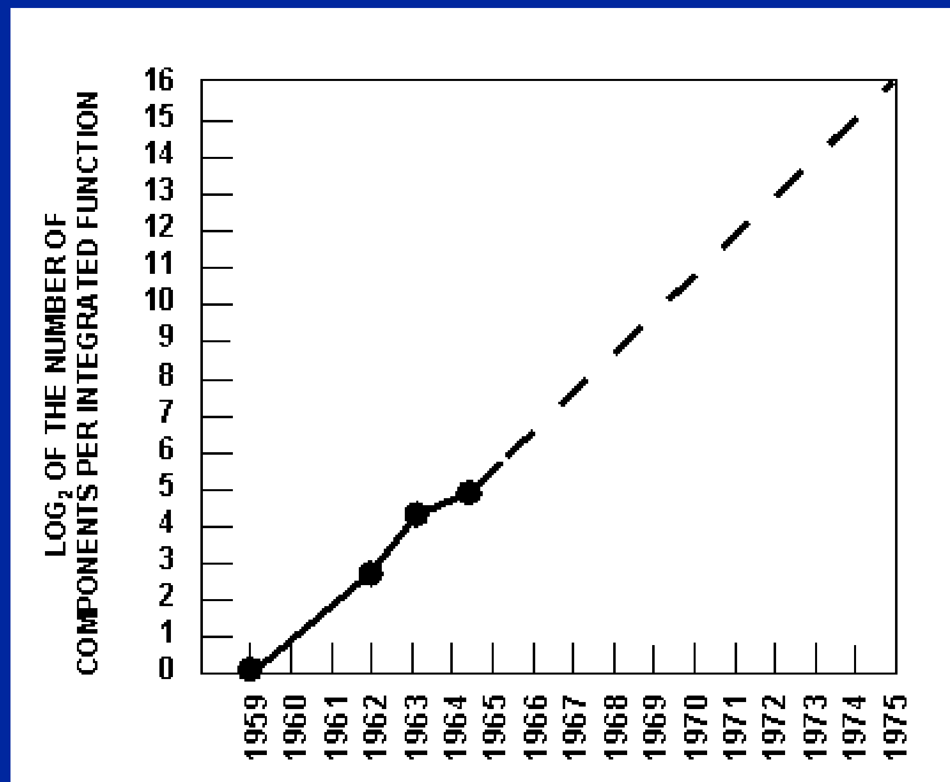
Abstract

The historical growth in speed for silicon-based computers, as described by Moore's law, may be nearing an end. This, plus the never-ending quest for faster computers for factoring and code-breaking, have stimulated searches for totally new computer architectures. Quantum and DNA computers have both been proposed as candidates for massively parallel computers, and have received significant attention in the popular and scientific press and growing governmental funding. Both types of computers represent major departures from conventional computing and thereby present an interesting intellectual and technical challenge. In this talk, I present the results of my first exploration into this area, and will provide a simple overview of how each technology computes, what kinds of computational problems are best suited for each technology, the practical limitations of each approach, and future prospects.

Moore’s Law

The Original Moore’s Law Plot



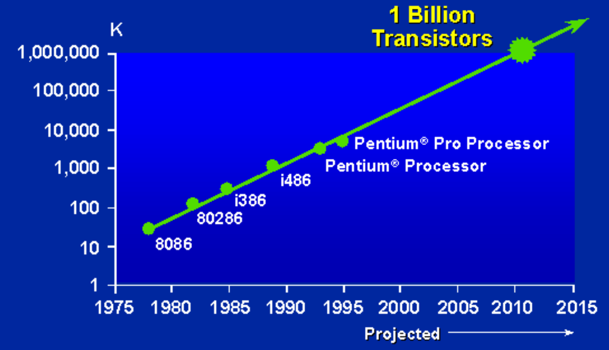
Electronics, April 1965

Using Moore’s Law to Project to 2011

Advanced Technological Education in Semiconductor Manufacturing

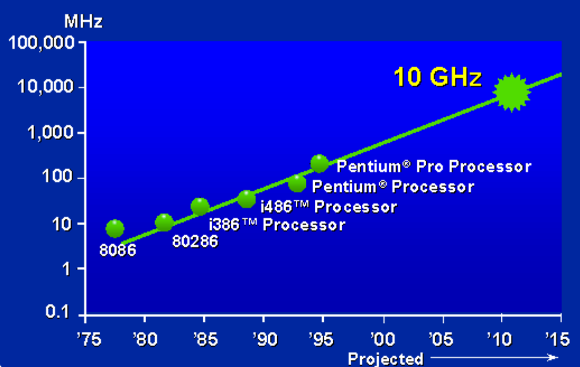
Craig R Barrett
President and Chief Operating Officer
Intel Corporation
30, July 1997

Transistor Count



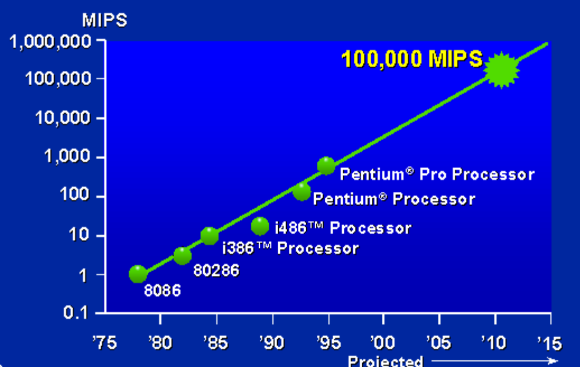
Source: Intel

Frequency On the Rise



Source: Intel

Performance



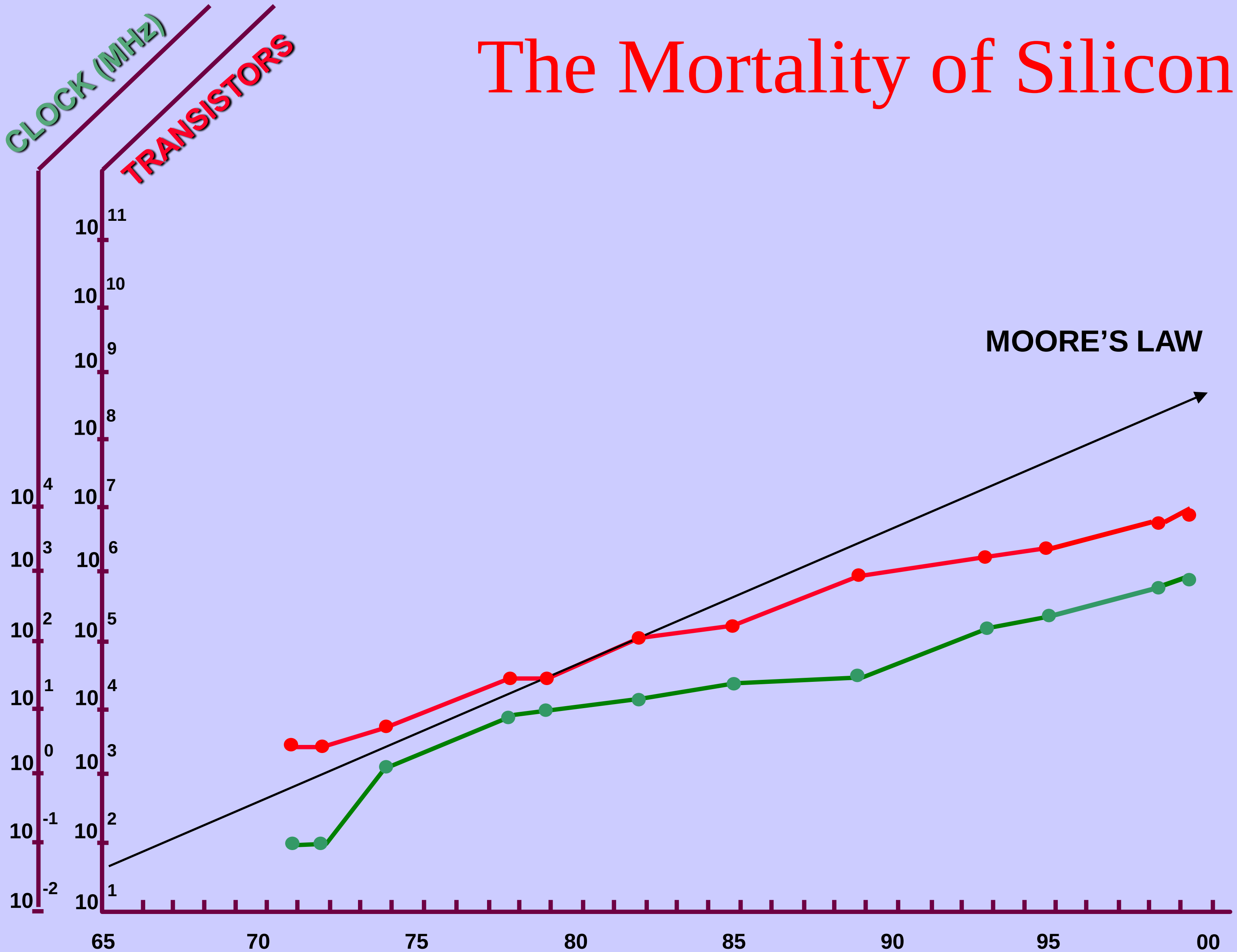
Source: Intel

Billion-Transistor Architecture Problems

- Extracting more parallelism out of code
- Memory bandwidth
- Interconnect delay
- Power consumption
- Future microprocessor workloads
- Retaining compatibility with existing code
- Design, verification and testing
- Economies of scale

http://www.doc.ic.ac.uk/~sp24/article2/

The Mortality of Silicon



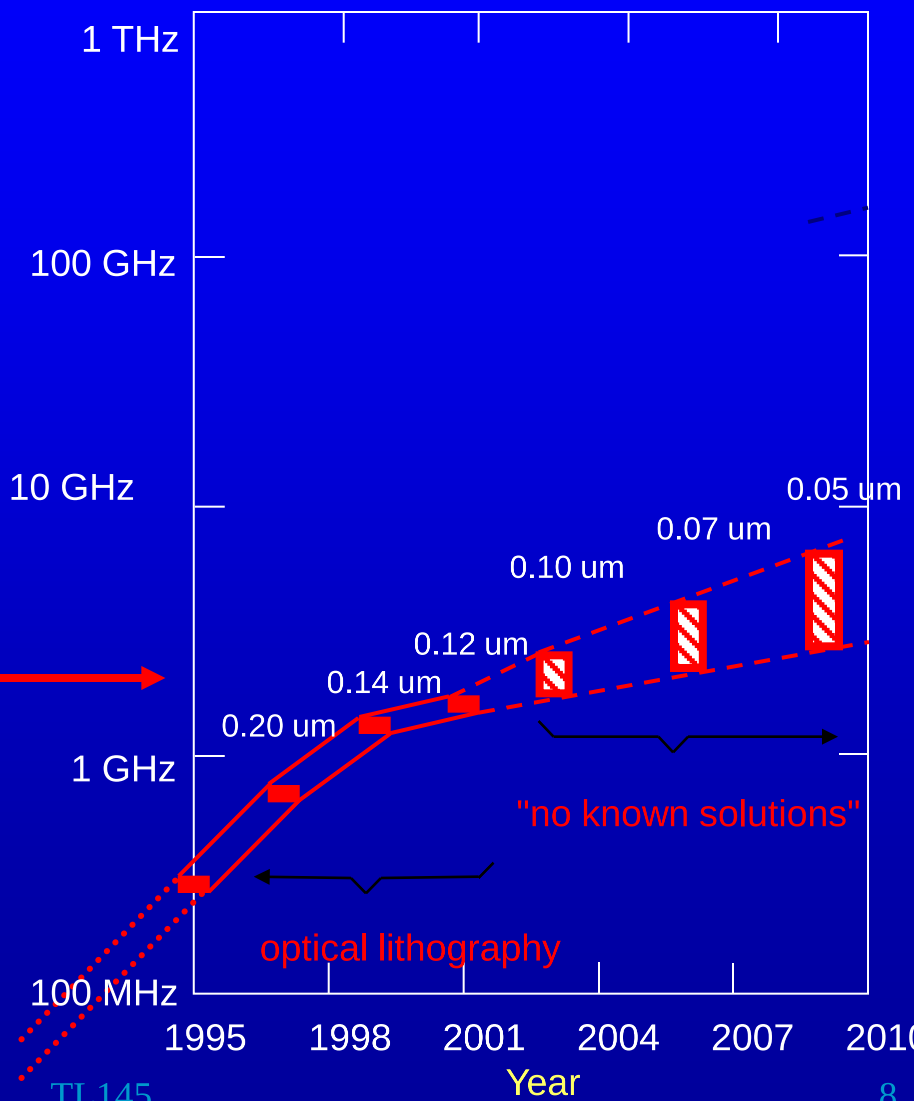
Physics -- Can Moore's Law Continue Below 50 nm and 2010?

- The Record Transistor: 60 nm x 60 nm, 1.2 nm oxide (180 x 180 x 3 atoms)
- Minimum oxide thickness: How many atomic layers? 3? 2? 1? ...
- Gates: New electrode and insulator materials with higher k? Is there an alternative to SiO_2 ?
- Interconnect delays and crosstalk: Lower resistivity and lower k
  "implementation through ... 100 nm .. will require … introducing new materials with each new technology generation"
- Smaller transistors: Electron quantization effects, tunnelling
- Thermal conductivity
- Dopant distribution statistics
- Power supply voltages: 1.5 to 1.8 V today. 0.5-0.6 V in 2012?
- Power dissipation: Cold CMOS?

In part from "National Technology Roadmap for Semiconductors"

How Certain is the Future?

CMOS (SIA Forecast 1997)



Courtesy of Konstantine Likharev

To the Rescue?

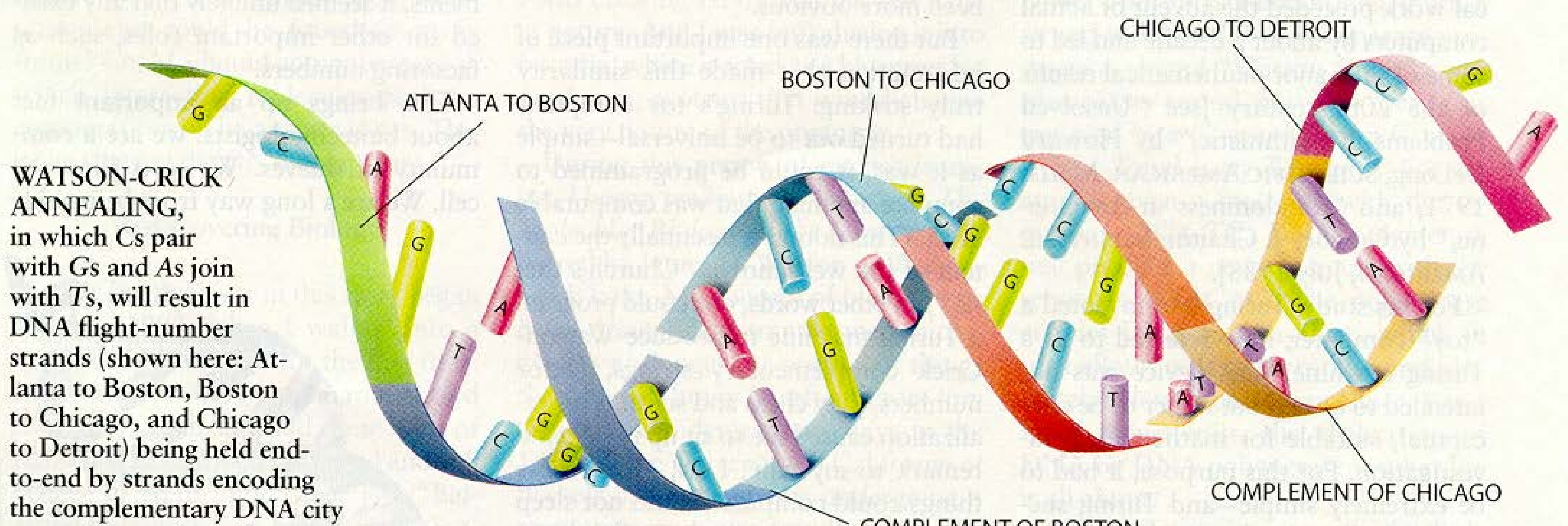
- DNA Computers
- Quantum Computers
- ...

The Appeal of DNA Computers

- Silicon: 10^6 transistors/cm^2, 10^7 per chip
- DNA
  - Today 10^{20} strands are easily manipulated
  - *Drosophila* genome of 140 M base-pairs = 40 mbyte
  - Gel electrophoresis and polymerase chain reaction 10^8 slower than silicon gate
  - **MASSIVE** parallelism
- Today's NP-complete algorithms ~ brute-force exhaustive search

Watson-Crick Annealing of DNA

- Four bases: Adenine, thymine, guanine, and cytosine
- Two strands built of A,T,C,G
- Complementary: A pairs with T, C with G



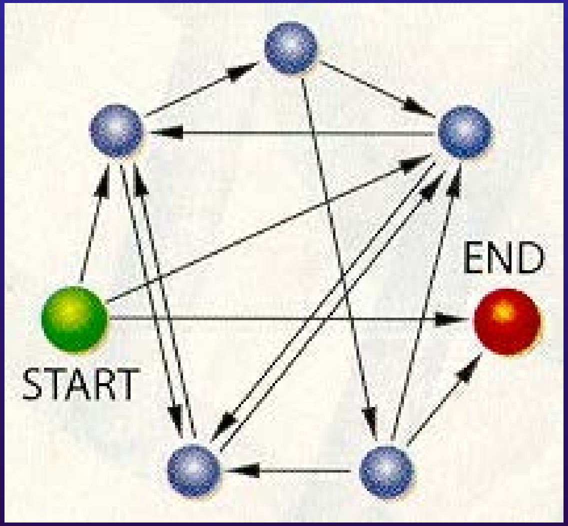
WATSON-CRICK ANNEALING, in which Cs pair with Gs and As join with Ts, will result in DNA flight-number strands (shown here: Atlanta to Boston, Boston to Chicago, and Chicago to Detroit) being held end-to-end by strands encoding the complementary DNA city names (shown here: Boston and Chicago).

Aldeman, Sci. Am., Aug 1998

Travelling Salesman Problem (Directed Path Hamiltonian Problem)

Given a set of flights and a set of cities, find all paths from **Buenos Aires** to **Hong Kong** that visit each city, but only once

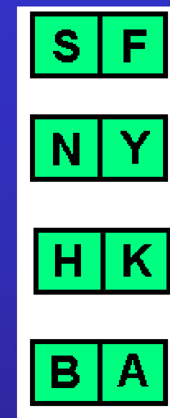
- 10^{23} parallel computers insufficient for 100 cities
- Conventional machines may fail on paths with 100 nodes



Aldeman, Sci. Am., Aug 1998

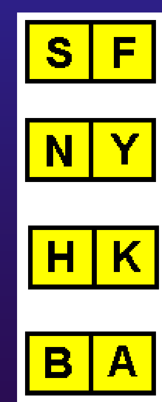
Step 1: Represent the Cities as Oligonucleotides

- San Francisco
- New York
- Hong Kong
- Buenos Aires



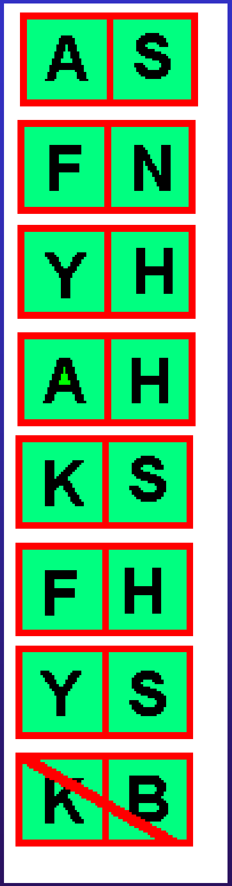
Step 2: Create the Watson-Crick City Complements

- San Francisco
- New York
- Hong Kong
- Buenos Aires

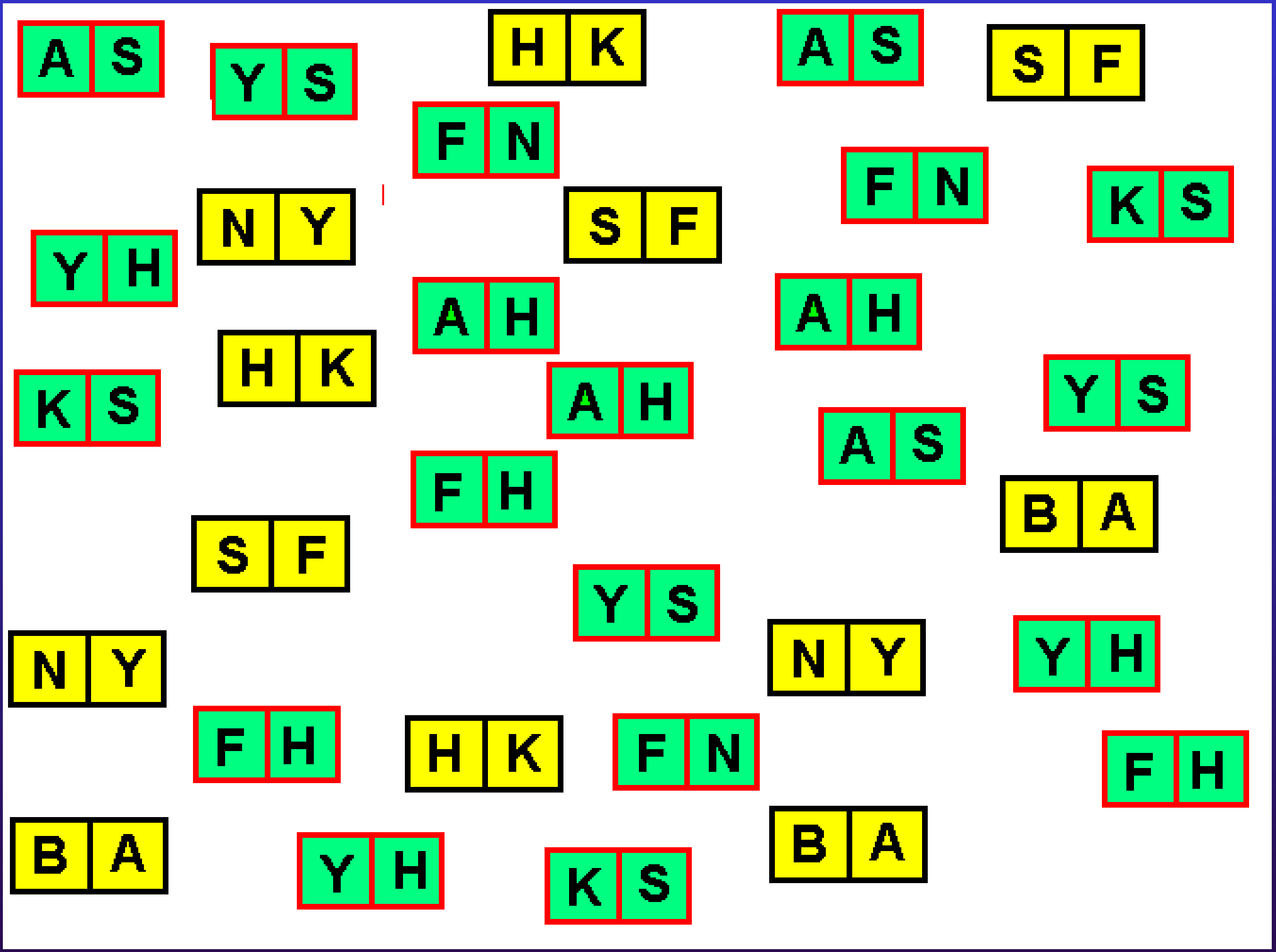


Step 3: Pick the Flights

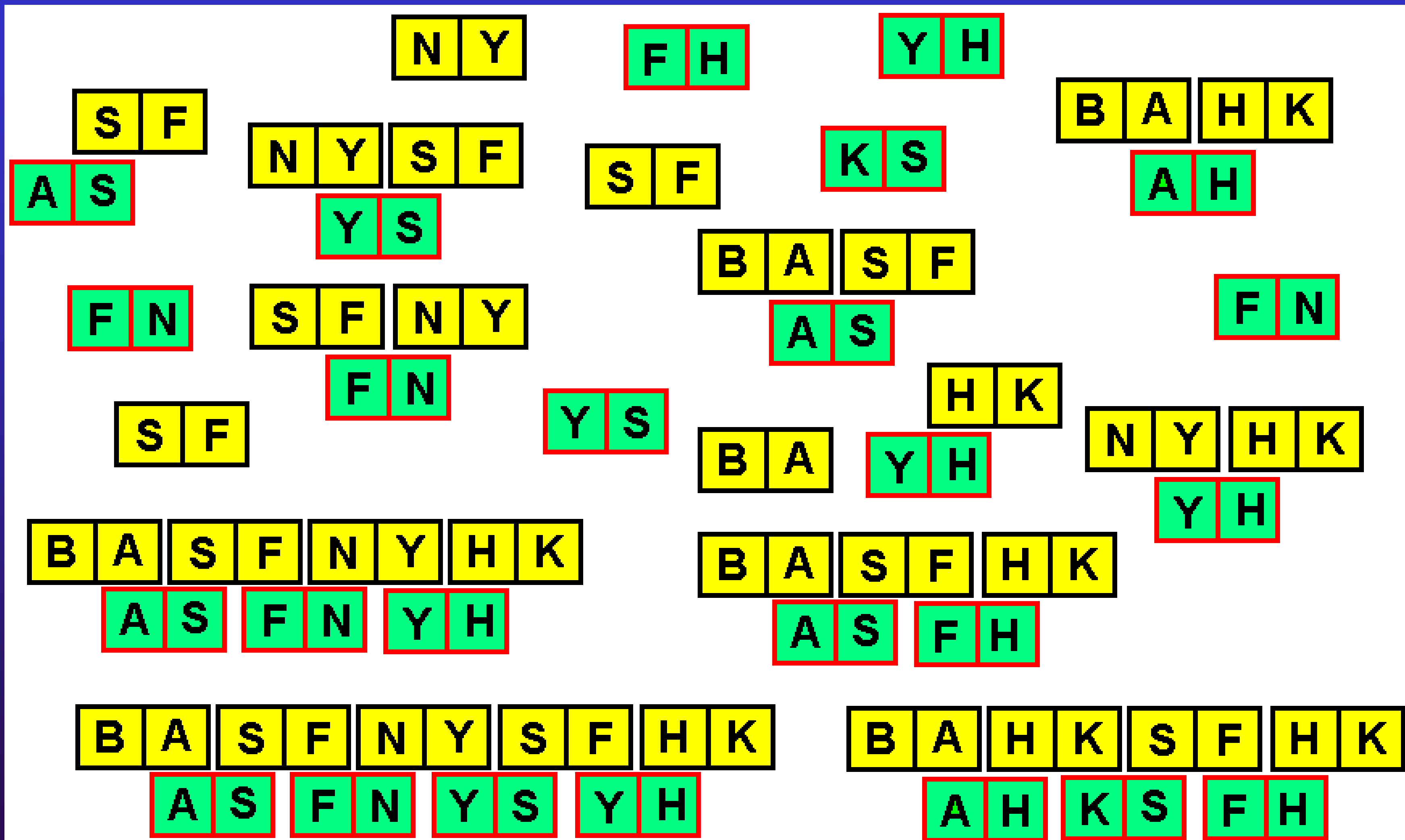
- Buenos Aires to San Francisco
- San Francisco to New York
- New York to Hong Kong
- Buenos Aires to Hong Kong
- Hong Kong to San Francisco
- San Francisco to Hong Kong
- New York to San Francisco
- NOT Hong Kong to Buenos Aires



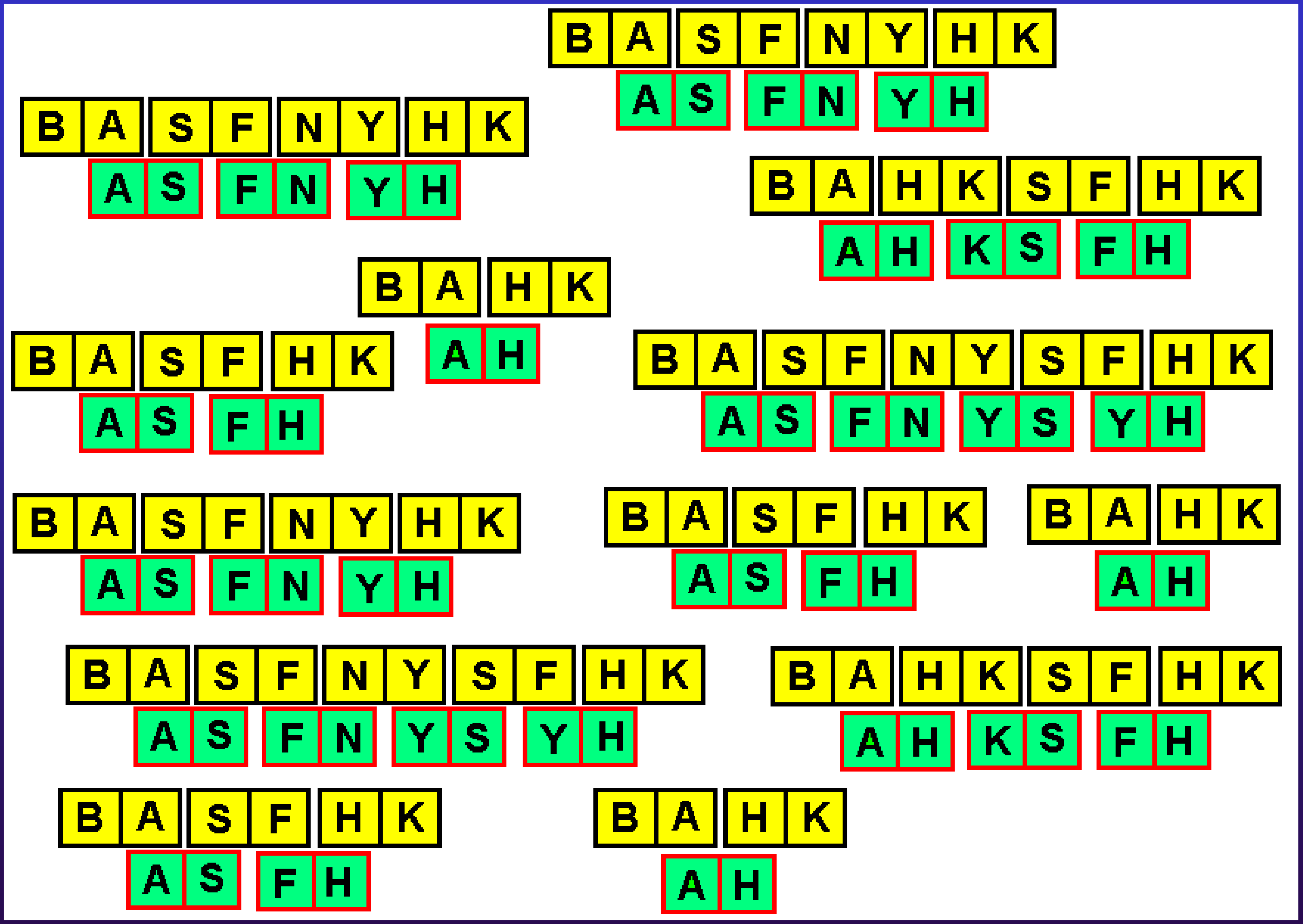
Step 4: Mix All the Components



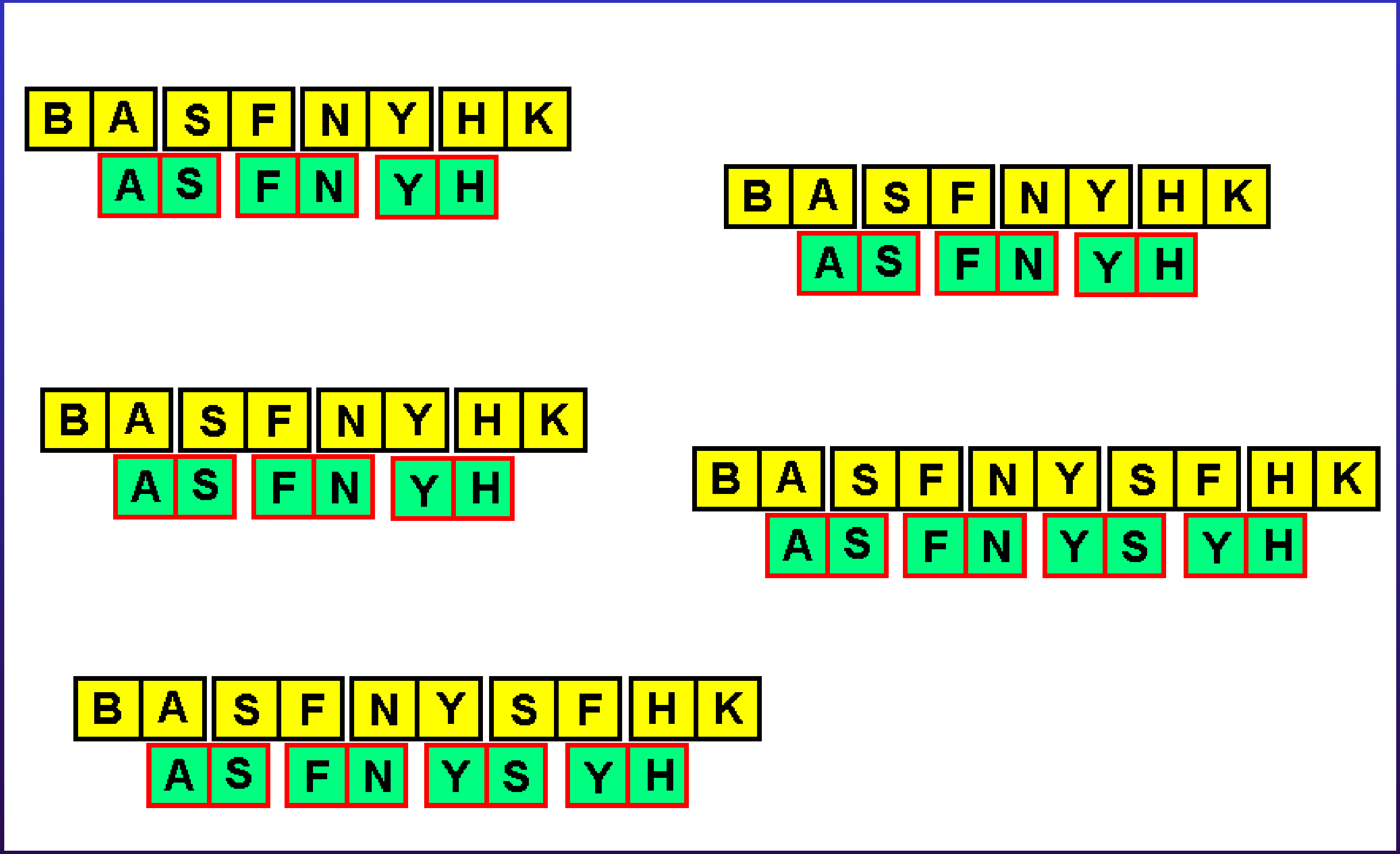
Step 5: Create Solution Set (10^{14} solutions)



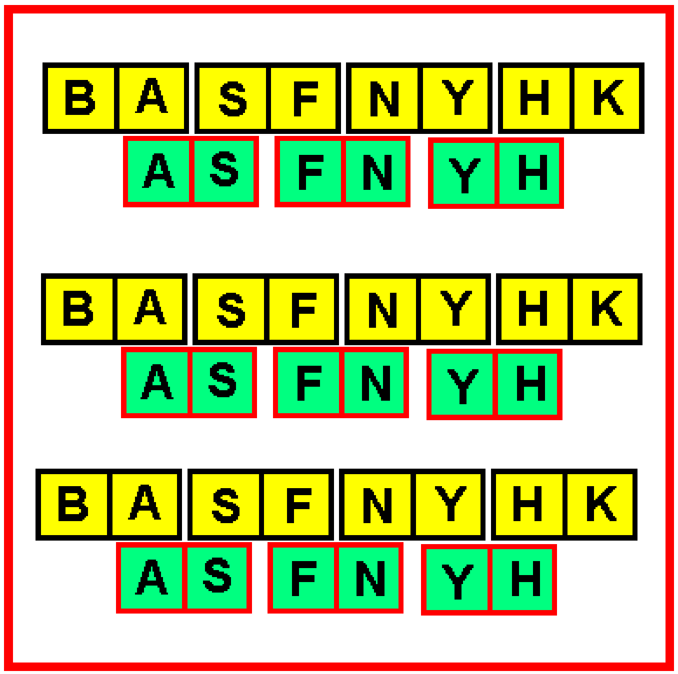
Step 6: Use PCR To Amplify Solutions With Correct Ends



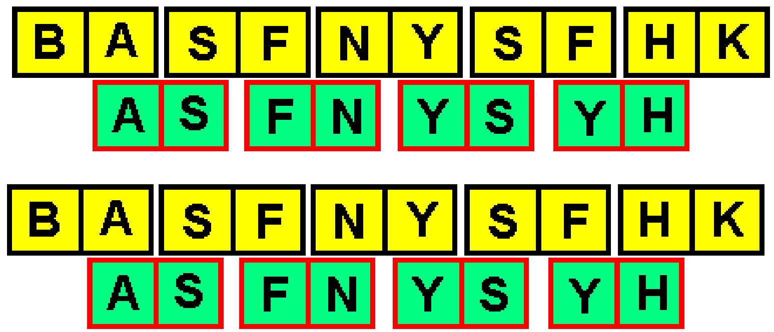
Step 7: Use Magnetic Affinity Purification to Eliminate (Wash Away) Solutions That Are Missing a City



Step 8: Use Gel Electrophoresis to Sort By Length



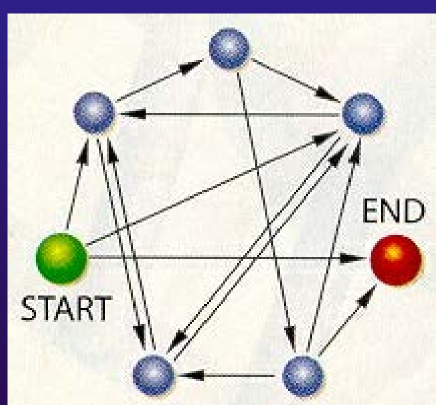
- One solution has an extra copy of SF, not identified by the magnetic affinity purification.

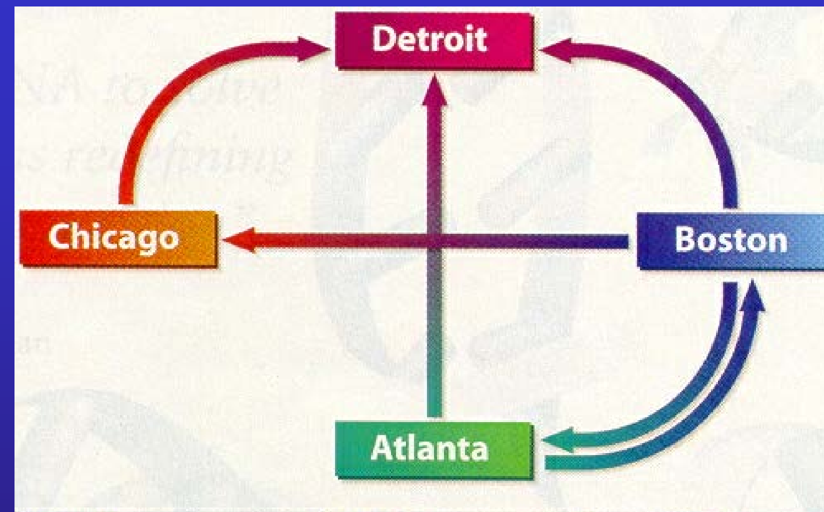


- The correct solution starts with BA, ends with HK, has all four cities, and no repeats.

In Actuality...

- Sequences of bases are used to label each city and flight (8 bases shown here)
- Adleman used 50 pmole each of 8 cities and 14 flights, plus seven days in the lab to find the solution...





CITY	DNA NAME	COMPLEMENT
ATLANTA	ACTTGCAG	TGAACGTC
BOSTON	TCGGACTG	AGCCTGAC
CHICAGO	GGCTATGT	CCGATACA
DETROIT	CCGAGCAA	GGCTCGTT

FLIGHT	DNA FLIGHT NUMBER
ATLANTA - BOSTON	GCAGTCGG
ATLANTA - DETROIT	GCAGCCGA
BOSTON - CHICAGO	ACTGGGCT
BOSTON - DETROIT	ACTGCCGA
BOSTON - ATLANTA	ACTGACTT
CHICAGO - DETROIT	ATGTCCGA

Aldeman, Sci. Am. Aug 1998

Some Numbers From Adleman and Kari

- 1 gm of dry DNA = 1 cm^3 = 10^{12} CD's
  - 1 bit/nm^3 vs 1 bit/(10^{12} nm^3)
- 10^{14} DNA flight numbers concatenated in 1 second in 1/50 of a teaspoon
- 2 x 10^{19} ligation operations per joule (versus thermodynamic limit of 34 x 10^{19} per joule and supercomputers of 10^9 per joule)
- 1.2 x 10^{18} operations/sec (1.2 x 10^6 faster than supercomputer)

Scaling

- An algorithm that scales as N^2 and takes 1 µs to solve a problem of size 10 will take 100 µs to solve a problem of size 100
- An algorithm that scales as 2^N and takes 1 µs to solve a problem of size 10 will take 3.9×10^{11} centuries to solve a problem of size 100

For a Problem of Size N...

- "Polynomial-time" class P (time scales as a polynomial in N)

  Harder than P is termed "intractable"
- "Non-deterministic polynomial-time" class NP
  - Apparently intractable
  - Can be solved in polynomial time by an unbounded number of independent computational searches in parallel, *i.e.*, a non-deterministic computer
  - The hardest subset: NP-complete. Other NP problems can be reduced to NP-complete problems in polynomial time
  - Directed Hamiltonian Path Problem is NP Complete
- "Exponential-time" class (time scales with N in the exponential)
- Universal

Cracking DES

- 64 bit messages encrypted with a 56 bit key
- Exhaustive search through 2^{56} keys at 10^5 operations/sec = 10^4 years on conventional computer
- DNA computer = 4 months. Subsequent solutions faster

Potential Applications of DNA Computing

- Travelling salesman problem
- Optimal shop scheduling
- Longest path in a graph
- Cryptography
- Checking CAD circuits or protocols
- Factoring
- Expansion of symbolic determinants
- Satisfiability problem: Finding variable (T/F) values to make an entire Boolean expression true
- Road coloring problem
- Matrix multiplication
- Addition
- Exascale computer algebra problems

The Downside

- Turing machine simulations require exponential volumes of DNA (Low error might require 23 earth-masses of DNA)
- Error rate: 1 in 10^6 in DNA operations
  - Polymerase Chain Reaction (PCR) is not noise free
  - Sheer forces from pouring and mixing can fragment DNA
  - DNA forms loops and knots
  - Free-floating strands lost in computation (bind to a surface?)
- DNA is not stable with time
- Affinity purification is error prone
- Experiments are slow, but massively parallel
- No great need to solve 70-edge HPP

The Future of DNA Computing

- Construct solutions rather than isolate them
- Enzymatic removal rather than affinity purification
- Surface-based rather than free-floating
- DNA chips versus gel electrophoresis
- Sticker models with read-write memory
- Vesicles with active membrane transport
- Self-assembly of complex branched structures as a computational tool
- "It is unlikely that DNA computers will be used for tasks like word processing, but they may ultimately find a niche for solving large-scale intractable combinatorial problems."

In part from Gibbons *et al.*, *Current Opinion in Biotechnology, 8:103-106 (1997)*

The Appeal of Quantum Computers

- Silicon computers are inefficient in simulating quantum computers
- A single 300 qubit computation = 2^{300} simultaneous computations with classical bits
- Factoring today:

  130-digit number - 100's of workstations for months

  400-digit number - 10^{9} years
- Quantum factoring, maybe

  130-digit number - seconds

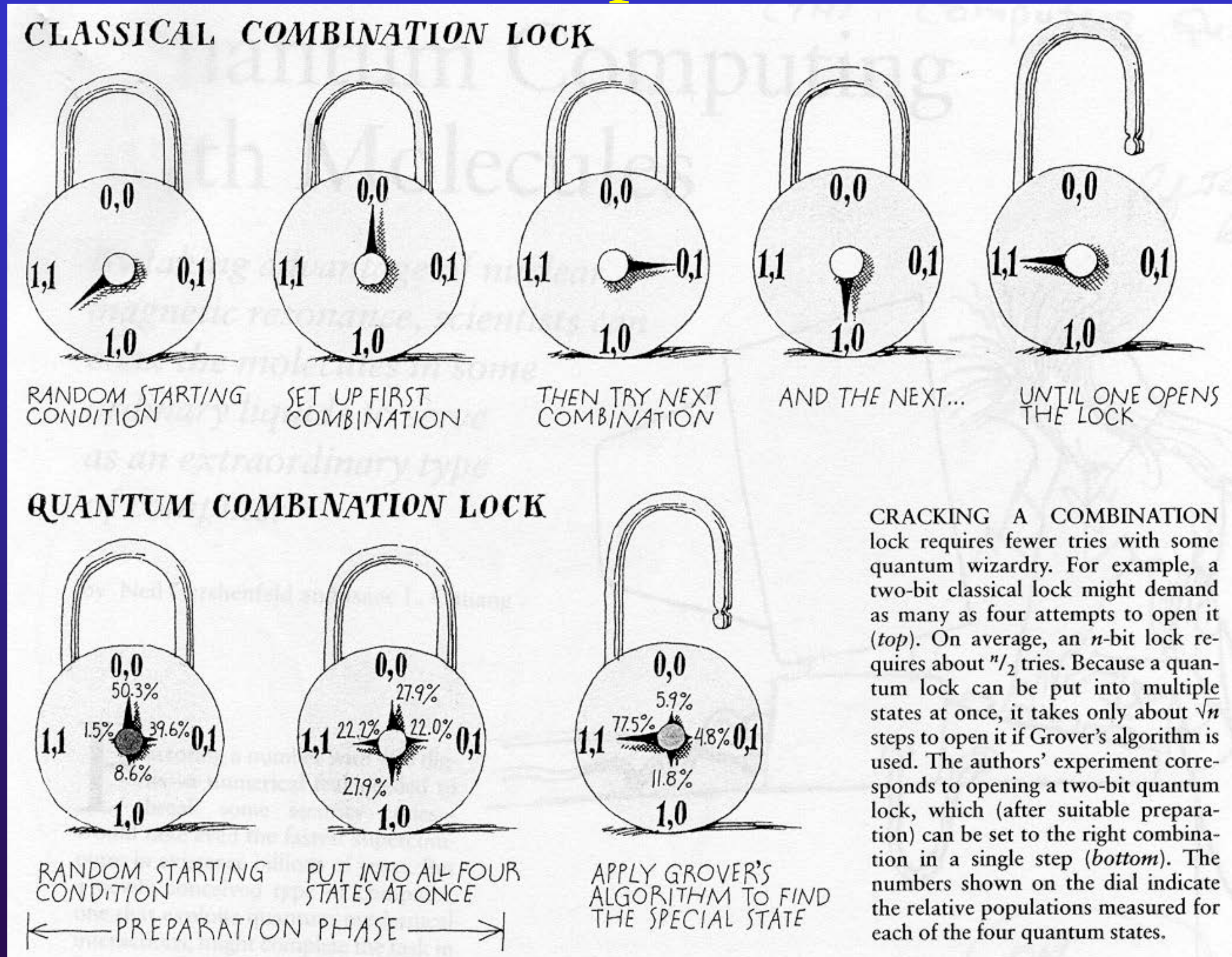
  400-digit number - minutes

Preskill Physics Today

52(6) 24-30 (1999)

Quantum Computers

- Use the superposition of quantum mechanical states to solve problems in parallel



CRACKING A COMBINATION lock requires fewer tries with some quantum wizardry. For example, a two-bit classical lock might demand as many as four attempts to open it (*top*). On average, an *n*-bit lock requires about $^n/_2$ tries. Because a quantum lock can be put into multiple states at once, it takes only about $\sqrt{n}$ steps to open it if Grover's algorithm is used. The authors' experiment corresponds to opening a two-bit quantum lock, which (after suitable preparation) can be set to the right combination in a single step (*bottom*). The numbers shown on the dial indicate the relative populations measured for each of the four quantum states.

Gershenfeld and Chuang, Sci. Am., June 1998, pp. 66-71

Superposition of States

- Horizontally polarized light

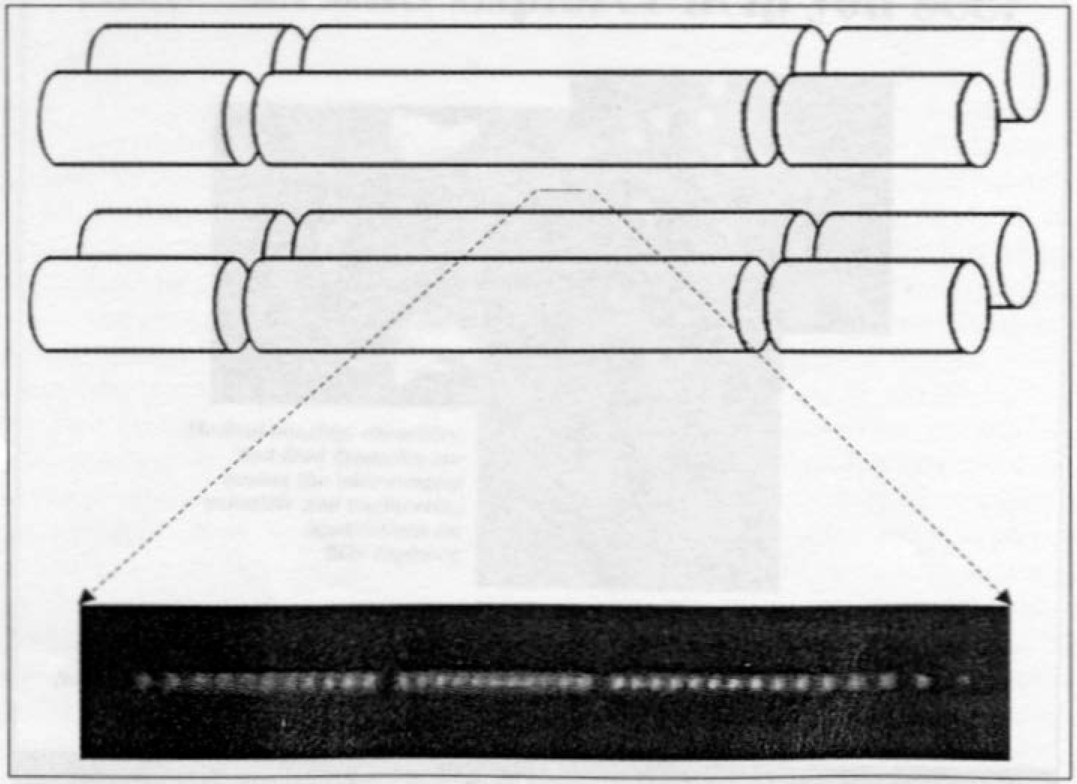
- Vertically polarized light

What Constitutes a Quantum Computer?

- A two-state quantum system, *i.e.*, a qubit (NMR spin 1/2 up or spin 1/2 down, either in a single nucleus or an ensemble)
- A means to prepare the initial quantum state of the qubits with an equal amplitude in each basis state (90^o NMR) pulse
- A means to implement interactions between various qubits through a series of unitary operations (ENDOR)
- A readout that collapses the system to a final basis state which is then observed as the answer

How Do You Build a Quantum Computer?

- An N-bit QC requires individual addressing and coupled manipulations of each spin in the system, *e.g.*, address a single spin, or couple spins 5, 19, 30
- Microscopic versus macroscopic quantization?



Linear trap (above sketch) aligns more than 30 mercury ions between its electrodes. Lower image shows the ions greatly enlarged. Ion trapping is one of several approaches to carrying out quantum computing. Figure courtesy of the National Institute of Standards and Technology, Boulder, CO.

Forbes & Lloyd, Comp. in Phys., 12:8-11 (1998)

Systems Suitable for Quantum Computing

Since all quantum mechanical operations are unitary (conserve probability), almost *any* quantum mechanical system can be used

- NMR (ensembles of nuclei or a single nucleus)
- Single beryllium ion in an ion trap
- Photon/atom interaction in an optical cavity
- Photons in a small superconducting cavity
- Quantum Hall effect
- Josephson junction/SQUID with Cooper pair tunnelling
- Quantum dots
- Polymeric molecules
- Electrons floating on a film of superfluid helium

QUBIT, Superposition, and Quantum Parallelism

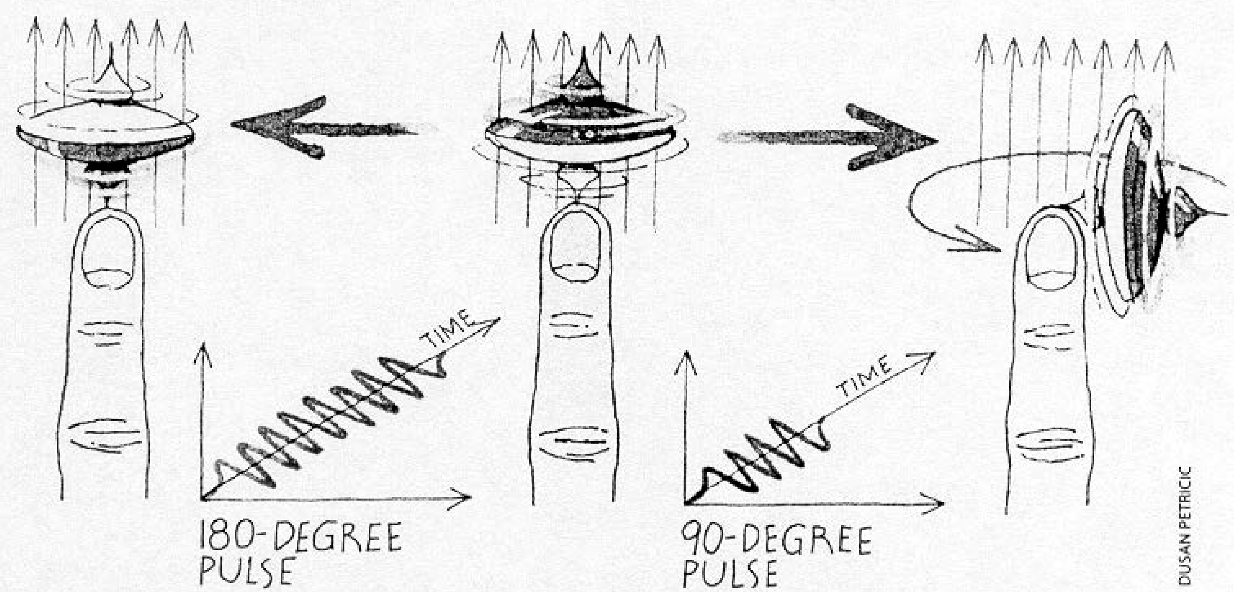
- Any quantum system with two accessible states represents a quantum bit or qubit
- In contrast to classical Boolean logic where a bit is *either* 1 or 0, a qubit can be in a superposition of two states $\Psi = 2^{-1/2}$ (|1> + |2>)
- Qubyte = 8 qubits
  - If the state of each of 8 qubits is a superposition of 0 and 1, then the qubyte represents the superposition of 00000000, 00000001,…11111111, *i.e.*, 2^8 or 256 combinations, which can be evaluated in "quantum parallelism"
  - 10 qubytes = $2^{80} = 10^{24}$ combinations = 1 mole of states

Basic QC Building Blocks - 1

- Prepare superposition of states, *e.g.*, 90º pulse to put spin in

$\Psi = 2^{-1/2}$ (|1> + |2>)

- Superposition of states can remain as long as the wave function is not collapsed by a measurement

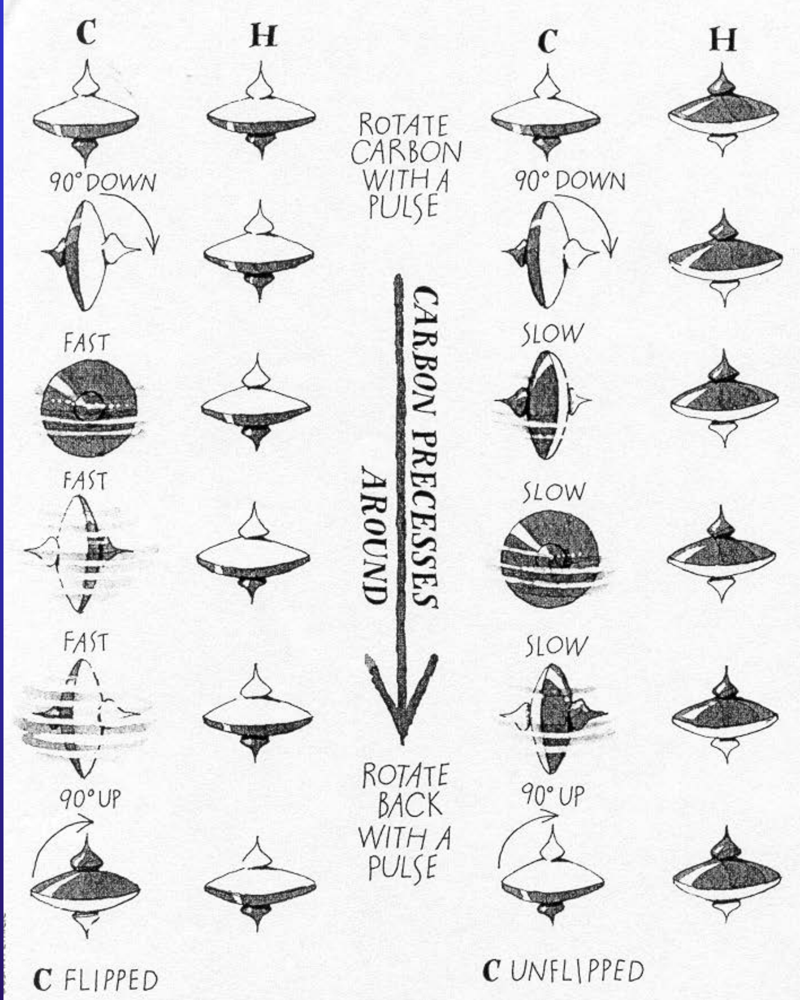


MAGNETIC NUCLEUS acts like a spinning top. The spin axis will normally align along the direction of a magnetic field applied constantly (*center*). A suitable oscillatory field can then induce the spin to reorient. For example, a 180-degree pulse (*left*) causes a spinning nucleus to flip entirely over. A 90-degree pulse (*right*) would force it to tip perpendicular to the constant magnetic field (*vertical arrows*). After it tips over, the spin axis will itself rotate slowly around, just as with a child's toy.

Gershenfeld and Chuang, Sci. Am., June 1998, pp. 66-71

Basic QC Building Blocks - 2

- Selective inversion of the phase of amplitudes in certain states, *e.g.*, H^1 and C^{13} in chloroform (Fig), or electron spin flip depending upon nuclear spin (controlled-NOT or exclusive OR)



CONTROLLED-NOT LOGIC GATE inverts one of two inputs conditionally on the state of the second. The authors created a quantum controlled-NOT gate using the interaction between the nuclear spins of hydrogen and carbon in chloroform molecules. First, an oscillatory pulse selectively rotates the carbon nucleus 90 degrees. This nucleus then precesses rapidly (if the adjacent hydrogen is in one state) or slowly (if the hydrogen is in the opposite state). Waiting a suitable amount of time and then applying another 90-degree pulse causes the carbon to invert (*left*) or to remain the same as it was originally (*right*), depending on the state of the neighboring hydrogen.

Gershenfeld and Chuang, Sci. Am., June 1998, pp. 66-71

Quantum versus Classical Gates: Square Root of NOT

- NOT
- CF
- QCF

Hayes, Am. Sci., 83: 304-308 (1995)

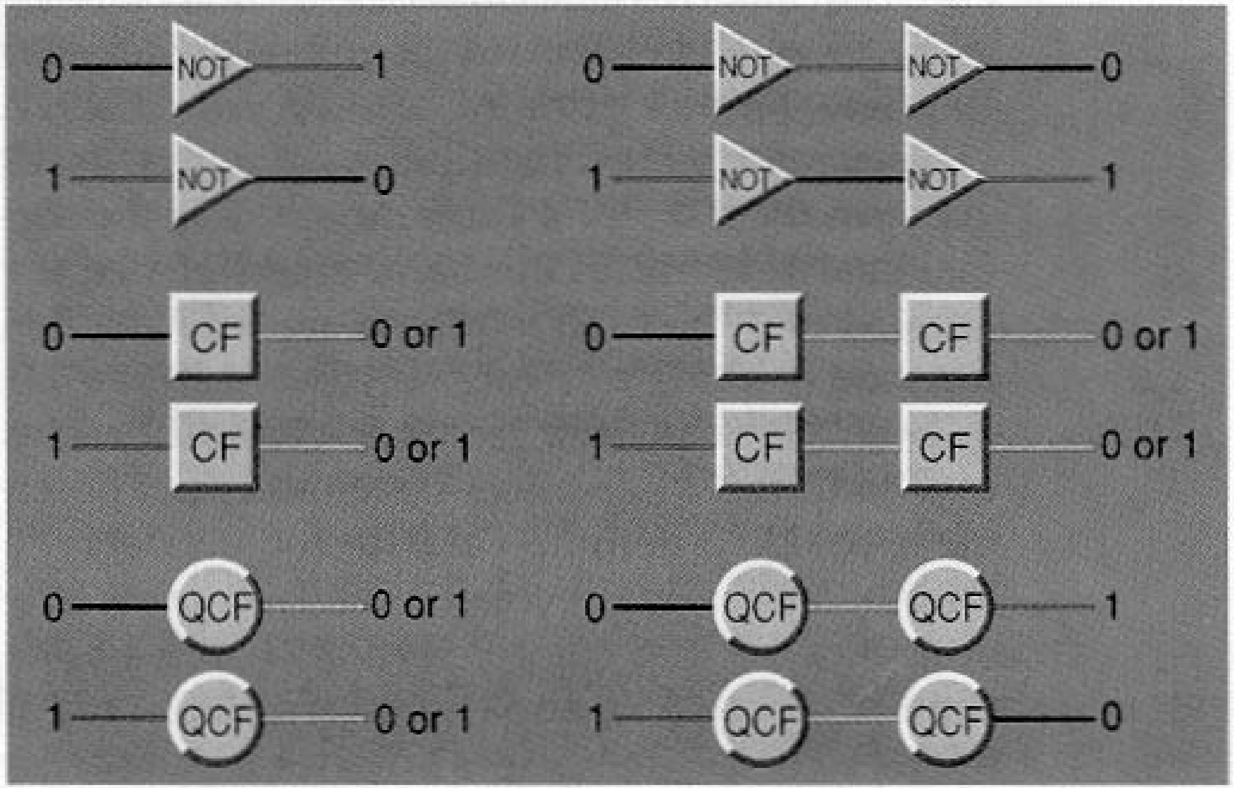


Figure 1. Logic gates are fundamental units of computer architecture—the NOT gate for classical machines, the coin-flip gate (CF) for probabilistic ones and the quantum coin flip (QCF) for quantum computers. The QCF gate calculates "the square root of NOT."

Amplitude vs Probabilities: Interference in QCF^2

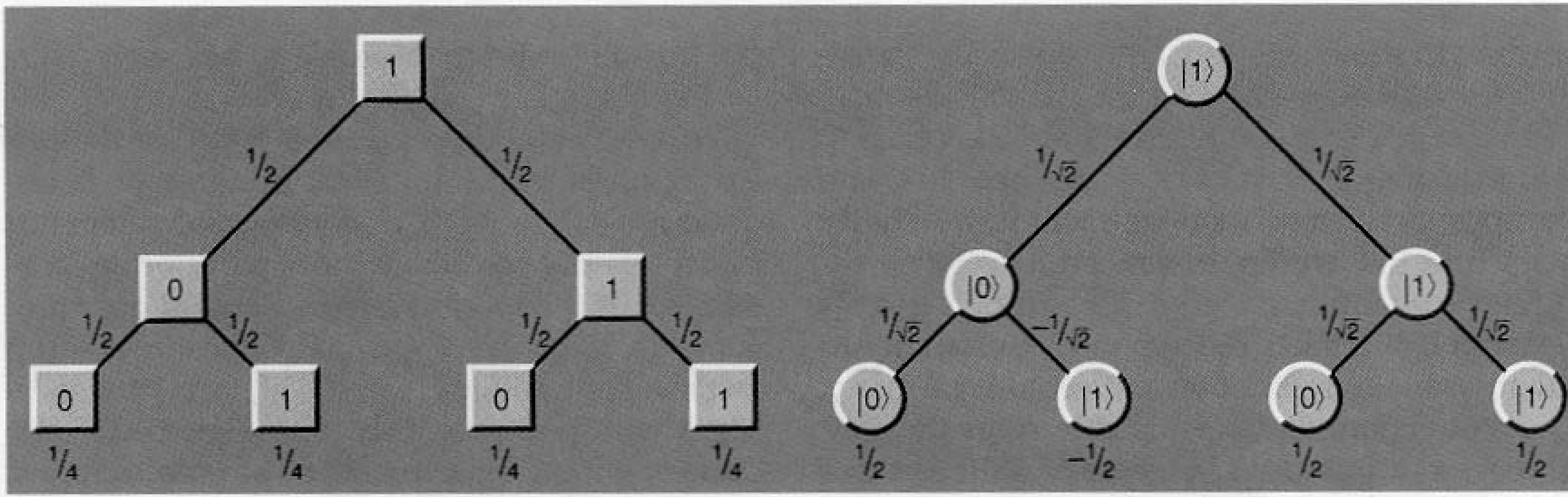


Figure 2. Four computational paths through a pair of CF gates *(left)* yield a 0 or 1 with equal probability, whereas two of the paths through a pair of QCF gates *(right)* have amplitudes that interfere destructively, making a 0 the certain outcome.

Hayes, Am. Sci., 83: 304-308 (1995)

- Classical: Probabilities
- QC: Wave Function Amplitude and Coherent Superposition The wave function phase is maintained throughout the calculation, so that multiple paths through indeterminant intermediate states can interfere constructively or destructively to produce a definite output value. Probability =Amplitude^2

Features of Quantum Logic

- Matrix of transition amplitudes must be unitary (probability conserved)
- Quantum logic is reversible
- Reversible gates must have the same number of inputs and outputs (3-wire AND)
- Reversible = arbitrarily low energy consumption
- 2 qubits = universal gate

Hayes, Am. Sci., 83: 304-308 (1995)

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Examples of Quantum Logic: NOT

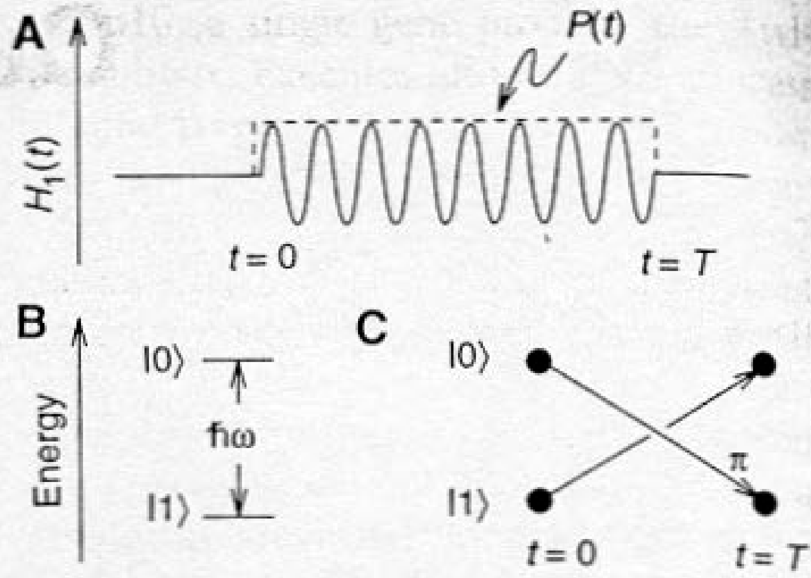


Fig. 1. The action of the NOT or inverter gate. The Hamiltonian describing the magnetic-resonance manipulation that results in the NOT operation is $\mathbf{H} = g\mu[H_0\sigma_z + H_1(t)\sigma_y]$. (**A**) The time dependence of the magnetic field of the tipping pulse, in this example a sinusoid at frequency ω multiplied by a square function $P(t)$ going from time $t = 0$ to $t = T$. (**B**) Energy level diagram for the qubit. The tipping pulse is tuned to be in resonance with the energy gap between the two stationary energy eigenstates $|0\rangle$ and $|1\rangle$. (**C**) State evolution diagram, showing the evolution paths of the two computational basis states. The π in this diagram denotes that on the path indicated, the state acquires a 180° phase shift (assuming the parameters are chosen such that $\omega T = 0$ and $\Omega T = \pi$).

DiVincienzo Science 270: 255-261 (1995)

Examples of Quantum Logic: XOR & ENDOR

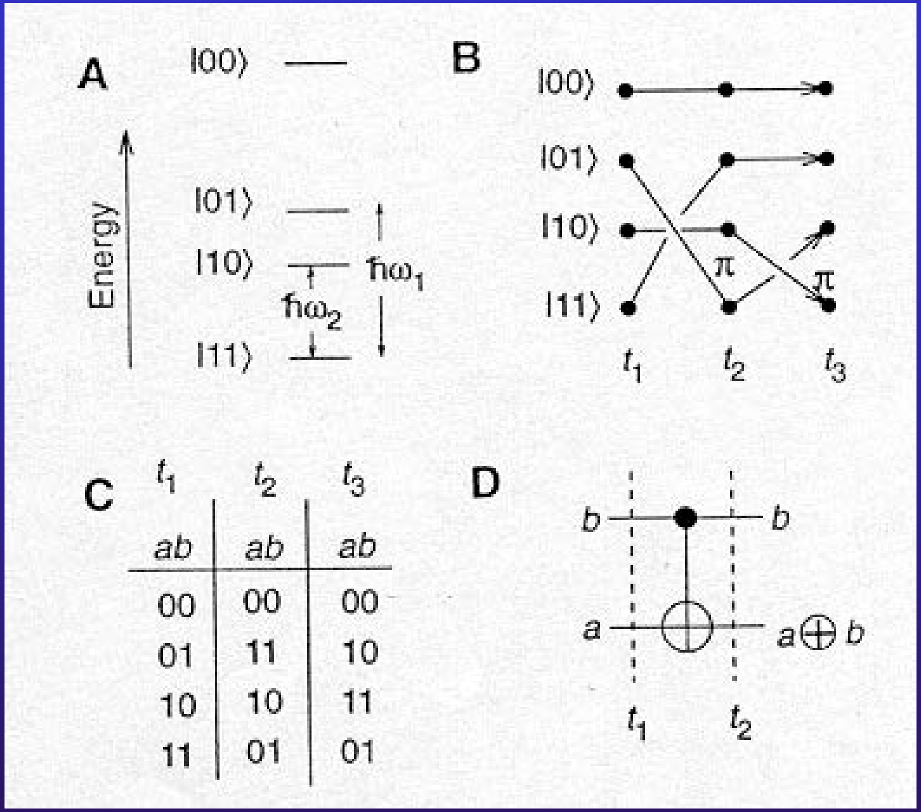
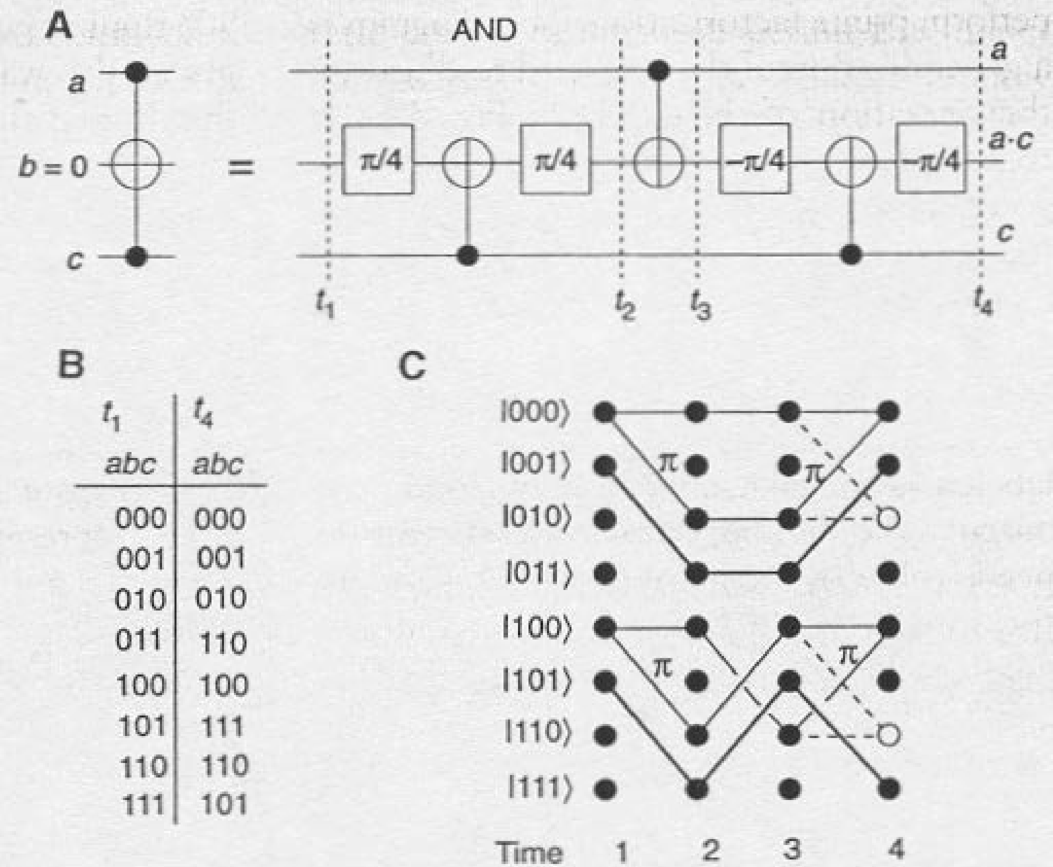


Fig. 2. The action of the two-qubit XOR gate. (**A**) Energy level diagram for the two qubits, showing the four stationary states of the Hamiltonian in Eq. 4. The states are labeled by the two qubit values of the two spins $|ab\rangle$. (**B**) The time evolution pathways of the quantum states under the action of the tipping-pulse protocol described in the text. Again, the π's denote 180° phase shifts along the indicated pathways. (**C**) The truth table summarizing the result of the time evolution of the gate from the initial state (time t_1) to after the first (time t_2) and second (time t_3) tipping pulses. (**D**) The gate notation used for the XOR operation, obtained by using just the first of the two pulses of the ENDOR protocol. The resulting gate leaves qubit b unchanged and leaves a in the state given by the sum of a and b, modulo 2.

DiVincienzo Science 270: 255-261 (1995)

Examples of Quantum Logic: AND



t_1 *abc*	t_4 *abc*
000	000
001	001
010	010
011	110
100	100
101	111
110	110
111	101

Fig. 3. Construction of the AND gate. (**A**) A notation for the three-qubit AND operation, and a gate construction of AND using three XOR gates and four single-qubit rotations. The $\pi/4$ gate corresponds to the operation in Eq. 3, with $\omega T = 0$ and $\Omega T = \pi/4$. When the work qubit b is initially set to $|0\rangle$, it ends up in the state $|a{\cdot}c\rangle$. (**B**) The full truth table of the three-qubit AND gate. (**C**) The state evolution diagram for the AND gate, showing the intermediate state along selected pathways at the times shown in (A). A new feature appears here: For some input states, the intermediate state is a superposition of two different computational pathways. The final state is definite again because constructive interference permits only one of the possible outcomes (the pathways that interfere destructively at the last step are dashed).

DiVincienzo Science 270: 255-261 (1995)

Examples of Quantum Logic:

Shor factorization procedure

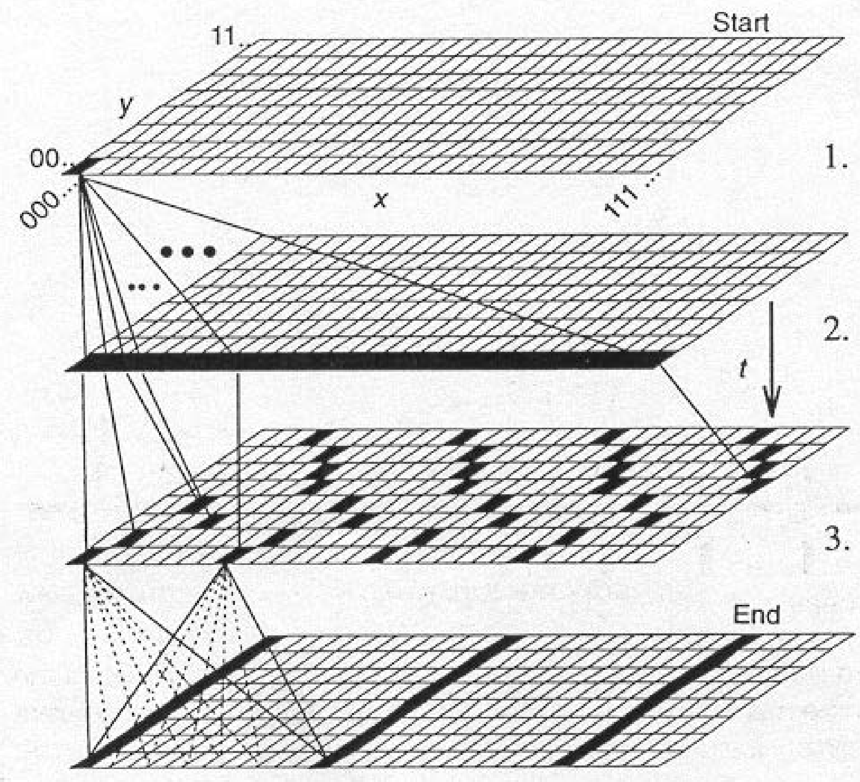


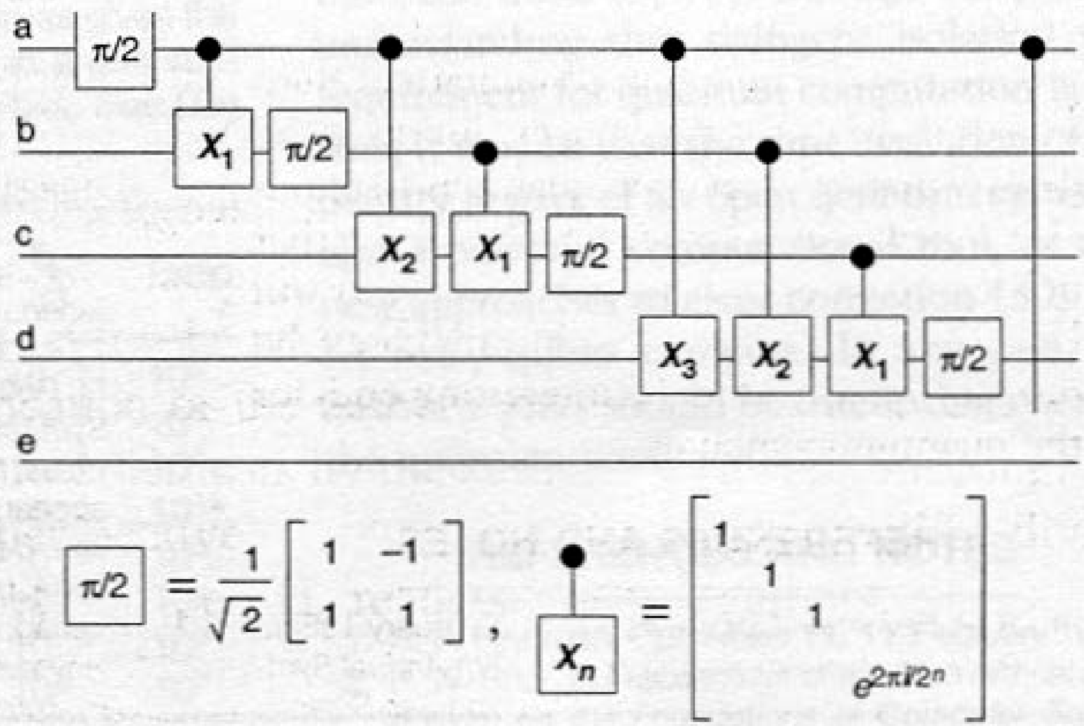
Fig. 5. A schematic depiction of the time evolution pathways in Shor's prime factoring procedure. The computational states appearing in the wave function at each selected instant in time are indicated by the filled rectangles. A few of the pathways are sketched out. Most of the pathways in the final step (dotted lines) interfere destructively, with only a few (solid lines) interfering constructively.

DiVincienzo Science 270: 255-261 (1995)

Examples of Quantum Logic:

Fourier transform for the Shor factorization procedure

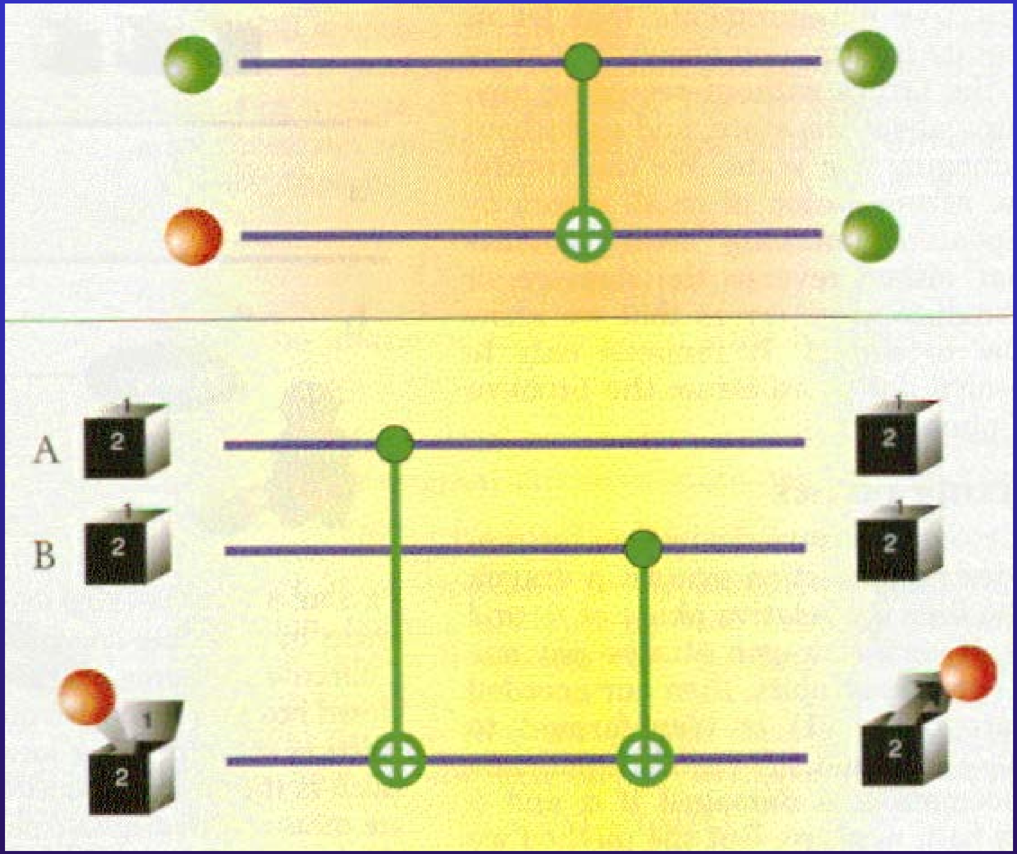
Fig. 6. The gate array introduced by Coppersmith (*25*) for performing the Fourier transform (step 3 of the Shor procedure in Fig. 5). The matrix unitary operators corresponding to the two types of quantum gates used in the figure are shown. The two-qubit X_n gate may be implemented by a simple combination of XORs and one-qubit gates (*12*). The X_n gate acts symmetrically on its two qubits. The process can be extended for inputs beyond a through e.



DiVincienzo Science 270: 255-261 (1995)

Quantum Error Correction

- Quantum non-clonability means that you can't read a qubit to see if it is flipped or has phase error without destroying the coherent information
- $\Psi = a\,|1> + b\,|2>$
- Create redundant states
- Compare contents of two states without collapsing either
- 9 qubits per needed qubit



Preskill Physics Today 52(6) 24-30 (1999)

Quantum Effects for Quantum Logic

- Superposition of states
- Interference
- Entanglement
- Decoherence
- Nonclonability and uncertainty
- EPR transponders
- Others?

Potential Applications of Quantum Computers

- Search of an unsorted database
  - Grover search algorithm $N^{1/2}$ QC versus N/2 steps classically
- Factorization
  - Shor's factorization algorithm (QM FT to estimate sequence periodicity)
  - Classical is exponential in N, QC is polynomial
- Parity problem -- determine the parity of a binary function over a domain of length N. Only 2x faster than classical! There are more parity problems than search or factorization problems
- Mean and median of a population
- NP-complete? travelling salesman, and Ising model problems
  - Graph coloring ($N^{1/2}$ of possibilities, exponential in problem size)
  - Were QM nonlinear, there would be efficient QC NPC algorithms, but that would lead to superluminal communication and non-causality
- Quantum mechanical calculations
- Encryption, EPR keys

The Future: 10^{23} qubits in a cm^3 of salt...

- Existing NMR spectrometers = 10 qubits at 300 K
  - Special NMR spectrometers 3-4x
  - Signal strength decays exponentially with number of qubits
  - Coherence time decreases and gate time increases with larger molecules
  - Optical pumping to align (cool) nuclei
- In fluids, 1000 operations in the decoherence time
  - For factoring, the ratio *R* of switching time to decoherence time should be (number of bits to be factored) ^{3}
  - To factor 15 need two 4-qubit registers with *R* = 64
  - To factor 1000 need two ten-qubit registers with *R* = 1000
  - Error correction….

The Future, Con't

- Few qubits for quantum teleportation
- 10 qubits for quantum cryptography
- 100 qubits for repeater for a noisy quantum cryptographic link
- Shor factoring
  - millions of operations on thousands of bits

Quantum system	t_{switch} (s)	t_{ϕ} (s)	Ratio*
Mössbauer nucleus	10^{-19}	10^{-10}	10^{9}
Electrons: GaAs	10^{-13}	10^{-10}	10^{3}
Electrons: Au	10^{-14}	10^{-8}	10^{6}
Trapped ions: In	10^{-14}	10^{-1}	10^{13}
Optical microcavity	10^{-14}	10^{-5}	10^{9}
Electron spin	10^{-7}	10^{-3}	10^{4}
Electron quantum dot	10^{-6}	10^{-3}	10^{3}
Nuclear spin	10^{-3}	10^{4}	10^{7}

DiVincienzo Science 270: 255-261 (1995)

* Factorable bits = $\text{Ratio}^{1/3}$

The Future: JJ?

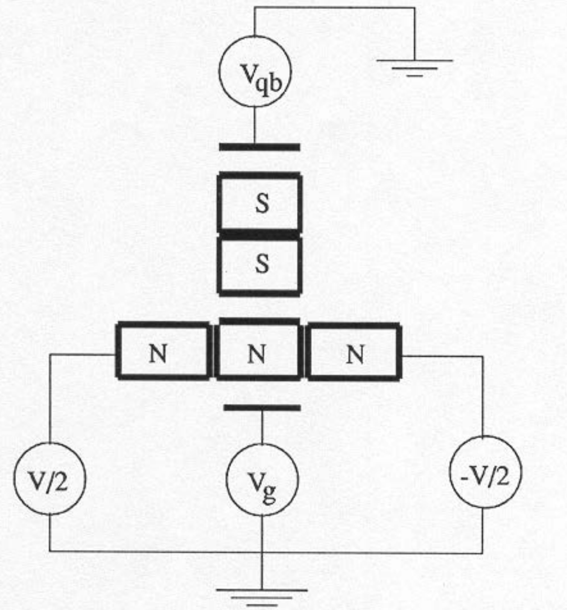


FIG. 1. The circuit consisting of a q-bit plus a SET transistor used as a measuring device.

PHYSICAL REVIEW B VOLUME 57, NUMBER 24 15 JUNE 1998-II

Quantum measurements performed with a single-electron transistor

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(Received 20 January 1998; revised manuscript received 11 March 1998)

Low-capacitance Josephson junction systems as well as coupled quantum dots, in a parameter range where single charges can be controlled, provide physical realizations of quantum bits, discussed in connection with quantum computing. The necessary manipulation of the quantum states can be controlled by applied gate voltages. In addition, the state of the system has to be read out. Here we suggest to measure the quantum state by coupling a single-electron transistor to the q-bit. As long as no transport voltage is applied, the transistor influences the quantum dynamics of the q-bit only weakly. We have analyzed the time evolution of the density matrix of the transistor and q-bit when a voltage is turned on. For values of the capacitances and temperatures which can be realized by modern nanotechniques, the process constitutes a quantum measurement process. [S0163-1829(98)03024-0]

The Future: JJ?

Josephson-junction qubits with controlled couplings

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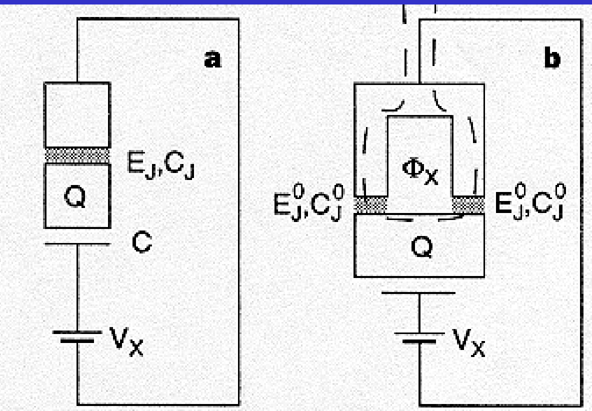

Figure 1 Josephson junction qubits. **a**, A simple realization of a qubit is provided by the superconducting electron box. A superconducting metallic island is coupled by a Josephson tunnel barrier (with capacitance C_J and Josephson coupling energy E_J; grey area) to a superconducting lead and through a gate capacitor C to a voltage source. The important degree of freedom is the Cooper-pair charge $Q = 2ne$ on the island. **b**, The improved design of the qubit. The island is coupled to the circuit via two Josephson junctions with parameters C_J^0 and E_J^0. This d.c.-SQUID can be tuned by the external flux Φ_x which is controlled by the current through the inductor loop (dashed line). If the self-inductance L_Φ of the SQUID is low, $\Phi_0^2/L_\Phi \gg 4\pi^2 E_J^0, e^2/C_J^0$, fluctuations of the flux from Φ_x are weak. Furthermore, if the frequency of flux oscillations is high, $\hbar\omega_\Phi = \hbar(L_\Phi C_J^0/2)^{-1/2} \gg E_J^0, E_{ch}, k_B T$, the Φ-degree of freedom is in the ground state. In this case, the set-up allows switching the effective Josephson coupling to zero. ($E_J = 0$ requires the Josephson energies of two junctions in the loop to be equal. This has been reached with a precision of 1% in quantum tunnelling experiments[17]. Even with this precision, taking into account[10] the finite value of E_J one can perform a large number of logical gates. On the other hand, by replacing one junction in **b** by another SQUID, one can tune the Josephson couplings to be equal.) The effective junction capacitance is $C_J = 2C_J^0$.

"Control over tunnel coupling is achieved by replacing one Josephson junction of the Cooper-pair box with a pair of junctions in a superconducting loop -- a system that is sensitive to an external magnetic field." D.V. Avrin"

Nature 298: 305-307 (1999)

The Future: JJ?

letters to nature

Coherent control of macroscopic quantum states in a single-Cooper-pair box

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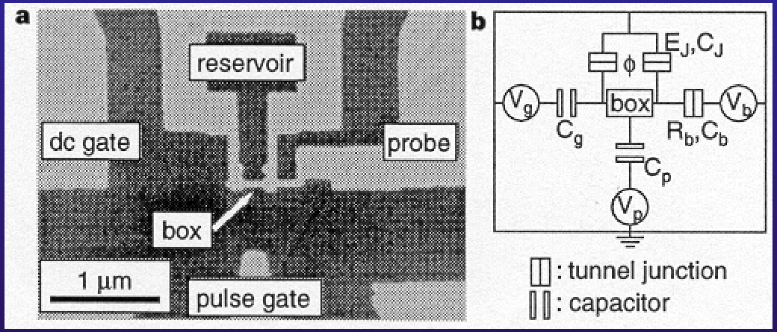


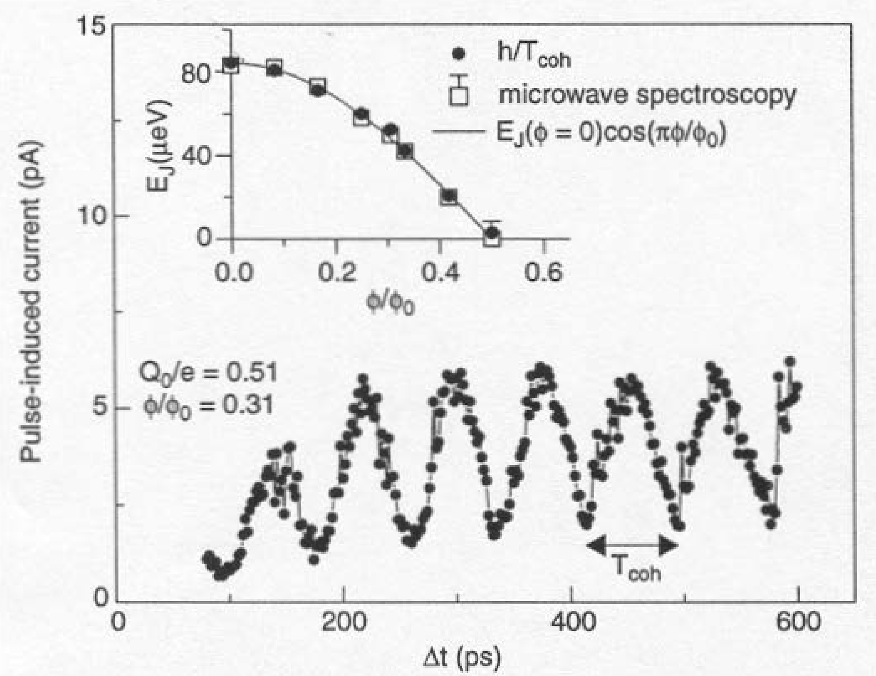


Figure 4 Pulse-induced current as a function of the pulse length Δt. The data correspond to the cross-section of Fig. 3a at $Q_0/e = 0.51$. Inset, Josephson energy E_J versus the magnetic flux ϕ penetrating through the loop. E_J was estimated by two independent methods. One was from the period of the coherent oscillation T_{coh} as h/T_{coh}. The other was from the gap energy observed in microwave spectroscopy[4]. The solid line shows a fitting curve with $E_J(\phi = 0) = 84\,\mu eV$ assuming cosine ϕ-dependence of E_J.

Nature 298: 786-788 (1999)

The Future?

Recommended Disclaimer: "This scheme, like all other schemes for quantum computation, relies on speculative technology, does not in its current form take into account all possible sources of noise, unreliability and manufacturing error, and probably will not work"

"After fifteen years and fifteen billion dollars, quantum computers will be able to factor the number 15."

Rolf Landauer

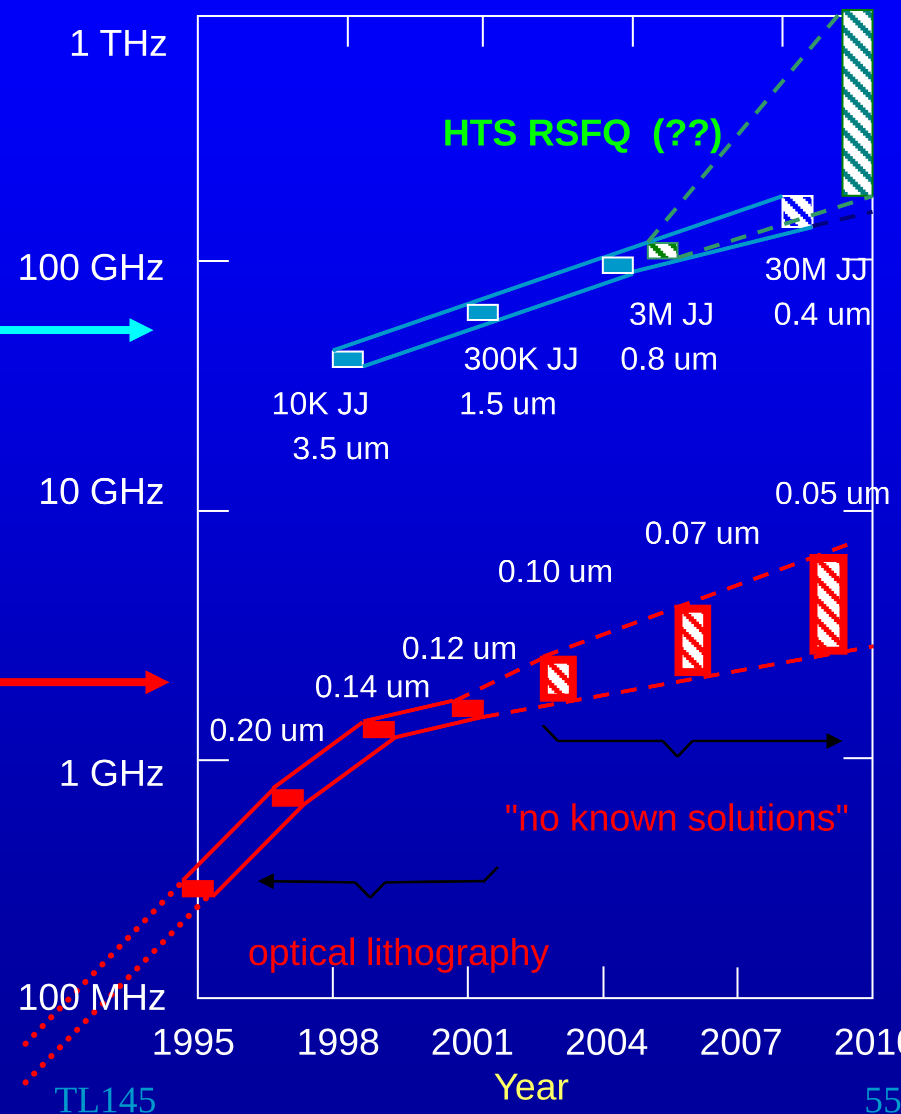
If Not QC or DNA, Then What?

- Have the steady progress in silicon since 1965 and the rosy industry statements led DARPA to expect that the next leap must be a giant one to QC and DNA?
- Will QC and DNA make the leap?
- A smaller leap is Josephson junctions using Rapid Single Flux Quantum (RSFQ) logic

RSFQ ROADMAP
(VLSI circuit clock frequency)

RSFQ (Stony Brook Forecast)

CMOS (SIA Forecast 1997)



Courtesy of Konstantine Likharev

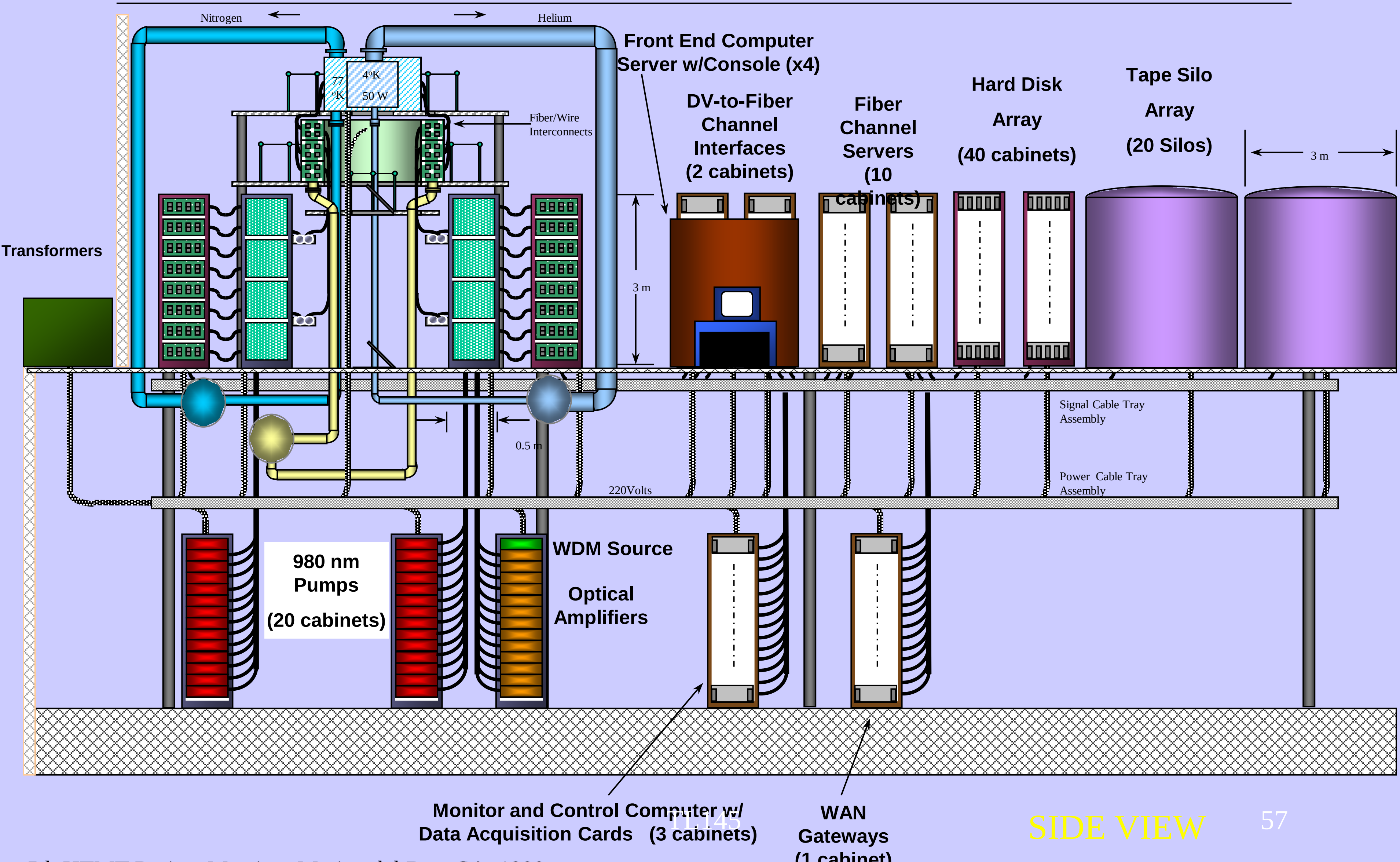
Possible Petaflops Scale Computers by Year 2006: Speed and Power Scales

	Semiconductors (CMOS)		COOL-0 (RSFQ)
Performance:	> 100K chips @ <10 Gflops each	Performance:	4K processors @ 256 Gflops each
Power:	>150 W per chip ⇒ total > 15 MW	Power:	0.05 W per SPELL ⇒ total 250 W @ 4.2 K (100 kW @ 300 K)
Footprint:	>30x30 m^2 ⇒ Latency > 1 μs	Footprint:	1x1 m^2 ⇒ Latency 20 ns

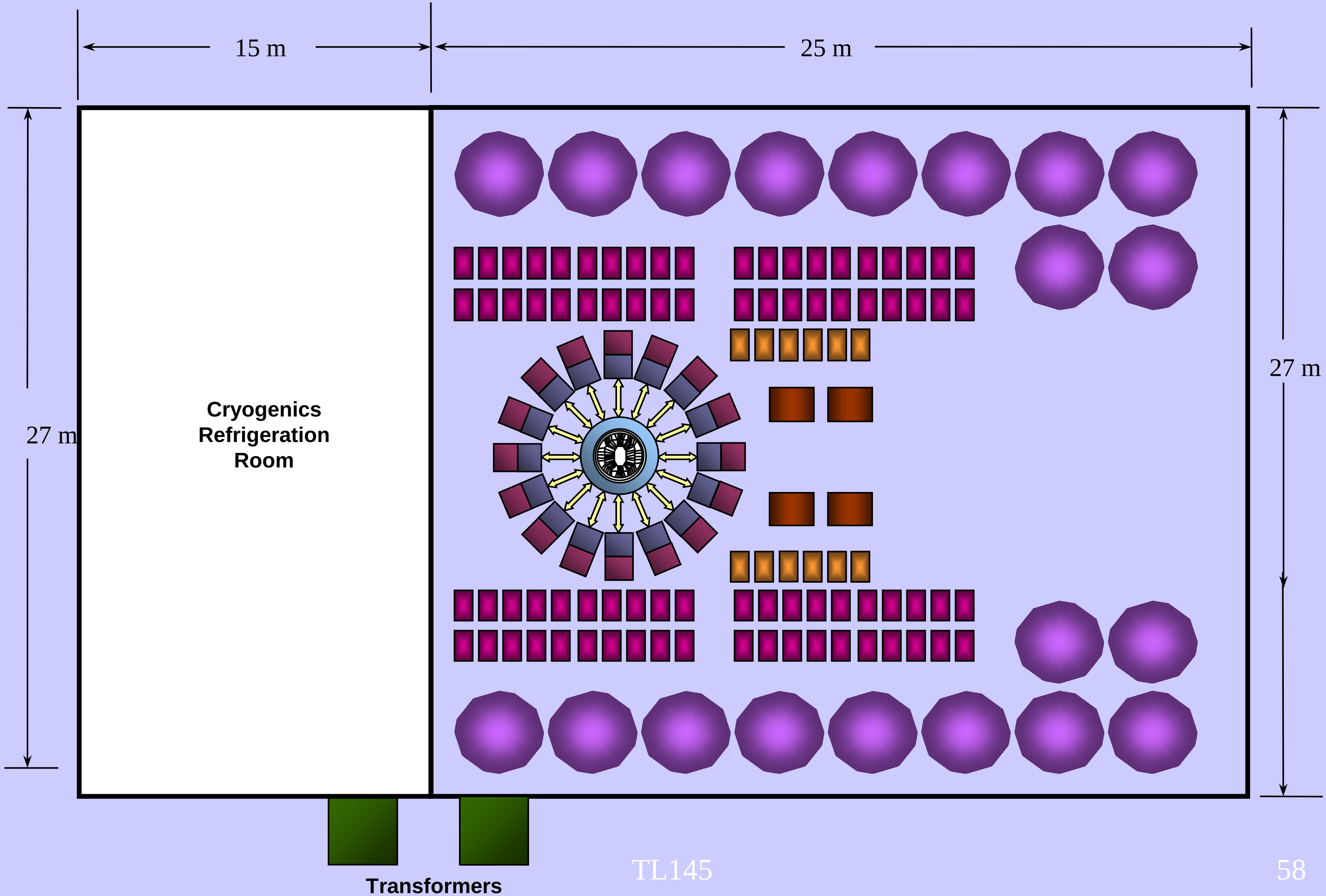
Courtesy of Konstantine Likharev

Hybrid Technologies MultiThreaded (HTMT) Machine Room

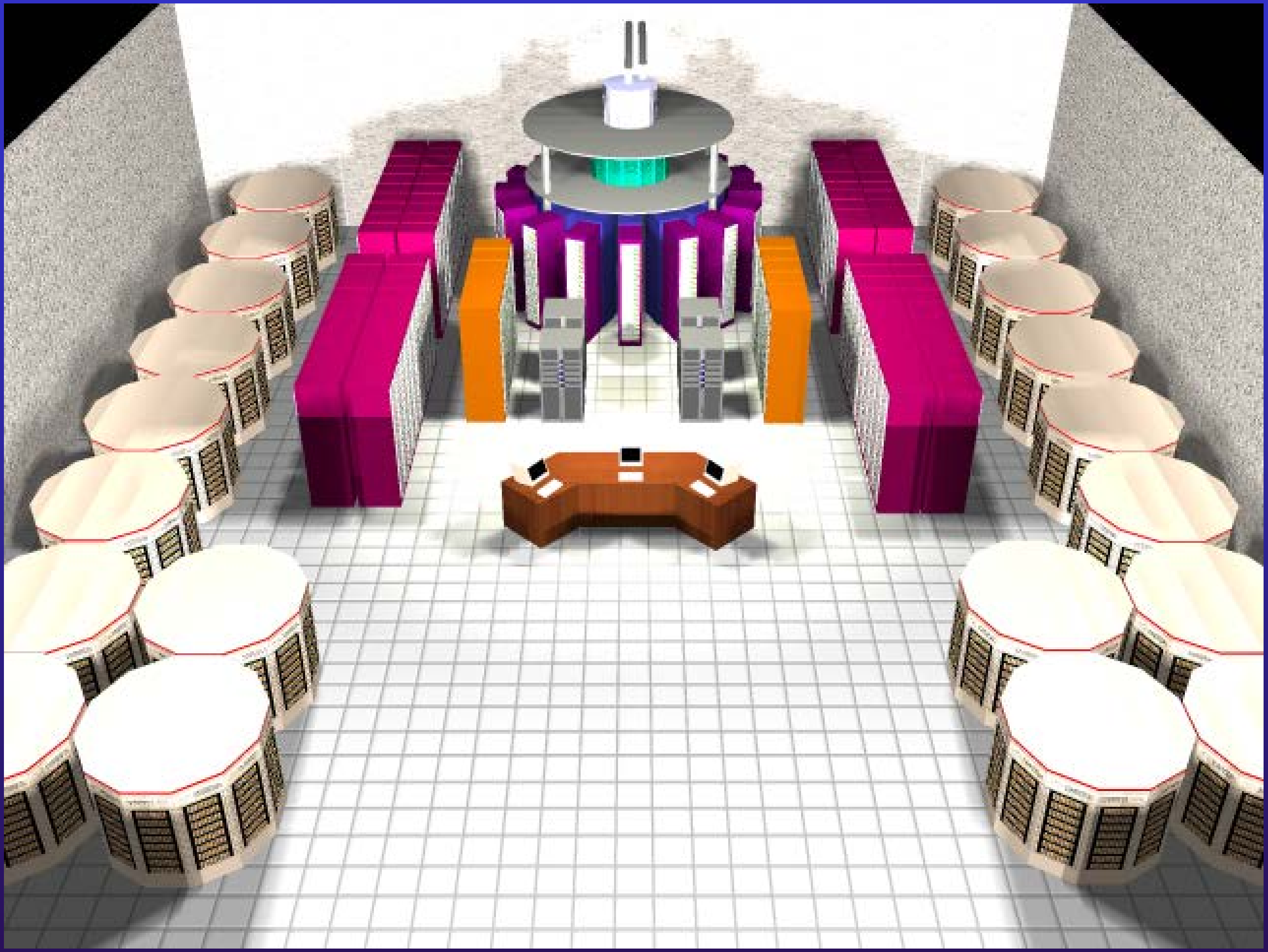
Steve Monacos, John Michael Morookian, Harold Kirkham, Larry Bergman, JPL



HTMT Facility (Top View)



HTMT Facility (Perspective)

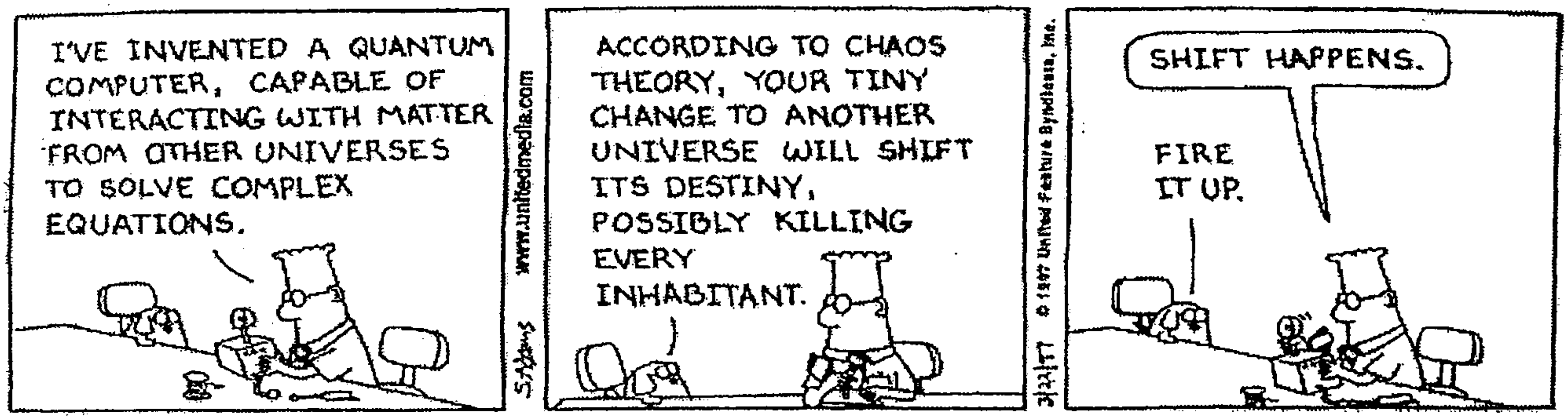


Closing Thoughts

- The search:
  - The “killer” application
  - The funding agency
- Life is the ultimate DNA Computer
  - *Homo computans*
- The Universe is the ultimate Quantum Computer

Next Talks in the Series

- Optical Computing -- Jon Gilligan
- Materials beyond silicon ...
- Computing with quantum dots ...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FIRE IT UP.