Is Quantum Computing a Solution for Semiconductor Scaling?

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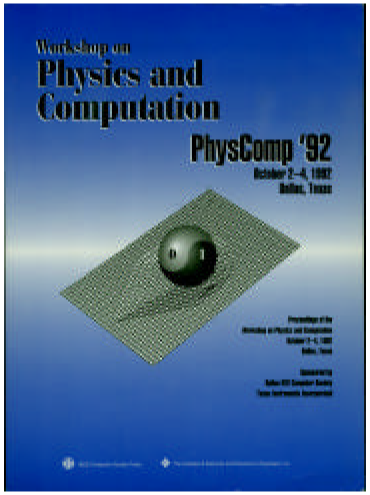
Introduction and Outline

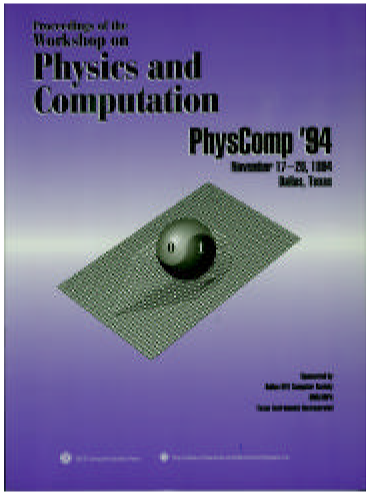
Topics in Presentation

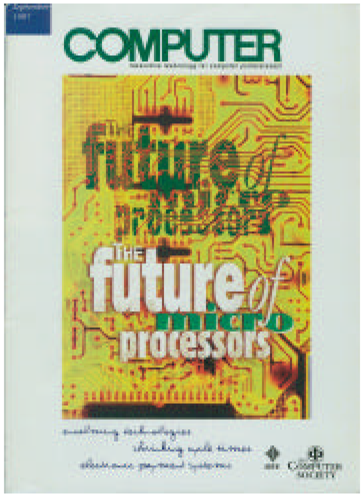
- What does it take to build a GP computer?
- Limits of semiconductor/computer scaling
- Introduce idealized model of computational costs
- Introduce Quantum computing
- Information is Physical
- Compare/Contrast Classical Comp vs. QuComp
- Computing Myths
- Conclusions

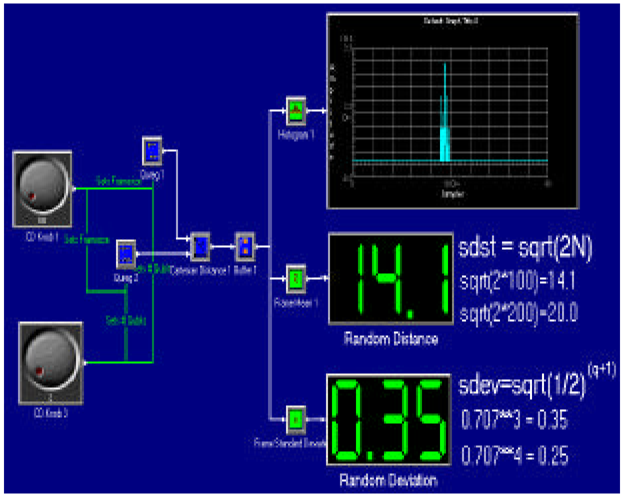
Motivation: Limits of Computation

- >25 Years in semiconductor company (HW/SW)
- PhysComp 1981, <u>1992</u>, <u>1994</u>, 1996 (<u>chairman</u>)
- Billion Transistor issue of Computer Sept 1997
- Ph.D in area of Quantum Computing May, 2002
- Quantum Computing Research contract 2003-2004









Conventional semiconductors will stop scaling in next 10+ years

End of Silicon Scaling

"Manufacturers will be able to produce chips on the 16-nanometer* manufacturing process, expected by conservative estimates to arrive in 2018, and maybe one or two manufacturing processes after that, but that's it."

This is actually a power density/heat removal limit!!

Quote from News.com article "Intel scientists find wall for Moore's Law" and Proc of IEEE Nov 2003 article: "Limits to Binary Logic Switch Scaling—A Gedanken Model"

*gate length of 9 nm, 93 W/cm^2 & 1.5×10^2 $gates/cm^2$

ITRS: International Technology Roadmap for Semiconductors

15 year forecast from 2003 ITRS - International Technology Roadmap for Semiconductors at: http://www.itrs.net/

These sizes are close to physical limits and technological limits.

Near-term Years

YEAR OF PRODUCTION	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*
Technology Node		**hp90**			**hp65**		
DRAM ½ Pitch (nm)	**100**	**90**	**80**	**70**	**65**	**57**	**50**
MPU/ASIC M1 ½ Pitch (nm)	**120**	**107**	**95**	**85**	**75**	**67**	**60**
MPU/ASIC Poly Si ½ Pitch (nm)	**107**	**90**	**80**	**70**	**65**	**57**	**50**
MPU Printed Gate Length (nm)	**65**	**53**	**45**	**40**	**35**	**32**	**28**
MPU Physical Gate Length (nm)	**45**	**37**	**32**	**28**	**25**	**22**	**20**

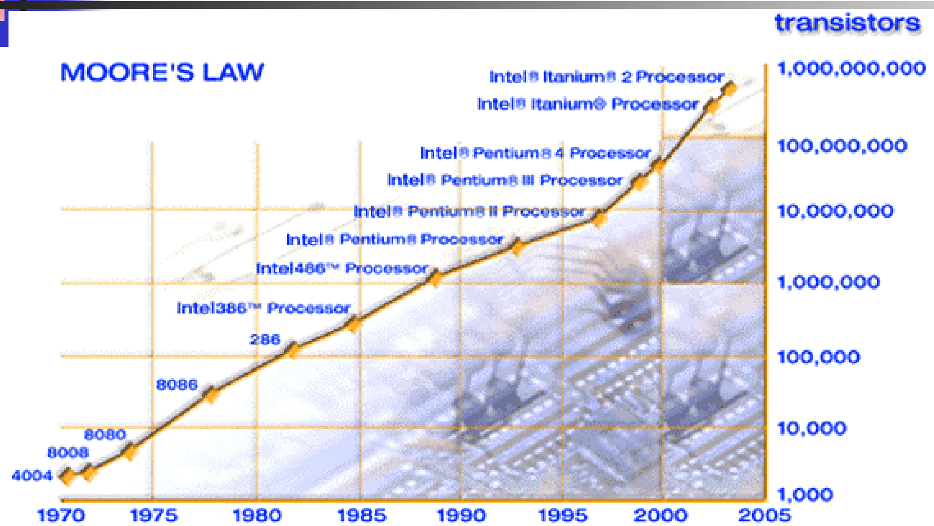
Long-term Years

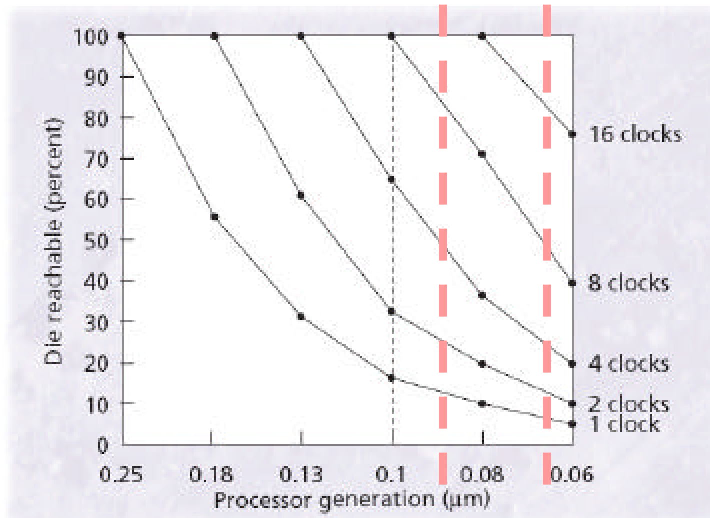
YEAR OF PRODUCTION	*2010*	*2012*	*2013*	*2015*	*2016*	*2018*
Technology Node	**hp45**		**hp32**		**hp22**	
DRAM ½ Pitch (nm)	**45**	**35**	**32**	**25**	**22**	**18**
MPU/ASIC M1 ½ Pitch (nm)	**54**	**42**	**38**	**30**	**27**	**21**
MPU/ASIC Poly Si ½ Pitch (nm)	**45**	**35**	**32**	**25**	**22**	**18**
MPU Printed Gate Length (nm)	**25**	**20**	**18**	**14**	**13**	**10**
MPU Physical Gate Length (nm)	**18**	**14**	**13**	**10**	**9**	**7**

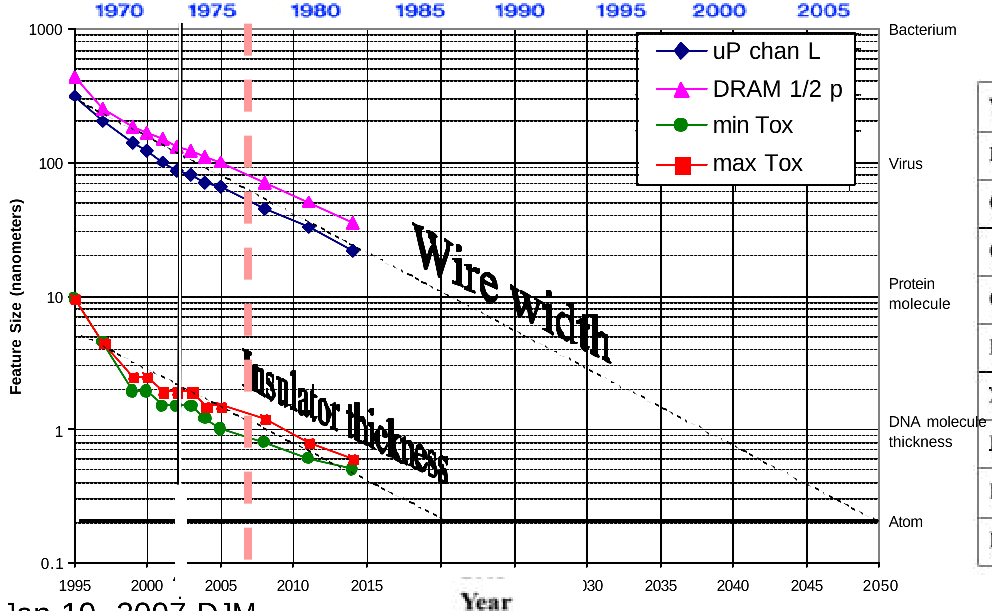
Computer Scaling Limits

- Physical Limits
  - Power density/Dissipation: max is 100 W/cm^2
  - Thermal/noise: E/f = 100h
  - Molecular/atomic/charge discreteness limits
  - Quantum: tunneling & Heisenberg uncertainty
- Technology Limits
  - Gate Length: min ~18-22 nm
  - Lithography Limits: wavelength of visible light
  - Power dissipation (100 watts) and Temperature
  - Wire Scaling: multicpu chips at ~ billion transistors
  - Materials

Charts and Tables Galore





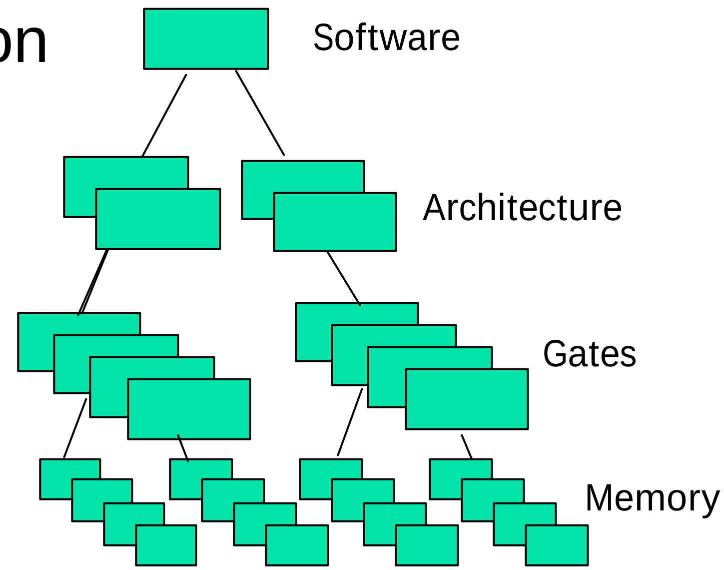


Year of Introduction	2001	2003	2006	2009
Minimum feature size (nm)	150	120	90	65
Overlay (nm)	55	45	35	25
Optical 193 nm	✔	✔		
Optical 157 nm		✔	✔	
Extreme Ultraviolet			✔	✔
X-rays				✔
Electron beam			✔	✔
Ion beam			✔	✔
Printing				✔

What does it take to build a general purpose computer?

Computing is the time-evolution of physical systems.

- Model of Computation
  - Representation of Information
  - Distinguishability of States
  - Memory/Algorithms
- Physical Computers
  - Matter/energy
  - Space/time
  - Noise/defect immunity
- Common Examples
  - Classical Mechanical/Semiconductor
  - Neurological/Biological/DNA
  - Quantum Computer – a *Paradigm Shift*



Introduce idealized model of computational costs

- *Space:* Information is in wrong place – Move it
  - Locality metrics are critical - context
  - Related to number of spatial dimensions - anisotropic
  - i.e. Busses, networks, caches, paging, regs, objects, …
- *Time:* Information is in wrong form – Convert it
  - Change rate and parallelism are critical (locality)
  - Related to temporal reference frame (i.e. time dilation)
  - i.e. consistency, FFT, holograms, probabilities, wholism
- All other physical costs
  - Creation/Erasure, Noise/ECC, Uncertainty, Precision, …
  - Decidability, Distinguishability, Detection, …

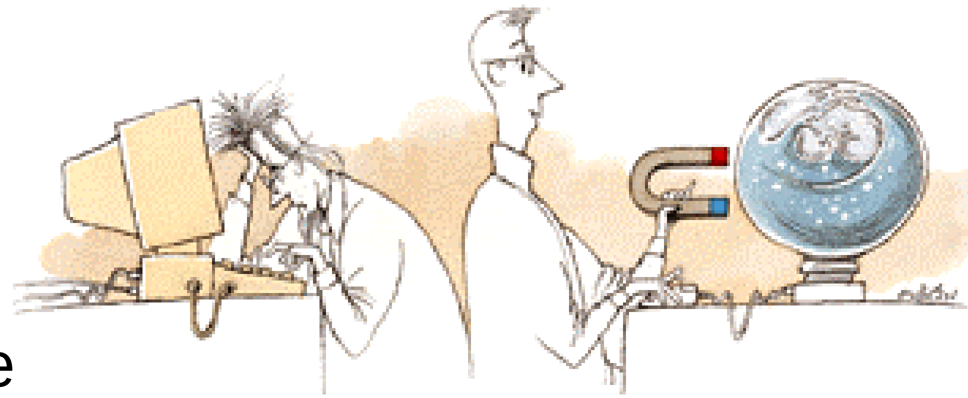
See my paper on this subject from 1986

Idealized Smarter Computers?

- If Information is always in right “local” place(s)
  - Possible higher number of dimensions
  - Possible selective length contraction
- If Information is always in “correct” form(s)
  - Multiple consistent wholistic representations
  - Change occurs outside normal time
- If other costs mitigated
  - Arbitrarily high precision and distinguishability, etc
  - Arbitrarily low noise and uncertainty, etc

Possible solutions may exist with quantum bits

Is Quantum the Solution?



- Pros (non-classical)
  - Superposition - qubits
  - Entanglement - ebits
  - Unitary and Reversible
  - Quantum Speedup for some algorithms
- Cons (paradigm shift)
  - Distinct states not distinguishable
  - Probabilistic Measurement
  - Ensemble Computing and Error Correction
  - Decoherence and noise
  - No known scalable manufacturing process

Classical vs. Quantum Bits

Topic	Classical	Quantum
Bits	Binary values 0/1	Qubits $c_0\|0\rangle + c_1\|1\rangle$
States	Mutually exclusive	Linearly independ.
Operators	Nand/Nor gates	Matrix Multiply
Reversibility	Toffoli/Fredkin gate	Qubits are unitary
Measurement	Deterministic	Probabilistic
Superposition	*Code division mlpx*	Mixtures of $\|0\rangle$ & $\|1\rangle$
Entanglement	*none*	Ebits $c_0\|00\rangle + c_1\|11\rangle$

Abstract Notions of Space & Time

Co-Occurrence and Co-Exclusion

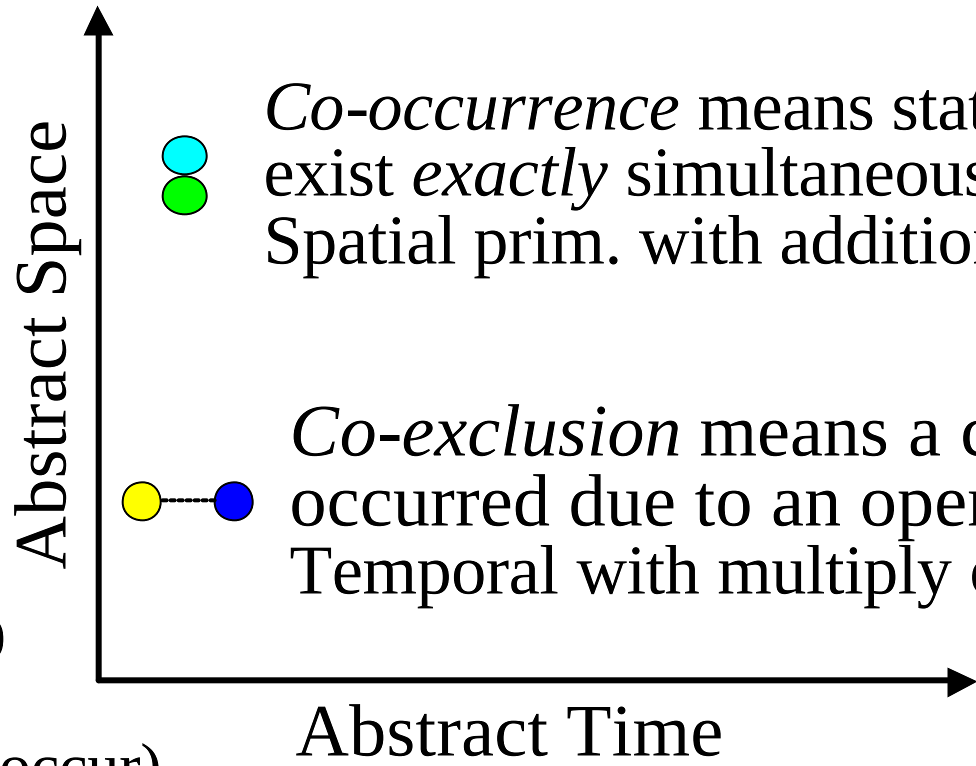
$$a + \bar{b} = \bar{b} + a$$

$$c - d \leftrightarrow d - c$$

$$c - d \mid d - c$$

$$c - d + d - c = 0$$

(0 means can not occur)



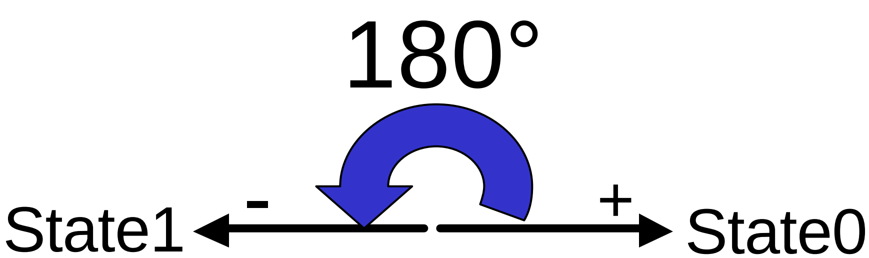
Co-occurrence means states exist *exactly* simultaneously: Spatial prim. with addition operator

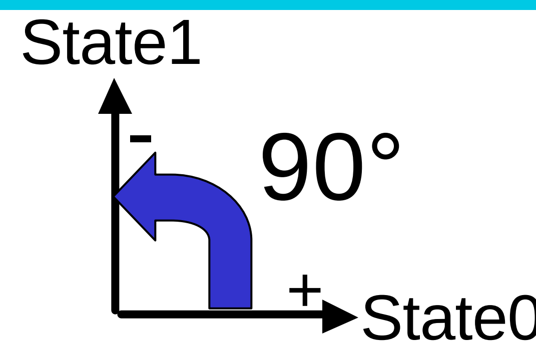
Co-exclusion means a change occurred due to an operator: Temporal with multiply operator

More & coin demonstration in my Ph.D dissertation

Quantum Bits – Qubits

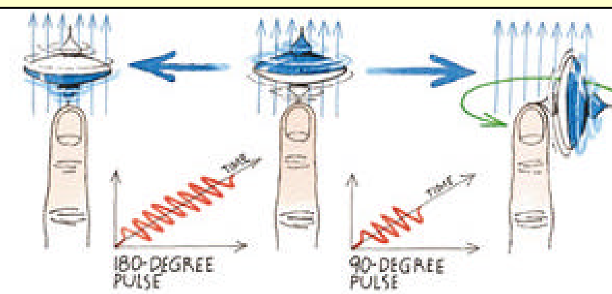
Classical bit states: *Mutual Exclusive*	Quantum bit states: *Orthogonal*





Classical states co-exclude others	Qubits states are called spin ½

Quantum States are *orthogonal:*
not mutually exclusive!



Qubit and Ebit Details

- Qubit

q0 | q1

c_0 **|0>** + c_1 **|1>** c_0 **|0>** + c_1 **|1>**

not * q0
phase * q1

- Qureg

q0 | q1 | q2

$q0 \otimes q1 \otimes q2$

c_0**|000>**+ c_1**|001>**+ c_2**|010>**+ c_3**|011>**+ c_4**|100>**+ c_5**|101>**+ c_6**|110>**+ c_7**|111>**

- Ebit

q0 | q1

$bell*(q0 \otimes q1)$

c_0 **|00>** + c_1 **|11>** or c_0 **|01>** + c_1 **|10>**

$\otimes$=tensor product

Quregister: Matrices 201

$$state0_0 = |0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$state1_0 = |1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

(tensor product) $\otimes$

$$state0_1 = |0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$state1_1 = |1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

=

$$state0 = |00\rangle = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad state1 = |01\rangle = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}$$

$$state2 = |10\rangle = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix} \quad state3 = |11\rangle = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

$\langle \; |$ Bra is row vector

$| \; \rangle$ Ket is column vector

(inner product) $\langle j | * | i \rangle = \langle j | i \rangle = 0 \quad when\ i \neq j$

Qubit Operators

Gate	Symbolic	Matrix	Circuit
Identity	$\sigma_0 * \psi$	$\sigma_0 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$	ψ ———
Not (Pauli-X)	$\sigma_1 * \psi$	$\sigma_1 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$	ψ —$\boxed{X}$—
Shift (Pauli-Z)	$\sigma_3 * \psi$	$\sigma_3 = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$	ψ —$\boxed{Z}$—
Rotate	$\theta * \psi$	$\begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$	ψ —$\boxed{\theta}$—
Hadamard	$H * \psi$	$H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$	ψ —$\boxed{H}$—

$$\begin{bmatrix} \lvert 0 \rangle & \lvert 1 \rangle \end{bmatrix}$$

Quantum Noise

- Pauli Spin Matrices

Identity	$s_0 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$	$s_0 * y$
Bit Flip Error	$s_1 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$	$s_1 * y$
Phase Flip Error	$s_3 = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$	$s_3 * y$
Both Bit and Phase Flip Error	$s_2 = \begin{bmatrix} 0 & i \\ -i & 0 \end{bmatrix}$	$s_2 * y$

$$\begin{bmatrix} a & b \\ b^* & c \end{bmatrix} = \frac{1}{2}(a+d)s_0 + \frac{1}{2}(b+b^*)s_1 + \frac{1}{2}i(b-b^*)s_2 + \frac{1}{2}(a-d)s_3$$

Entangled Bits – Ebits

- EPR (Einstein, Podolski, Rosen)
- Bell States

$$B_0 = \Phi^+ = c_0\left(|00\rangle + |11\rangle\right), \qquad B_1 = \Phi^- = c_0\left(|00\rangle - |11\rangle\right)$$

$$B_2 = \Psi^+ = c_0\left(|01\rangle + |10\rangle\right), \qquad B_3 = \Psi^- = c_0\left(|01\rangle - |10\rangle\right)$$

- Magic States

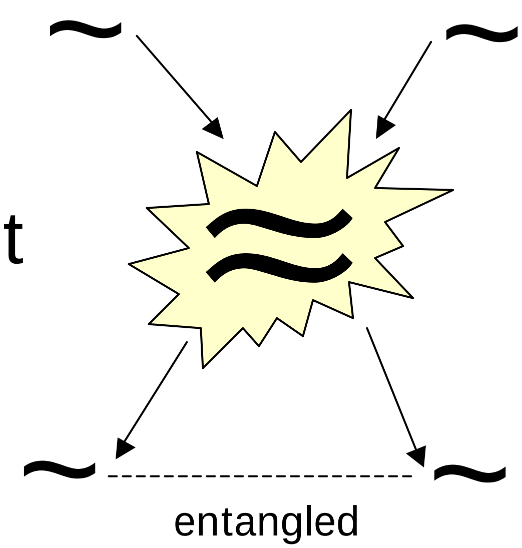
$$M_0 = c_0\left(|00\rangle + |11\rangle\right), \qquad M_1 = c_1\left(|00\rangle - |11\rangle\right)$$

$$M_2 = c_1\left(|01\rangle + |10\rangle\right), \qquad M_3 = c_0\left(|01\rangle - |10\rangle\right)$$

$$c_0 = 1/\sqrt{2} \qquad c_1 = i/\sqrt{2}$$

EPR: Non-local connection

- Step1: Two qubits
- Step2: Entangle →Ebit
- Step3: Separate



$$|0_0\rangle, |0_1\rangle$$

$$\Phi^{\pm} = |00\rangle \pm |11\rangle$$

$$\Psi^{\pm} = |01\rangle \pm |10\rangle$$

$$|?\rangle, |?\rangle$$

- Step4: Measure a qubit
  - Other is same if $\Phi^{\pm}$
  - Other is opposite if $\Psi^{\pm}$

$$answer = 1, other = 1$$

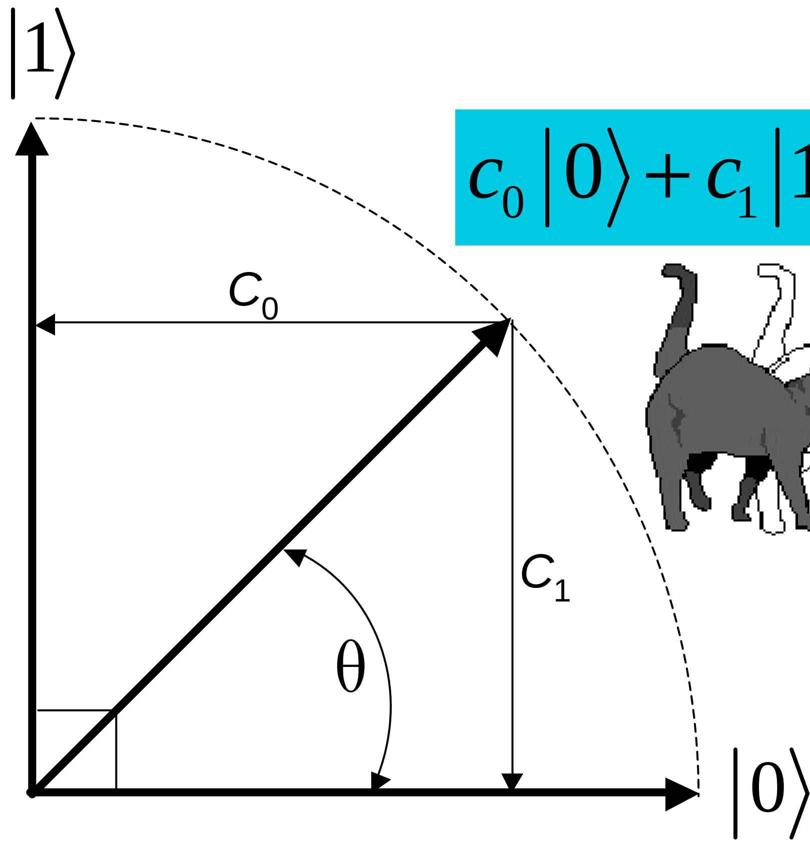
$$answer = 1, other = 0$$

Linked coins analogy

Quantum Measurement

Probability of state $c_i|i\rangle$ is $p_i = c_i^2$ and $p_1 = 1 - p_0$

$$c_0|0\rangle + c_1|1\rangle$$



Destructive and Probabilistic!!

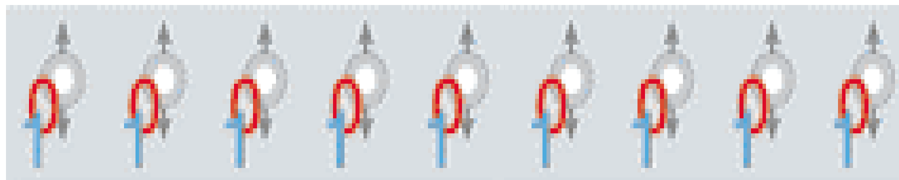
When $c_0 = c_1 = \sqrt{\frac{1}{2}}$

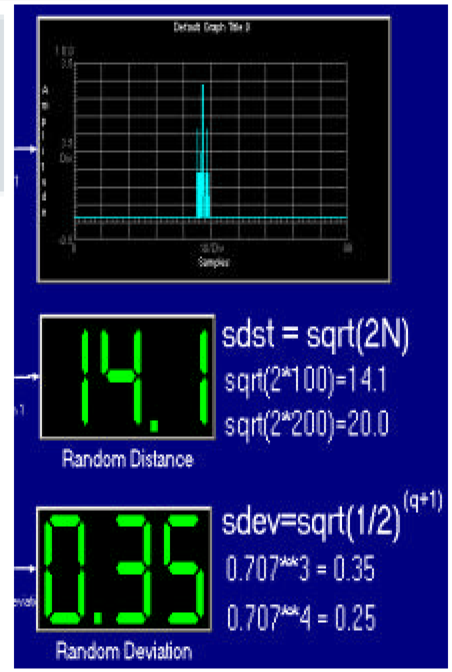
then $p_0 = p_1 = \frac{1}{2}$

or 50/50 random!

Measurement operator is *singular* (not unitary)

Ensemble Computing





- Ensemble
  - A set of "like" things
  - States can be all the same or all random!!
- Examples
  - Neurons: pulse rate
  - Photons: phase angle
  - Qubits: used in NMR quantum computing
  - Kanerva Mems: Numenta, On Cognition, Jeff Hawkins
  - Correlithm Objects: Lawrence Technologies

Ensembles can use randomness as a resource.

Why is quantum information special?

Quantum Computing requires a paradigm shift!!

- Quantum states are high dim (Hilbert space)
  - Can be smarter in higher dims with **no** time
  - Superposition creates new dims (tensor products)
- Quantum states are non-local in 3d & atemporal
  - Causality and determinacy are not the primary ideas
  - Large scale unitary consistency constraint system

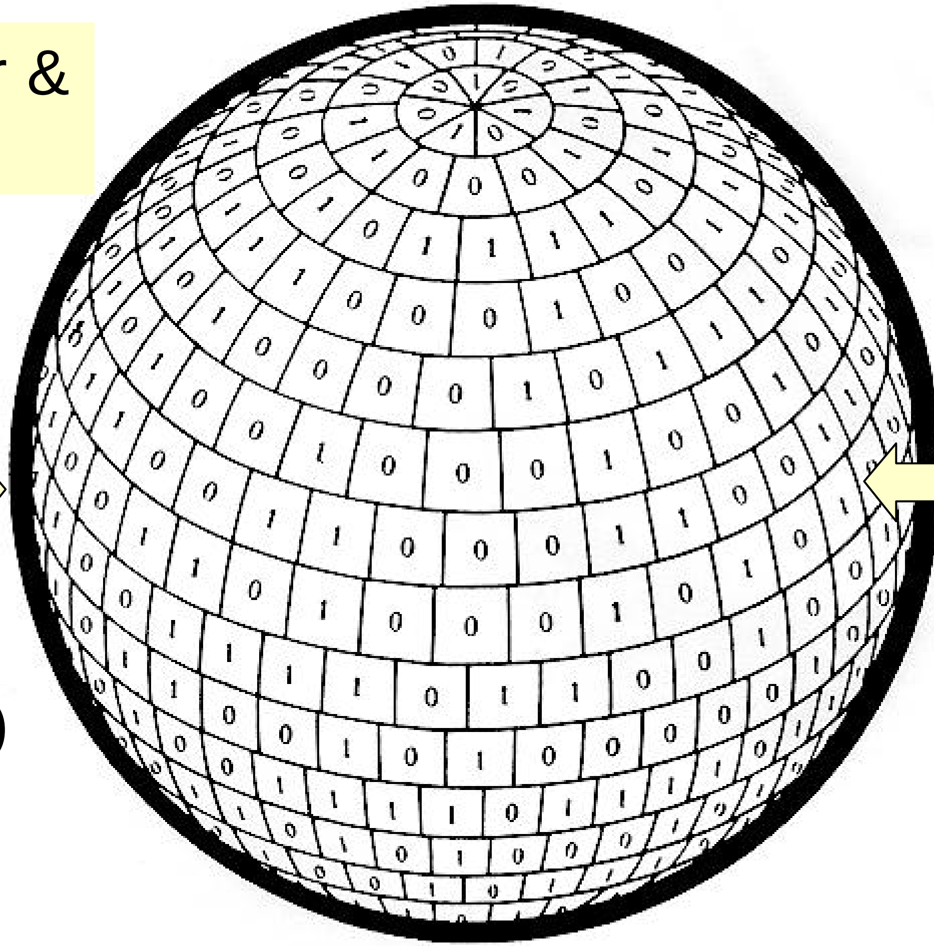
Quantum information precedes space/time and energy/matter - Wheeler's "It from Bit"

Information is Physical

Rolf Landauer & phase spaces

Quantum Information is consistent with Black Hole Mechanics

Black Hole event horizon (inside is a singularity)

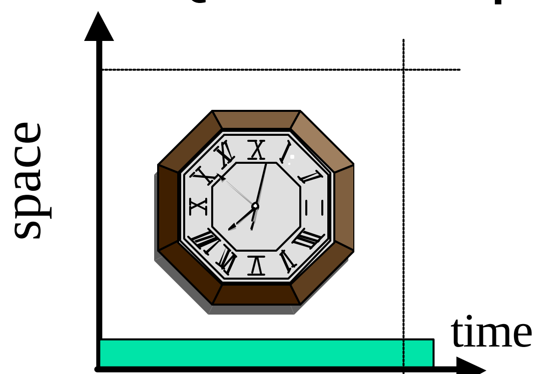


Bits as entropy (Planck's areas on surface)

Wheeler's "It from Bit"

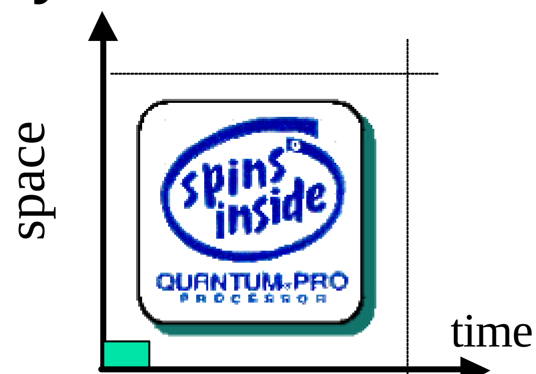
Quantum Computing Speedup

- Peter Shor’s Algorithm in 1994
- Quantum Fourier Transform for factoring primes
- Quantum polynomial time algorithm



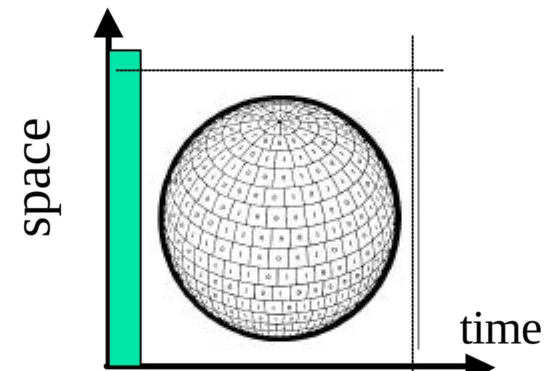
Spatially bound
exceeds universe life

classical



Quantum polynomial
time *can solve it.*

quantum



Temporal bound
exceeds black hole

classical

Solutions to some problems don’t fit in classical universe!!

Computing Paradoxes

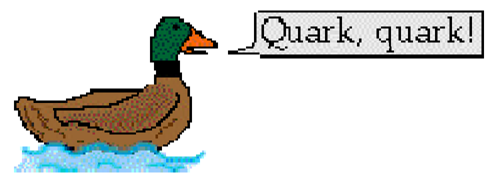
Property	*Choices*	*Contradiction*
Size	Larger/Smaller	Larger is less localized
Speed	Faster/Slower	Faster is more localized
Power	Less/more	Less power is slower
Grain Size	Gates/wires	No distinction at quantum level
Dimensions	More/less	Physical vs. mathematical dims
Parallelism	Coarse/fine	Sequential vs. Concurrent
Complexity	Less/More	Makes programming hard
Noise	Less/More	Use noise as resource
Velocity	Fast/Slow	Time Dilation slows computing

Computing Myths

- Quantum/Neural/DNA don't solve scaling
  - Quantum only applied to gate level
  - Not generalized computing systems – niches
  - Nano-computers (nanites) are science fiction
- Smarter Computers? What is Genius?
  - No generalized learning – Failure of AI
  - No general parallel computing solutions
  - Computers don't *know* anything (only data)
  - Computers don't *understand* (speech&image)
  - Computers have no *meaning* (common sense)

Scaling Predictions

- Semiconductors will stop scaling in ~10 yrs
  - Nanocomputers won’t stop this; only delay it
  - Breakthrough required or industry stagnates
  - College students consider non-semiconductor careers
- Research needed in these areas:
  - Deep meaning and automatic learning
  - Programming probabilistic parallel computers
  - Noise as valued resource instead of unwanted
  - Higher dimensional computing
  - Investigate non-local computing
  - Biological inspired computing – Quantum Brain?



Conclusions

- Computer scaling creates uncertainty
- Quantum Computing not yet a solution
- Watch for unexpected aspects of noise
- Industry is not open on scaling problems
- Research money is lacking
- Costs may slow before limits
- Must think outside 3d box
- Focus on Human Acceleration

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