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SAND 2005-2689C

# Reversible Logic for Supercomputing

*How to save the Earth with Reversible Computing*

**Erik P. DeBenedictis**

**Sandia National Laboratories**

**May 5, 2005**

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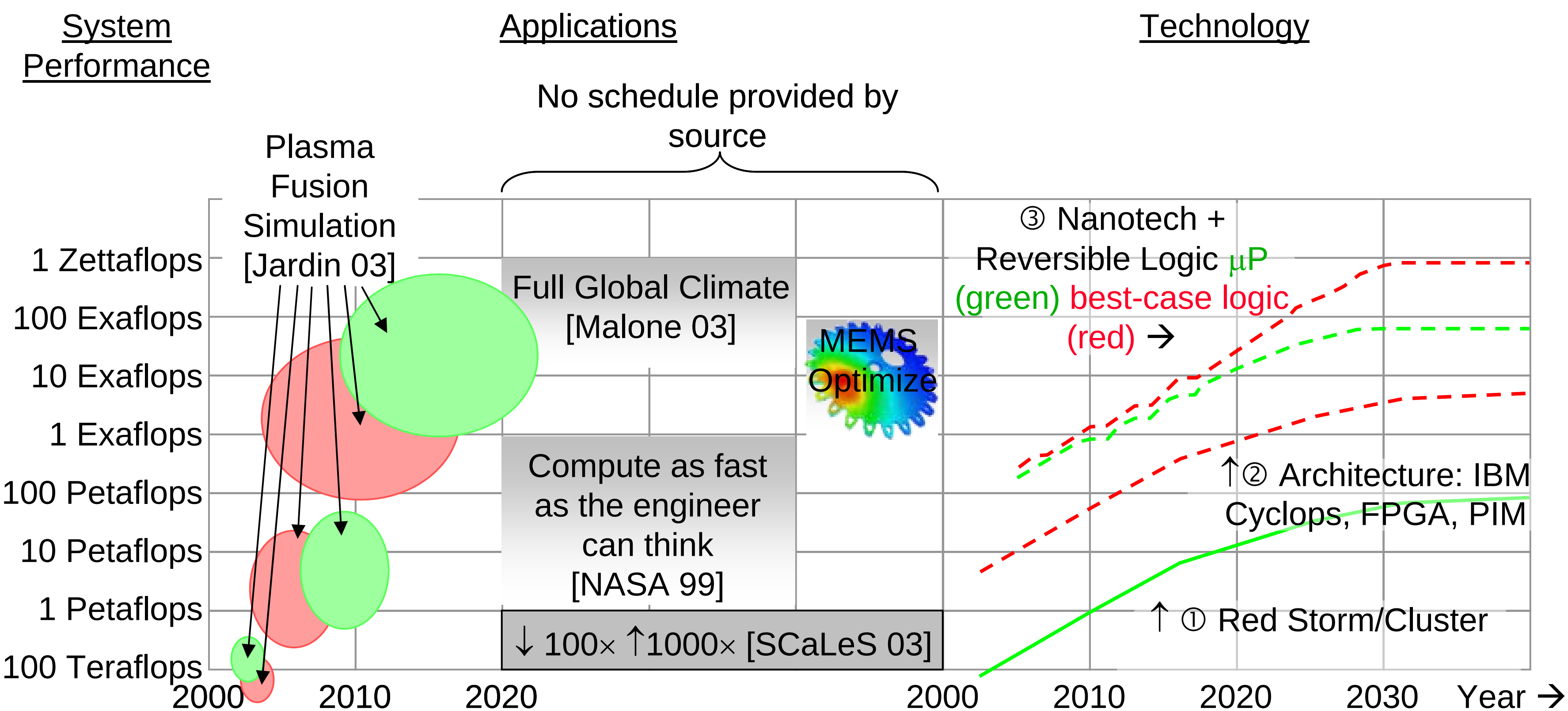
# Applications and $100M Supercomputers




[Jardin 03] S.C. Jardin, "Plasma Science Contribution to the SCaLeS Report," Princeton Plasma Physics Laboratory, PPPL-3879 UC-70, available on Internet.
[Malone 03] Robert C. Malone, John B. Drake, Philip W. Jones, Douglas A. Rotman, "High-End Computing in Climate Modeling," contribution to SCaLeS report.
[NASA 99] R. T. Biedron, P. Mehrotra, M. L. Nelson, F. S. Preston, J. J. Rehder, J. L. Rogers, D. H. Rudy, J. Sobieski, and O. O. Storaasli, "Compute as Fast as the Engineers Can Think!" NASA/TM-1999-209715, available on Internet.
[SCaLeS 03] Workshop on the Science Case for Large-scale Simulation, June 24-25, proceedings on Internet a http://www.pnl.gov/scales/.
[DeBenedictis 04], Erik P. DeBenedictis, "Matching Supercomputing to Progress in Science," July 2004. Presentation at Lawrence Berkeley National Laboratory, also published as Sandia National Laboratories SAND report SAND2004-3333P. Sandia technical reports are available by going to http://www.sandia.gov and accessing the technical library.

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# Objectives and Challenges

- Could reversible computing have a role in solving important problems?
  - Maybe, because power is a limiting factor for computers and reversible logic cuts power
- However, a complete computer system is more than “low power”
  - Processing, memory, communication in right balance for application
  - Speed must match user’s impatience
  - Must use a real device, not just an abstract reversible device

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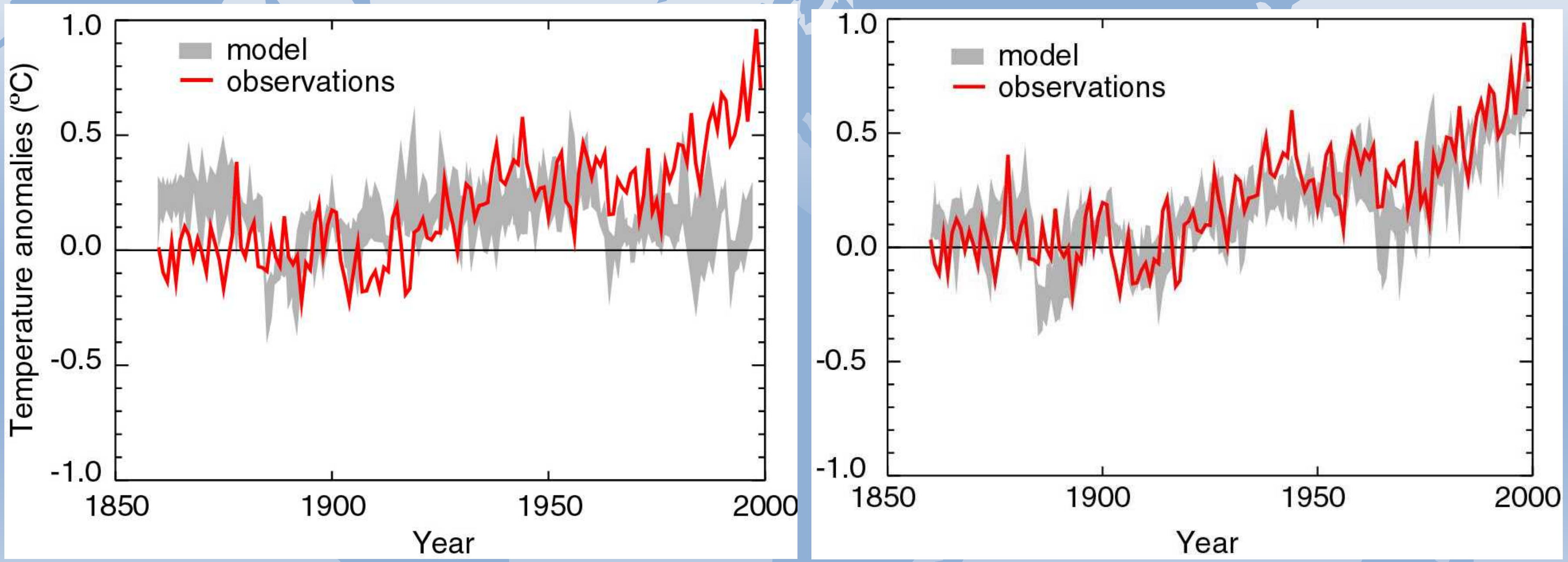
# Outline

- An Exemplary Zettaflops Problem
- The Limits of Current Technology
- Arbitrary Architectures for the Current Problem
  - Searching the Architecture Space
  - Bending the Rules to Find Something
  - Exemplary Solution
- Conclusions

# Simulation of Global Climate




Stott et al, Science 2000

**"Simulations of the response to natural forcings alone … do not explain the warming in the second half of the century"**

**"..model estimates that take into account both greenhouse gases and sulphate aerosols are consistent with observations over this*period" - IPCC 2001**

Office of Science U.S. DEPARTMENT OF ENERGY

SciDAC Scientific Discovery through Advanced Computing

The World's Greatest Science Protecting America

Los Alamos NATIONAL LABORATORY EST.1943

# FLOPS Increases for Global Climate

- 1 Zettaflops
- 100 Exaflops
- 1 Exaflops
- 10 Petaflops
- 100 Teraflops
- 10 Gigaflops

| Issue | Scaling |
|---|---|
| Ensembles, scenarios 10× | Embarrassingly Parallel |
| Run length 100× | Longer Running Time |
| New parameterizations 100× | More Complex Physics |
| Model Completeness 100× | More Complex Physics |
| Spatial Resolution $10^4\times$ ($10^3\times$-$10^5\times$) | Resolution |
| Clusters Now In Use (100 nodes, 5% efficient) | |

Ref. "High-End Computing in Climate Modeling," Robert C. Malone, LANL, John B. Drake, ORNL, Philip W. Jones, LANL, and Douglas A. Rotman, LLNL (2004)

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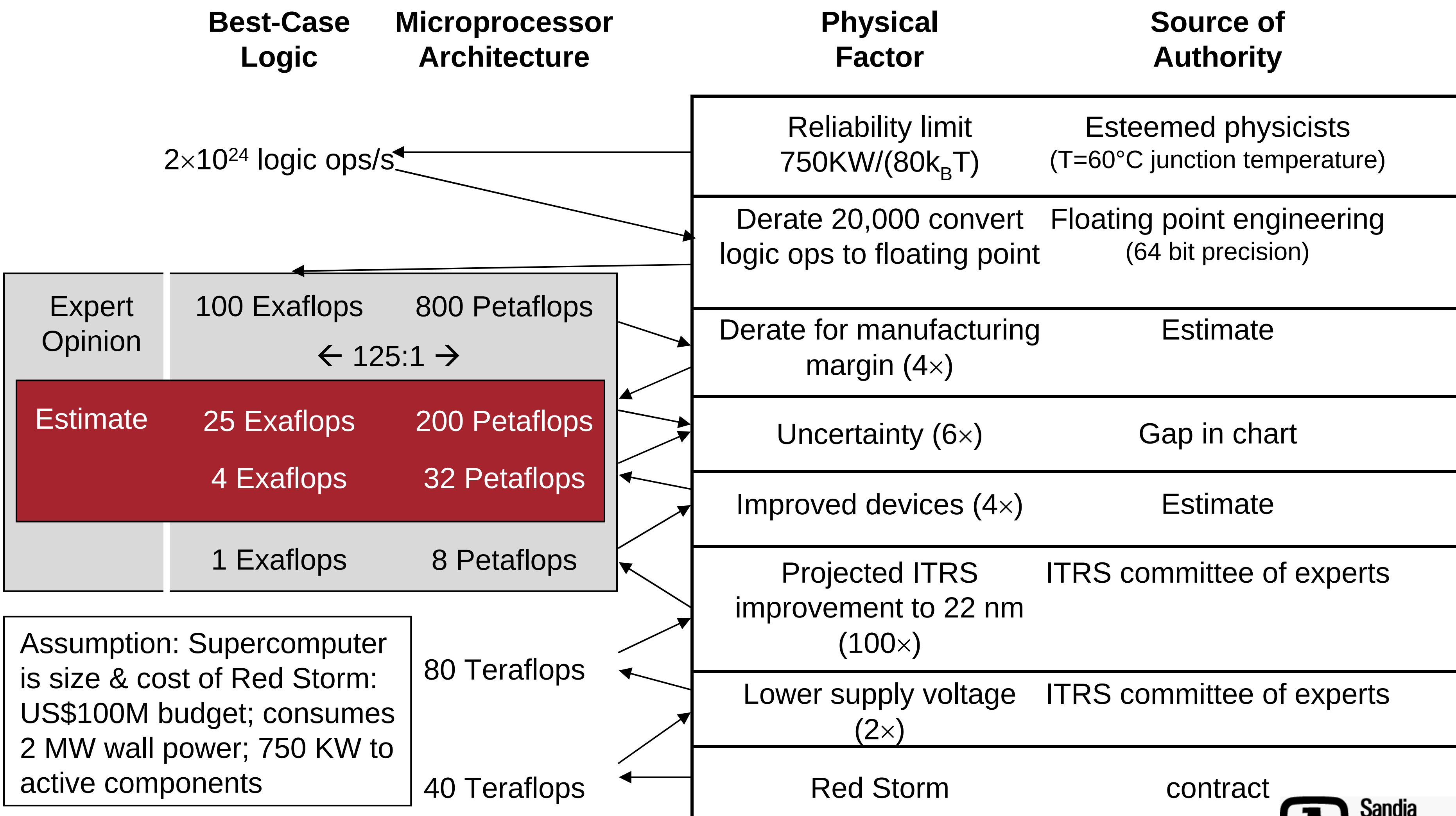
# Scientific Supercomputer Limits

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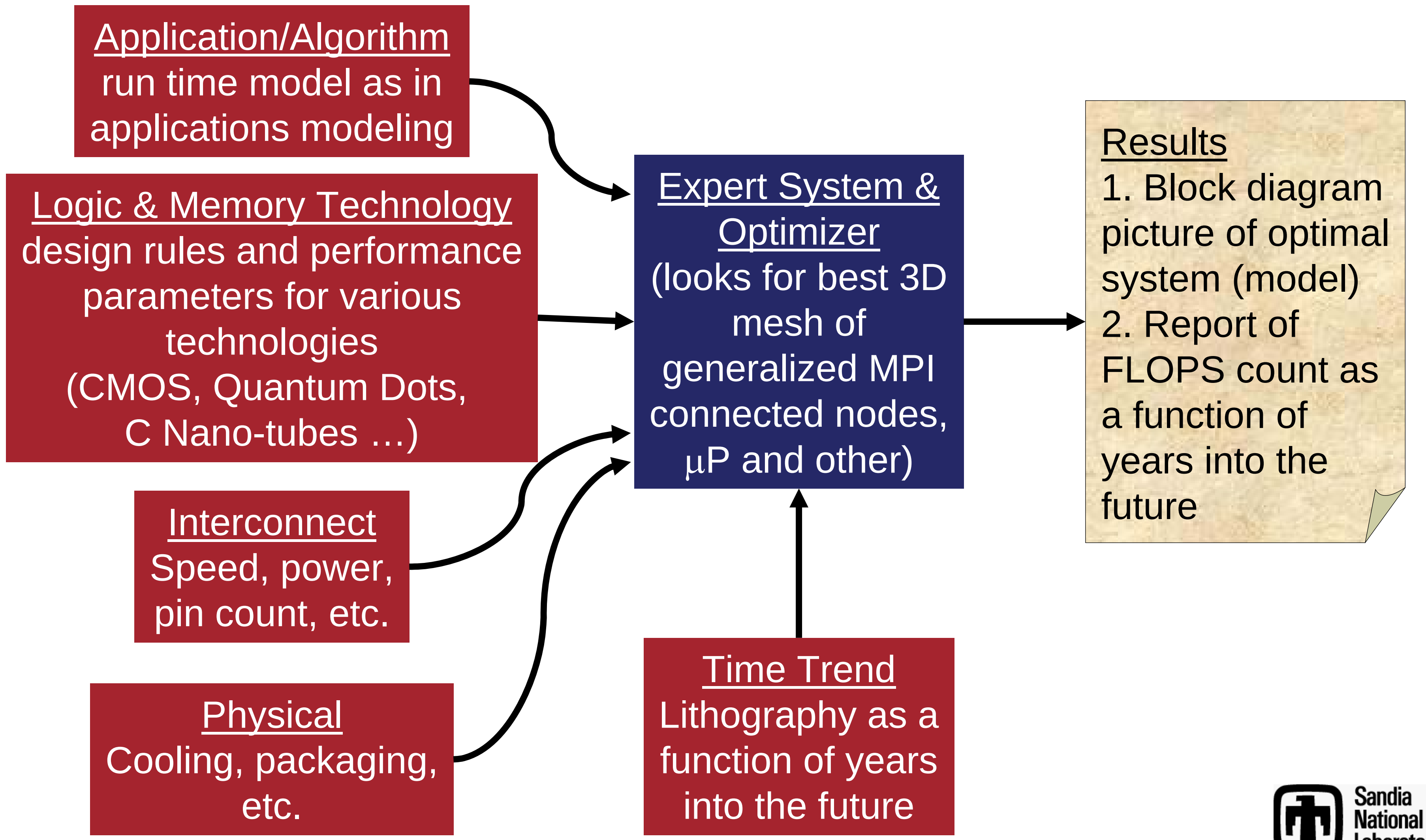
# Supercomputer Expert System

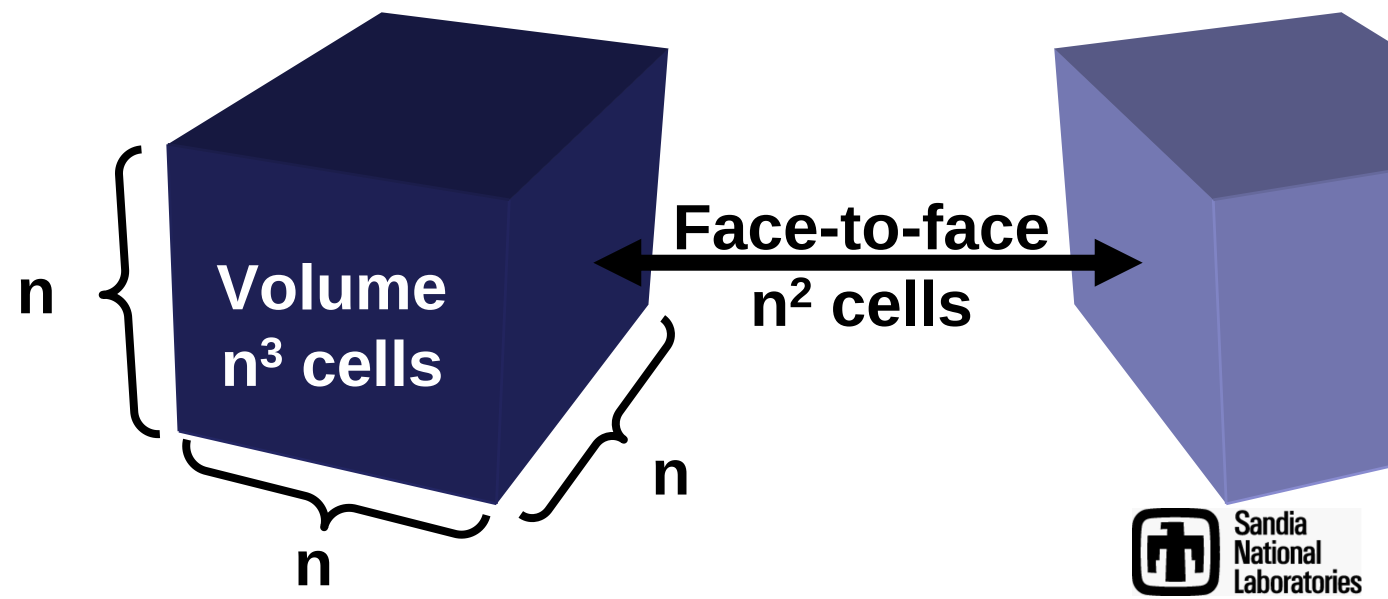


# Sample Analytical Runtime Model

- Simple case: finite difference equation
- Each node holds n×n×n grid points

- Volume-area rule
  - Computing $\propto n^3$
  - Communications $\propto n^2$

$$T_{step} = 6\,n^2\,C_{bytes}\,T_{byte} + n^3\,F_{grind}/\text{floprate}$$



# Expert System for Future Supercomputers

- **Applications Modeling**
  - **Runtime**
    $T_{run} = f_1(n, design)$
- **Technology Roadmap**
  - **Gate speed = $f_2$(year),**
  - **chip density = $f_3$(year),**
  - **cost = $(n, design), …**
- **Scaling Objective Function**
  - **I have $$C_1$ & can wait $T_{run}=C_2$ seconds. What is the biggest n I can solve in year Y?**

- **Use “Expert System” To Calculate:**

$$\max_{\text{All designs}} \; n: \$<C_1,\ T_{run}<C_2$$

- **Report:**

$$\frac{\text{Floating operations}}{T_{run}(n, design)}$$

**and illustrate “design”**

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# The Big Issue

- **Initially, didn't meet constraints**

More Parallelism ↓

Scaled Climate Model

2D → 3D mesh,
one cell per processor

Parallelize cloud-resolving model and ensembles

One Barely Plausible Solution

Consider special purpose logic with fast logic and low-power memory

Consider only highest performance published nanotech device QDCA

Initial reversible nanotech

More Device Speed ↑

# ITRS Device Review 2016 + QDCA

| Technology | Speed (min-max) | Dimension (min-max) | Energy per gate-op | Comparison |
|---|---|---|---|---|
| CMOS | 30 ps-1 μs | 8 nm-5 μm | 4 aJ | |
| RSFQ | 1 ps-50 ps | 300 nm- 1μm | 2 aJ | Larger |
| Molecular | 10 ns-1 ms | 1 nm- 5 nm | 10 zJ | Slower |
| Plastic | 100 μs-1 ms | 100 μm-1 mm | 4 aJ | Larger+Slower |
| Optical | 100 as-1 ps | 200 nm-2 μm | 1 pJ | Larger+Hotter |
| NEMS | 100 ns-1 ms | 10-100 nm | 1 zJ | Slower+Larger |
| Biological | 100 fs-100 μs | 6-50 μm | .3 yJ | Slower+Larger |
| Quantum | 100 as-1 fs | 10-100 nm | 1 zJ | Larger |
| QDCA | 100 fs-10ps | 1-10 nm | 1 yJ | Smaller, faster, cooler |

Data from ITRS ERD Section, data from Notre Dame

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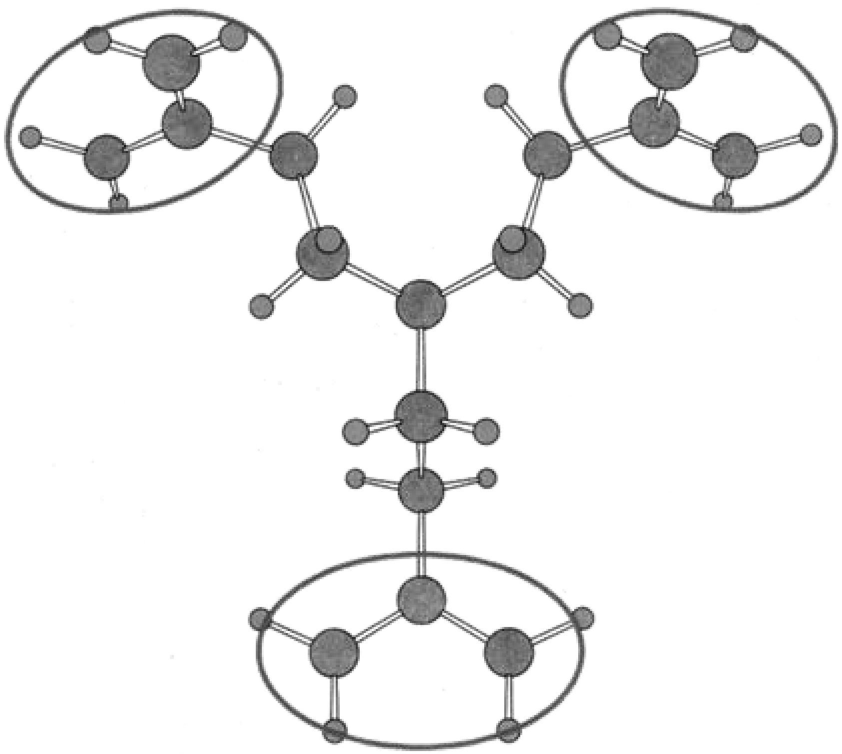
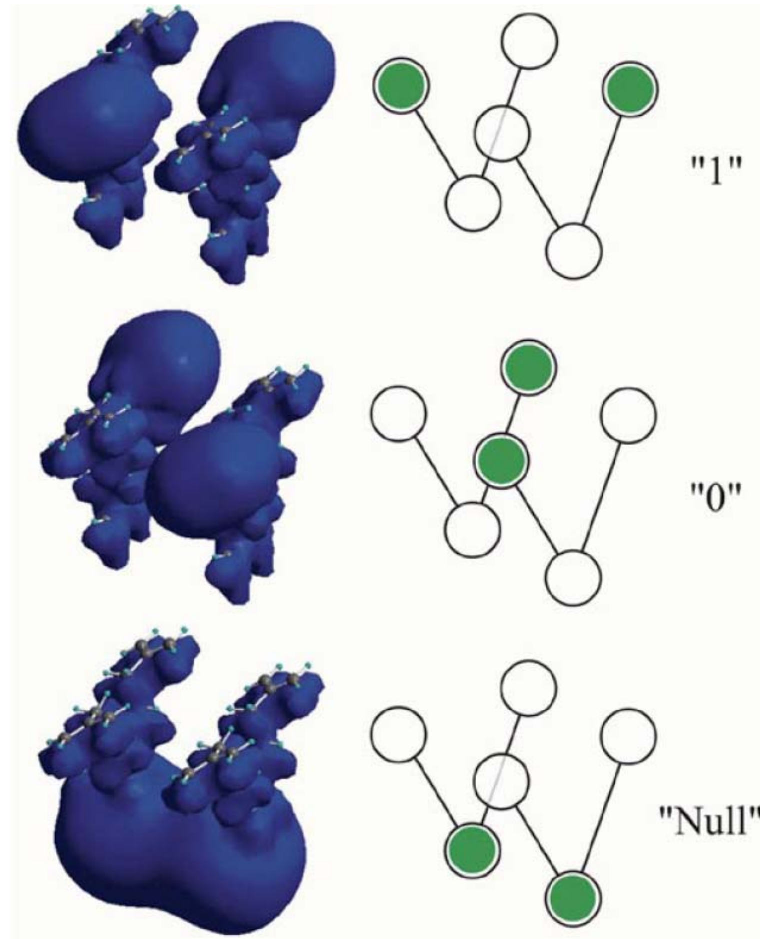
# An Exemplary Device: Quantum Dots

- **Pairs of molecules create a memory cell or a logic gate**

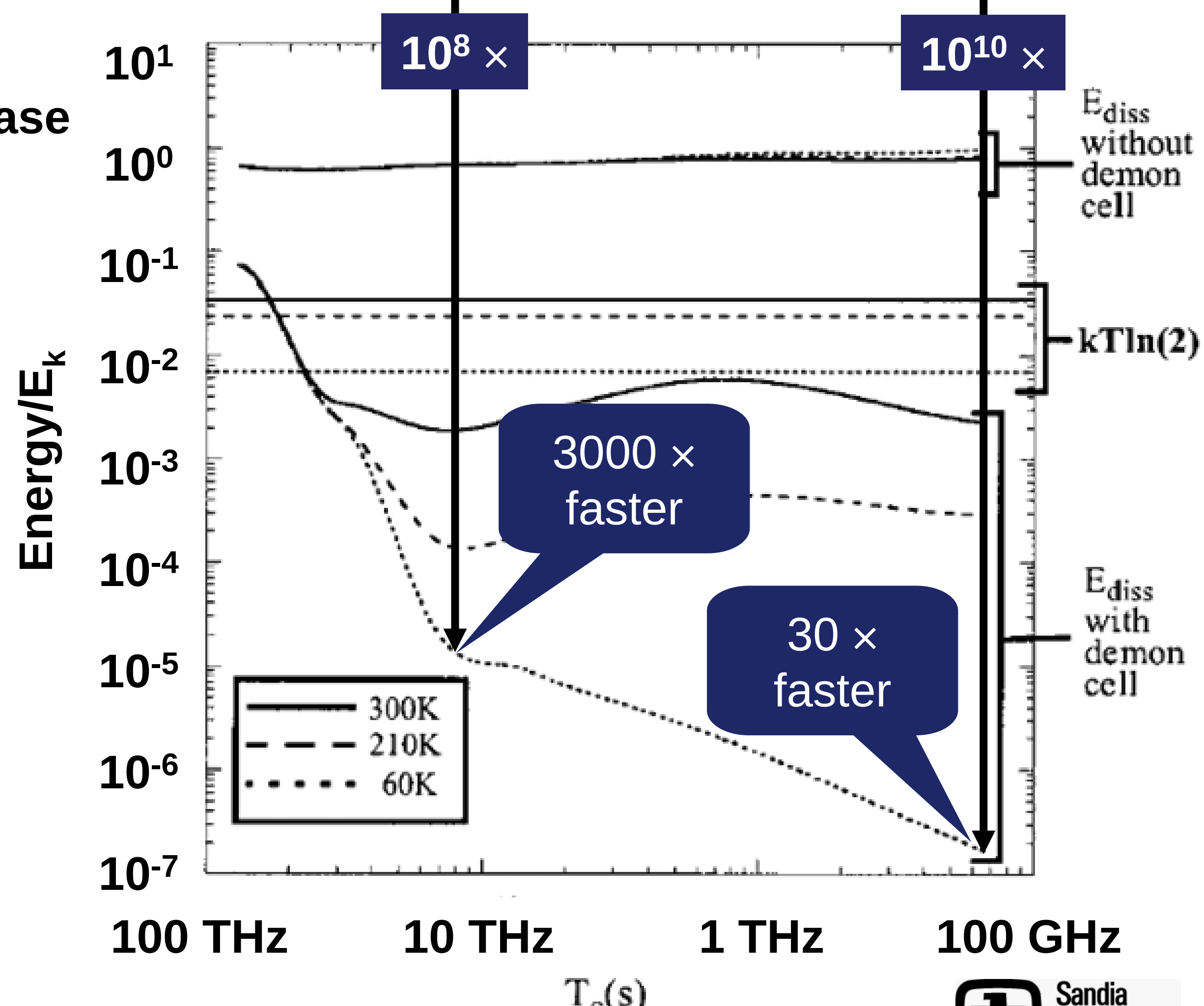





**Ref. "Clocked Molecular Quantum-Dot Cellular Automata," Craig S. Lent and Beth Isaksen**
**IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 50, NO. 9, SEPTEMBER 2003**

# 1 Zettaflops Scientific Supercomputer

- **How could we increase "Red Storm" from 40 Teraflops to 1 Zettaflops?**
- **Answer**
  - **>2.5×10^7 power reduction per operation**
  - **Faster devices × more parallelism >2.5×10^7**
  - **Smaller devices to fit existing packaging**




Ref. "Maxwell's demon and quantum-dot cellular automata," John Timler and Craig S. Lent, JOURNAL OF APPLIED PHYSICS 15 JULY 2003

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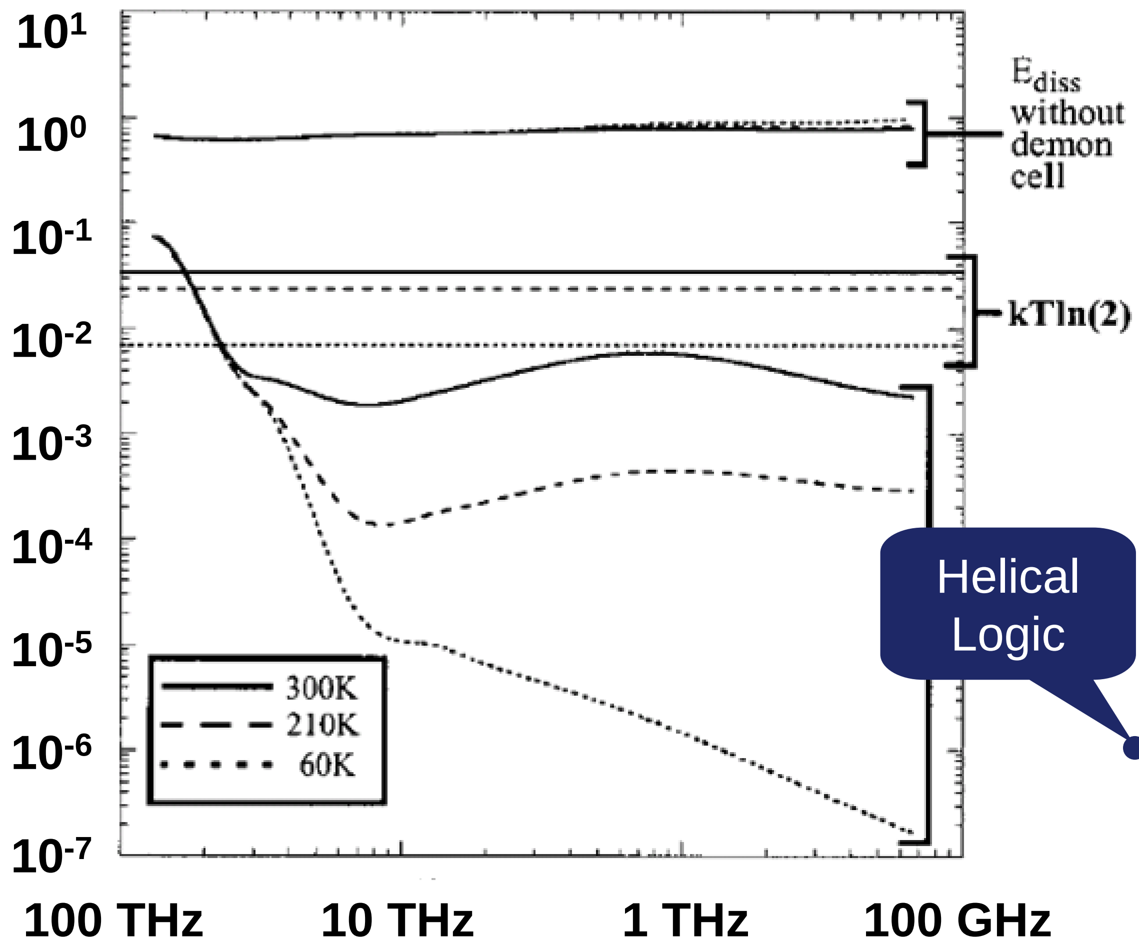
# Not Specifically Advocating Quantum Dots

- A number of post-transistor devices have been proposed
- The shape of the performance curves have been validated by a consensus of reputable physicists
- However, validity of any data point can be questioned
- Cross-checking appropriate; see →




Ref. "Maxwell's demon and quantum-dot cellular automata," John Timler and Craig S. Lent, JOURNAL OF APPLIED PHYSICS 15 JULY 2003.
Ref. "Helical logic," Ralph C. Merkle and K. Eric Drexler, Nanotechnology 7 (1996) 325–339.

# QCA Microprocessor Status

- M. Niemier Ph. D. Thesis, University of Notre Dame
- 12 Bit $\mu$P
- CAD design tool principles
  - 10× circuit density of CMOS at same $\lambda$
- Applies to various devices
  - Metal dot 4.2 $nm^2$
  - Molecular 1.1 $nm^2$

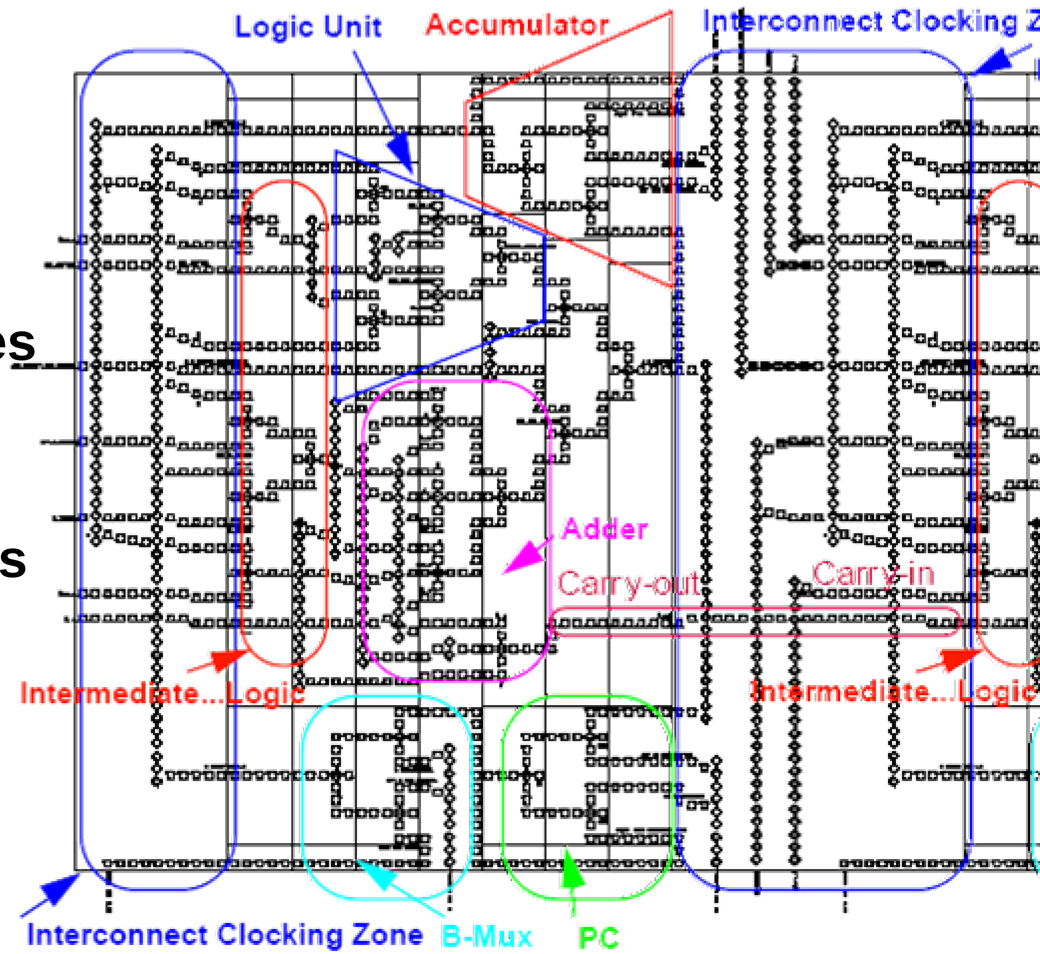



Figure 4.6. A 2-bit QCA Simple 12 ALU with registers

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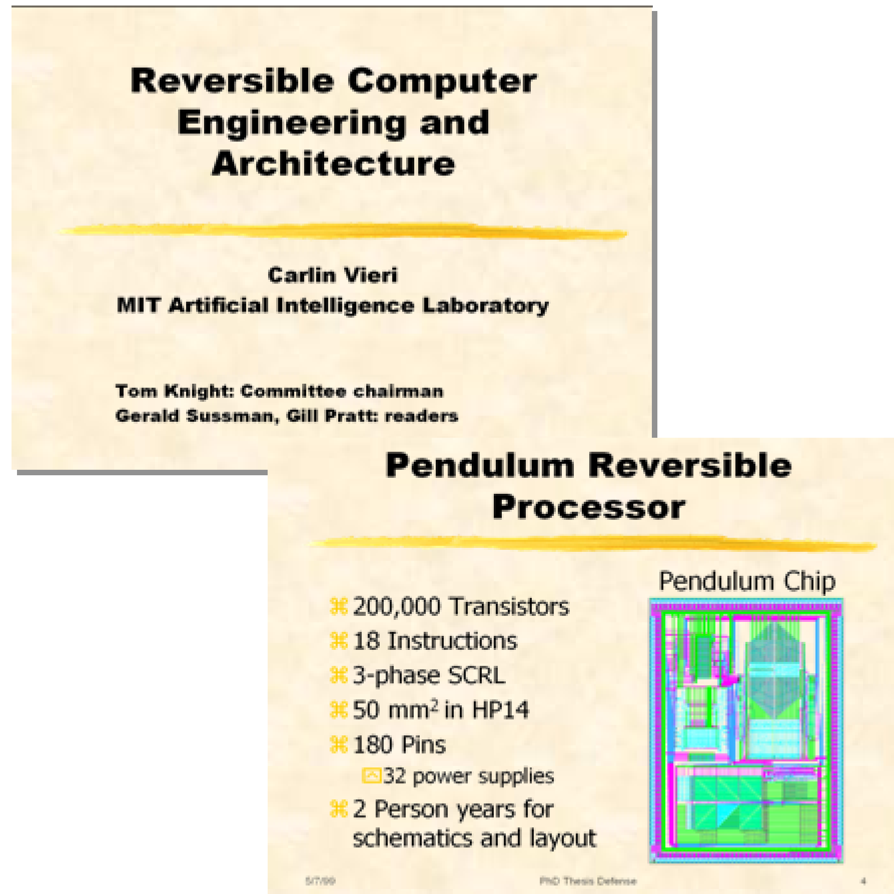
# Reversible Microprocessor Status

- Status
  - Subject of Ph. D. thesis
  - Chip laid out (no floating point)
  - RISC instruction set
  - C-like language
  - Compiler
  - Demonstrated on a PDE
  - However: really weird and not general to program with +=, -=, etc. rather than =

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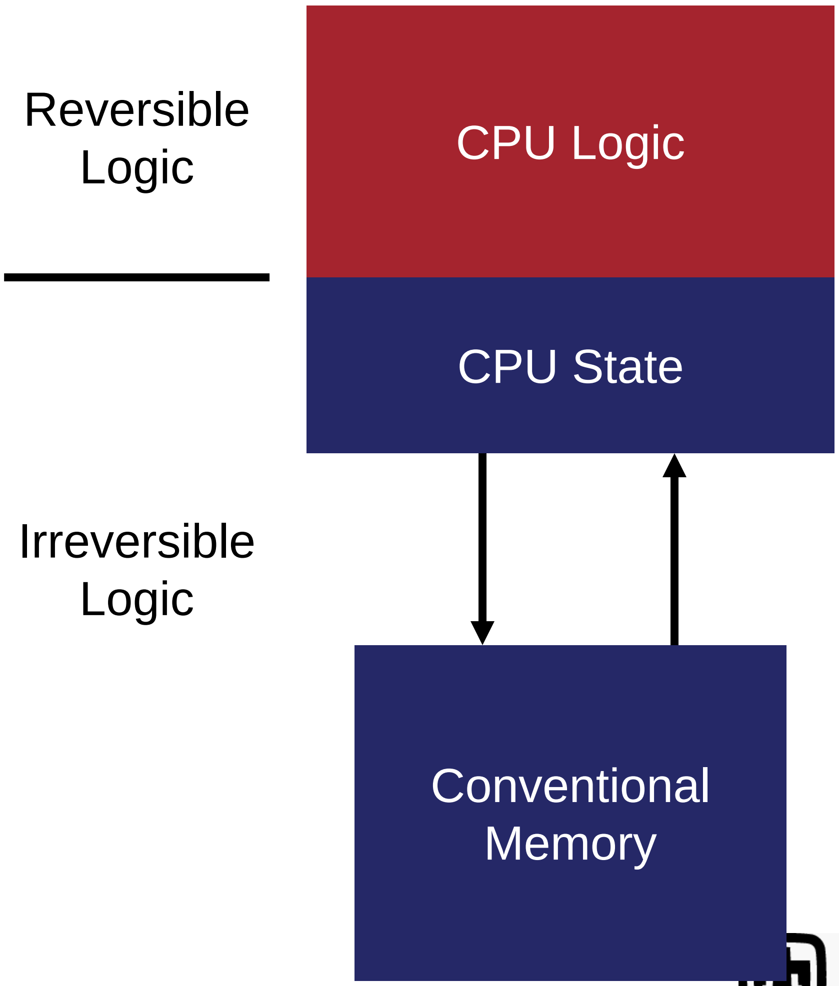
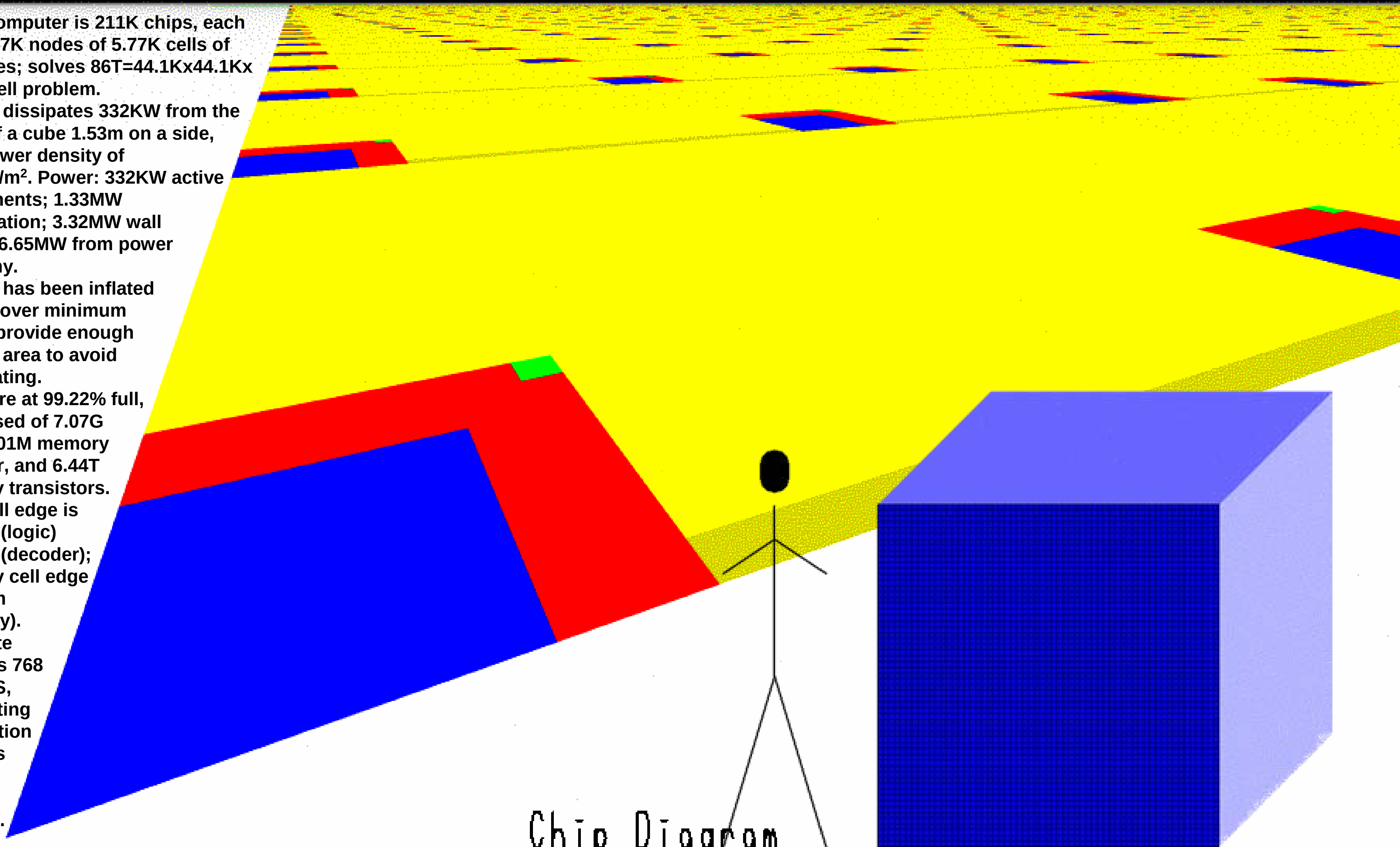
# CPU Design

- **Leading Thoughts**
  - **Implement CPU logic using reversible logic**
    - **High efficiency for the component doing the most logic**
  - **Implement state and memory using conventional logic**
    - **Low efficiency, but not many operations**
  - **Permits programming much like today**

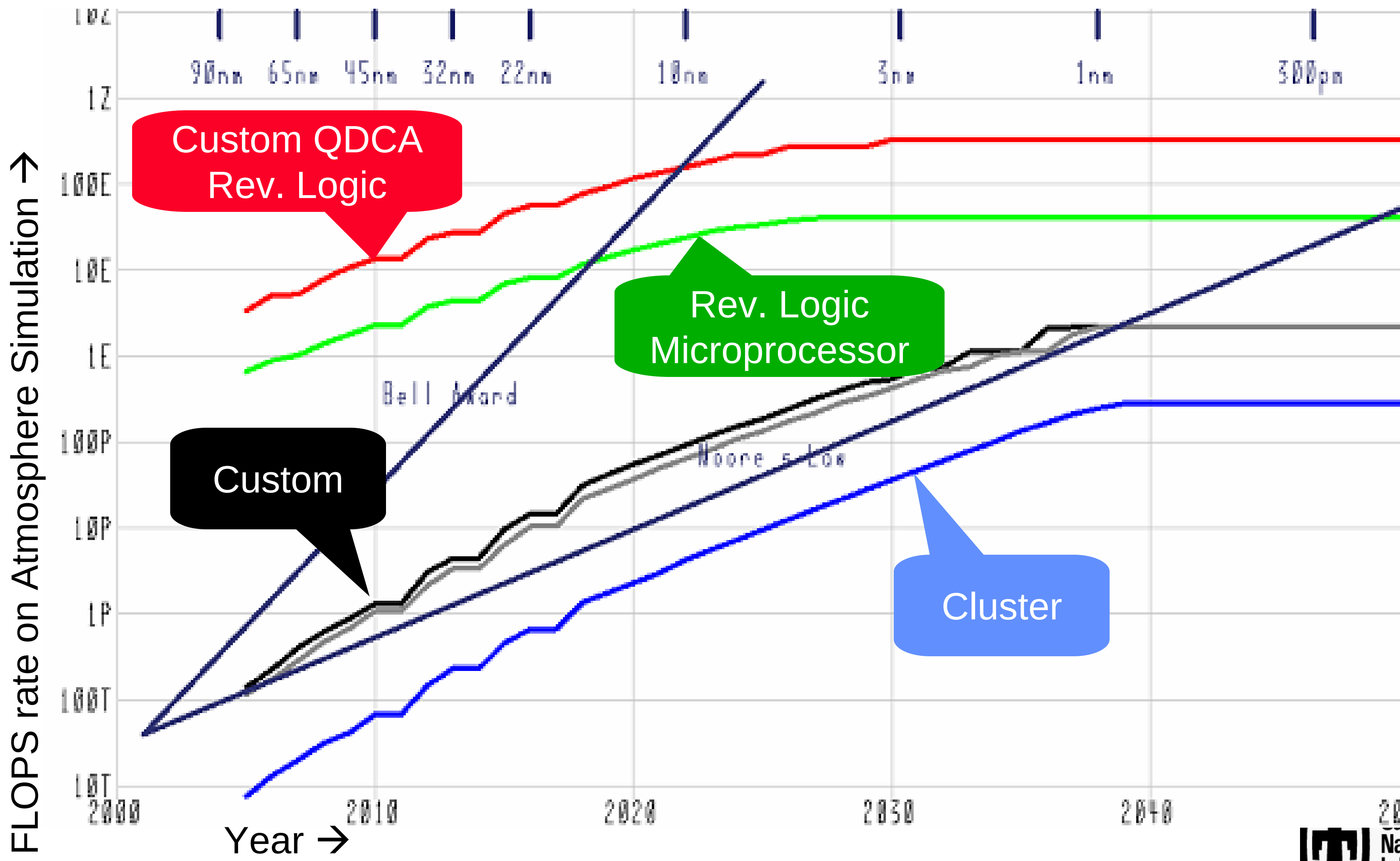


# Atmosphere Simulation at a Zettaflops

Supercomputer is 211K chips, each with 70.7K nodes of 5.77K cells of 240 bytes; solves 86T=44.1Kx44.1Kx 44.1K cell problem.
System dissipates 332KW from the faces of a cube 1.53m on a side, for a power density of 47.3KW/m$^2$. Power: 332KW active components; 1.33MW refrigeration; 3.32MW wall power; 6.65MW from power company.
System has been inflated by 2.57 over minimum size to provide enough surface area to avoid overheating.
Chips are at 99.22% full, comprised of 7.07G logic, 101M memory decoder, and 6.44T memory transistors.
Gate cell edge is 34.4nm (logic) 34.4nm (decoder); memory cell edge is 4.5nm (memory).
Compute power is 768 EFLOPS, completing an iteration in 224μs and a run in 9.88s.



# Performance Curve

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# Conclusions

- There are important applications that are believed to exceed the limits of irreversible logic
  - At US$100M budget
  - E. g. solution to global warming
- Reversible logic & nanotech point in the right direction
  - Low power
- Device Requirements
  - Push speed of light limit
  - Substantially sub-$k_BT$
  - Molecular scales
- Software and Algorithms
  - Must be much more parallel than today
- With all this, just barely works
- Conclusions appear to apply generally

# Backup

# *** This is a Preview ***

| Best-Case Logic | Microprocessor Architecture | Physical Factor | Source of Authority |
|---|---|---|---|
| $2\times10^{24}$ logic ops/s | | Reliability limit 750KW/(80$k_B$T) | Esteemed physicists (T=60°C junction temperature) |
| | | Derate 20,000 convert logic ops to floating point | Floating point engineering (64 bit precision) |
| Expert Opinion: 100 Exaflops | 800 Petaflops | Derate for manufacturing margin (4×) | Estimate |
| Estimate: 25 Exaflops | 200 Petaflops | Uncertainty (6×) | Gap in chart |
| 4 Exaflops | 32 Petaflops | Improved devices (4×) | Estimate |
| 1 Exaflops | 8 Petaflops | Projected ITRS improvement to 22 nm (100×) | ITRS committee of experts |
| | 80 Teraflops | Lower supply voltage (2×) | ITRS committee of experts |
| | 40 Teraflops | Red Storm | contract |

← 125:1 →

Assumption: Supercomputer is size & cost of Red Storm: US$100M budget; consumes 2 MW wall power; 750 KW to active components

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# Metaphor: FM Radio on Trip to in USA

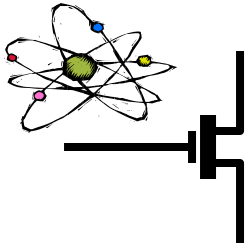
- You drive to a distant listening to FM radio
- Music clear for a while, but noise creeps in and then overtakes music

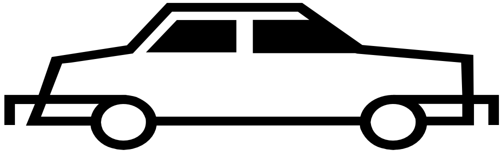
- Analogy: You live out the next dozen years buying PCs every couple years
- PCs keep getting faster
  - clock rate increases
  - fan gets bigger
  - won’t go on forever
- Why…see next slide

Details: Erik DeBenedictis, “Taking ASCI Supercomputing to the End Game,” SAND2004-0959

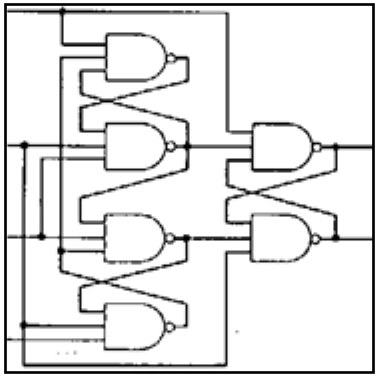
# FM Radio and End of Moore's Law

Distance

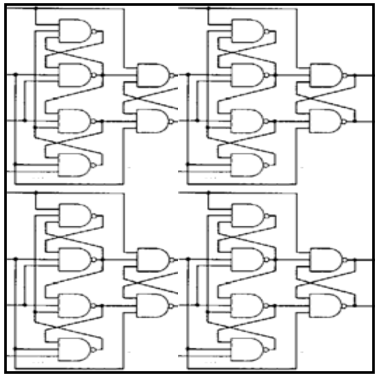




Driving away from FM transmitter→less signal
Noise from electrons → no change



Shrink



Increasing numbers of gates→less signal power
Noise from electrons → no change