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Enabling Nanocomputing: Opportunities for Computer Science

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Outline

- **My definition of Nanocomputing**
- **Bending Moore's Law**
- **After CMOS: what?**
- **Some opportunities**
- **Quantum Computing**

Nanocomputing

- **We don't have to wait long for Nanocomputing.**
  - Sub 100nm Poly gates in production.
  - Several hundred DRAM cells in area of Red Blood cell.
  - 2GHz processors in commodity market.
- **It's already here.**
- **It's called CMOS**

Will CMOS die in 10 years?

- Over the past 20 years, many experts have been asked to predict the end of downscaling (and therefore the end of CMOS). I have developed a simple algorithm to determine his or her answer:

  Year CMOS dies = (Year question is asked) + 10

Opportunity #1

Massively parallel processors

- **Current drive, interconnect delay, and other issues will favor arrays of smaller processors over a few mega-processors.**
- **Operating systems and algorithms that can parallelize general computing problems will play a major role in increasing computational power.**
- **Parallelism will pay dividends later.**

Opportunity #2

Fault Tolerance / Error Correction

- Soft errors (Cosmic Rays), low voltages, manufacturing tolerances, etc. will all drive down circuit reliability.
- This will become a growing issue in CMOS and will certainly be an issue for other nanocomputing technologies.
- Fault tolerant and error correcting algorithms and or architectures will be essential.

Opportunity #3

Multi – Level Logic (speculative)

- Binary has been beaten to (near) death.
- Multi-valued logic allows one to do more with a given number of devices.
- Redundant Digit Logic:

```
 10011010111001101010011001001011
+01100100101110011010111001101010
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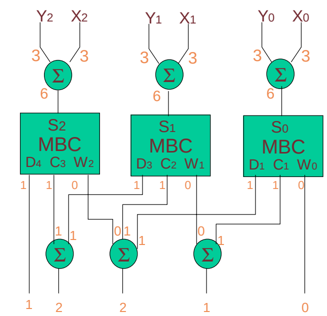
```
 10011010111001101010011001001011
+01100100101110011010111001101010
 11111110212111112120122002102021
```

Base 2 Radix 4 Redundant Digit Adder



Base10	Base2
21	333
+21	+333
42	666

6*4 + 6*2 + 6*1 = 42

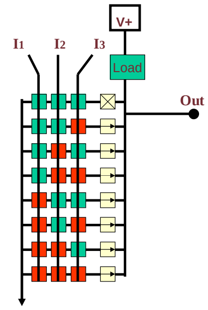
1*16 + 2*8 + 2*4 + 1*2 + 0*1 = 42

Replacing CMOS?

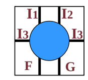
The Contenders

- GaAs, InP, SiC, GaN or other semiconductors of the future.
- Resonant tunneling devices
- Single Electron Transistors
- Nanotube memory devices
- Nanotube transistors
- Computing with DNA
- Molecular electronics
  - — The industry is littered with failed efforts to produce useful circuits with two terminal devices.

Universal 3-Input Cell



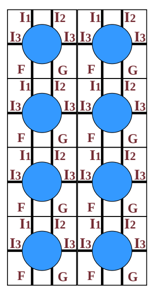
I1	I2	I3	Out
0	0	0	1
0	0	1	0
0	1	0	0
0	1	1	0
1	0	0	0
1	0	1	0
1	1	0	0
1	1	1	0



Vertical Rail Cellular Cascade

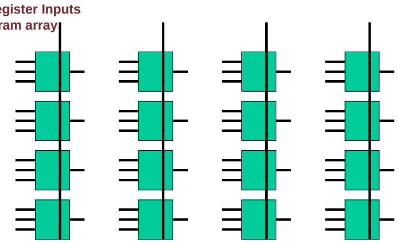
Vertical Rail Cellular Cascade

- R. A. Short (1965)
- Given Independent 3-Input functions F & G, this architecture has been shown to be functionally complete.
- However, no general design approach was developed.



Opportunity ??

Shift Register Inputs to program array

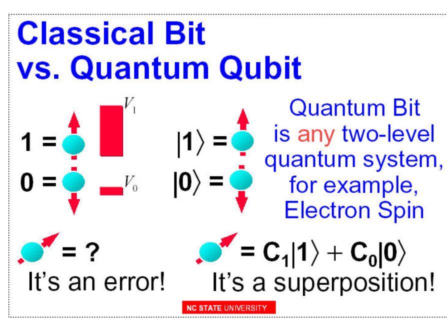


- I want someone to consider a gate array architecture where both custom wiring and programmable functions are used.
- Or take advantage of this programmable cell in some

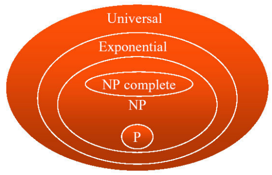
Quantum Computing

- A distinctly new paradigm in computation.
- Using coupled quantum states it has been demonstrated that intermediate superposition of states can carry enormously more information than is possible with a classical computer.
- Several implementations are being pursued, including Si solid state devices.

Qubits



Problem Solving:
tractable vs. intractable



- A classical computer solves problems of type P
- An N-bit quantum computer solves <u>exponential</u> problems

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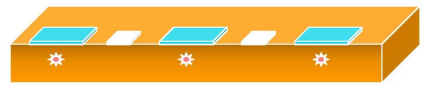
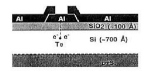
Solid State Implementation

P – impurities with spin = ½ interact through trapped electron to form coupled system

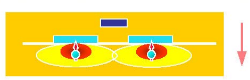




SET used to measure spin-state of final state

Kane
Nature **393** 133 14 May 1999

Electron Spins Trapped Beneath Coupled Quantum Dots



- Hamiltonian for a single quantum dot pair.

$$H = \mu_B g B_1 S_1 + \mu_B g B_2 S_2 + J S_1 \bullet S_2$$

- Exchange coupling between adjacent quantum dots.

$$2J = \int u(\vec{r}_1 - \vec{r}_2)\psi_1(\vec{r}_1)\psi_1^*(\vec{r}_2)\psi_2(\vec{r}_2)\psi_2^*(\vec{r}_1)dV$$

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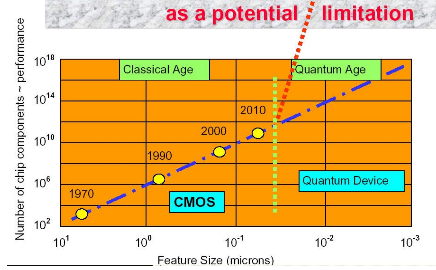
Beating Moore's Law

Moore's Law as a potential limitation



Quantum Computing

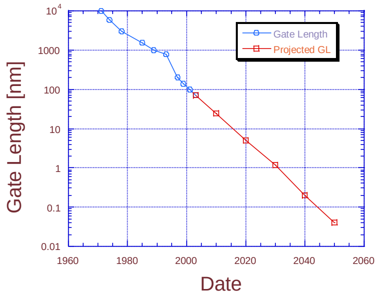
The BIG Deal

- **The electronics industry has managed 3 decades of exponential growth in computing power mainly because a linear decrease in L produces a $(1/L)^2$ increase in devices.**
- **With a classical approach, computational power increases linearly with the number of devices.**
- **With quantum computing, computational power goes up exponentially with the number of devices.**

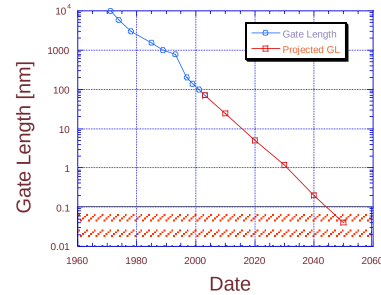
Opportunity #4

- **So far only a few algorithms (Shor's & Grover's) have been demonstrated as very efficient QC algorithms.**
- **Get to know a physicist.**

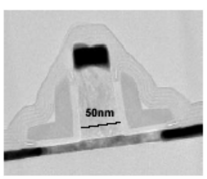
Moore's-curve

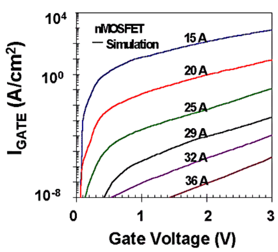


Moore's-curve



Tunneling Limits Gate Oxide





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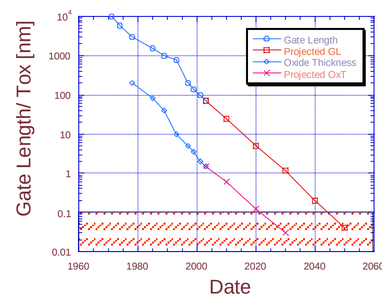

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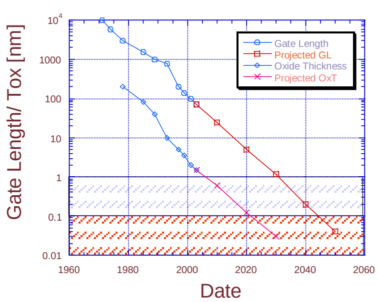
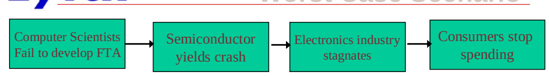


Worst Case Scenario*



* P. Ware & M. Levenson,

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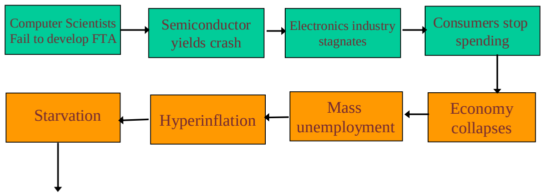

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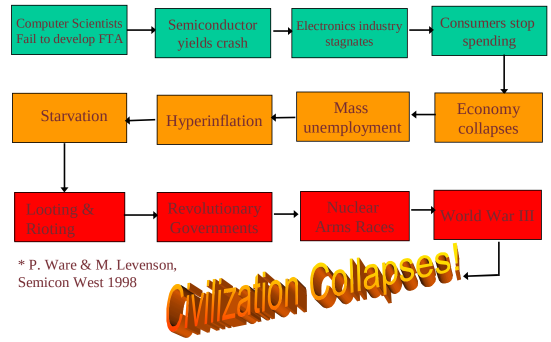

* P. Ware & M. Levenson, Semicon West 1998

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Two spins:

Four states in superposition: 2^2

$= C_{00}|00\rangle + C_{01}|01\rangle + C_{10}|10\rangle + C_{11}|11\rangle$

Entanglement of spins 1 and 2

N spins:

2^N states in superposition

0...00 + 0…01 + … + 1…11

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