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### Submittal Details

<b>Document Info</b>			
Title : Reversible Logic for Supercomputing			
Document Number : 5231909	SAND Number : 2005-2689 C		
Review Type : Electronic	Status : Approved		
Sandia Contact : <a href="#">DEBENEDICTIS,ERIK P.</a>	Submittal Type : Conference Paper		
Requestor : <a href="#">DEBENEDICTIS,ERIK P.</a>	Submit Date : 04/22/2005		
Peer Reviewed? : N			
<b>Author(s)</b>			
DEBENEDICTIS,ERIK P.			
<b>Event (Conference/Journal/Book) Info</b>			
Name : Computing Frontiers 2005			
City : Ischia	State :	Country : Italy	
Start Date : 05/04/2005	End Date : 05/06/2005		
<b>Partnership Info</b>			
Partnership Involved : No			
Partner Approval :	Agreement Number :		
<b>Patent Info</b>			
Scientific or Technical in Content : Yes			
Technical Advance : No	TA Form Filed : No		
SD Number :			
<b>Classification and Sensitivity Info</b>			
Title : Unclassified-Unlimited	Abstract :	Document : Unclassified-Unlimited	
Additional Limited Release Info : None.			
DUSA : None.			

### Routing Details

Role	Routed To	Approved By	Approval Date
Derivative Classifier Approver	<a href="#">SUMMERS,RANDALL M.</a>	<a href="#">SUMMERS,RANDALL M.</a>	04/22/2005
Conditions:			

<b>Classification Approver</b>	<a href="#">WILLIAMS, RONALD L.</a>	<a href="#">WILLIAMS, RONALD L.</a>	<b>04/25/2005</b>
<b>Conditions:</b>			
<b>Manager Approver</b>	<a href="#">PUNDIT, NEIL D.</a>	<a href="#">PUNDIT, NEIL D.</a>	<b>04/29/2005</b>
<b>Conditions:</b>			
<b>Administrator Approver</b>	<a href="#">LUCERO, ARLENE M.</a>	<a href="#">KRAMER, SAMUEL</a>	<b>06/05/2007</b>

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For Review and Approval process questions please contact the **Application Process Owner**

# Reversible Logic for Supercomputing

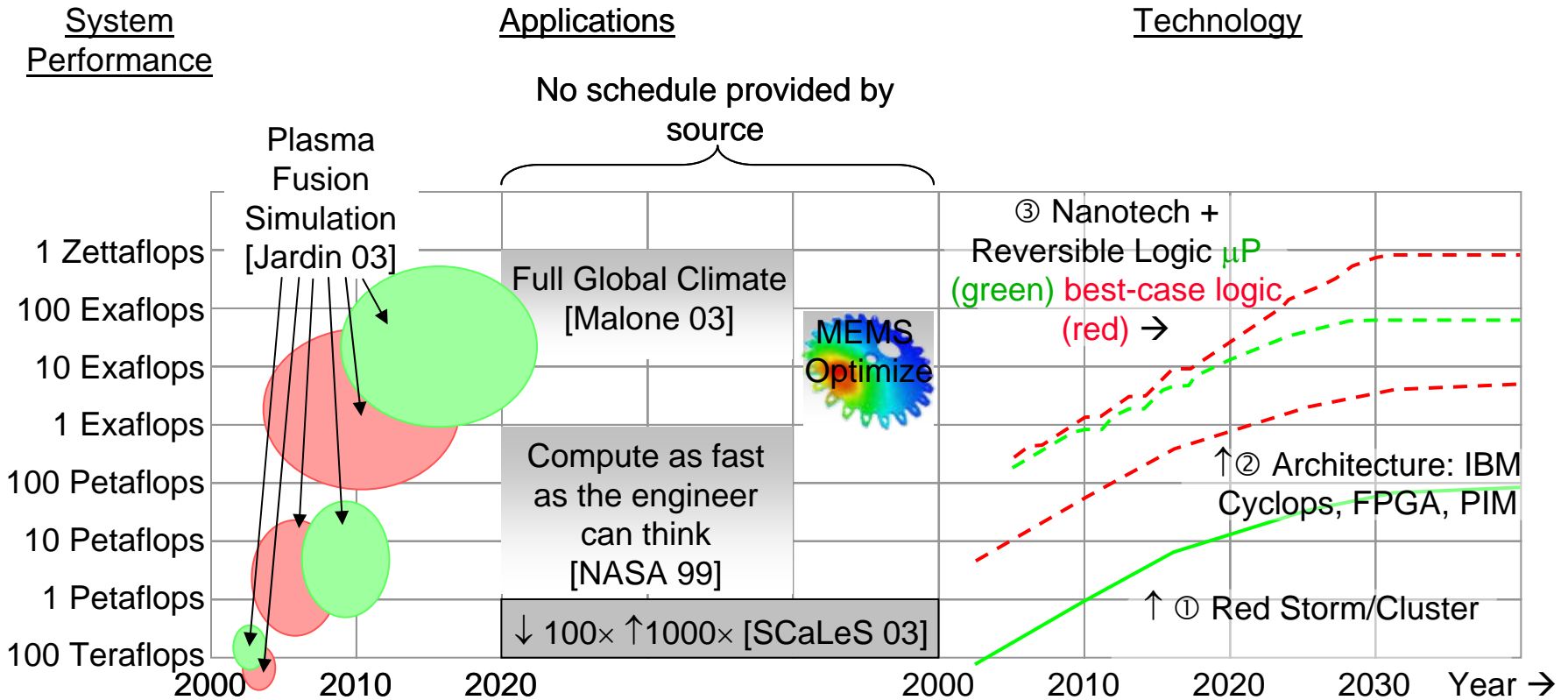
*How to save the Earth with Reversible Computing*

**Erik P. DeBenedictis**  
**Sandia National Laboratories**

**May 5, 2005**



# 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.



# Objectives and Challenges

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- **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**

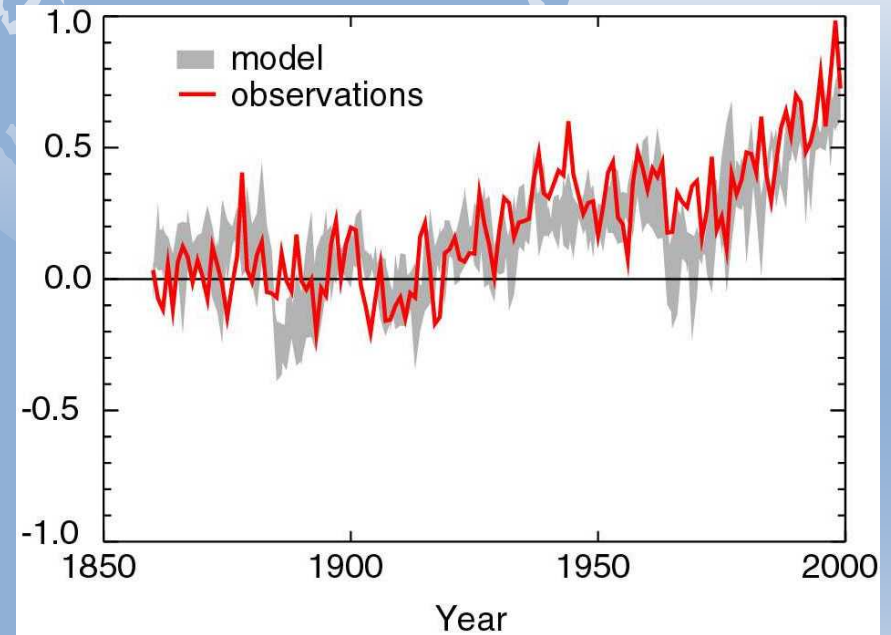
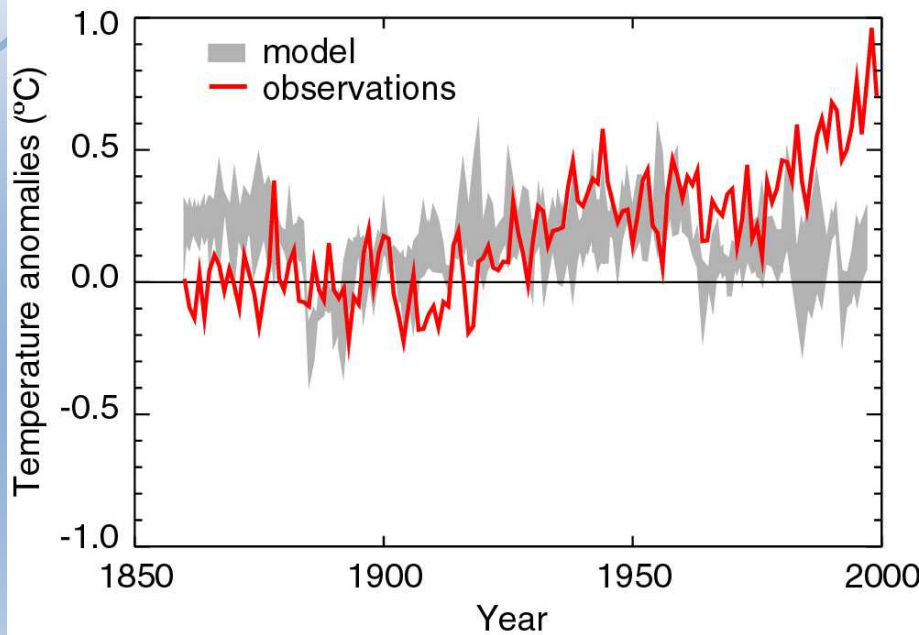


# Outline

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- **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



**“Simulations of the response to natural forcings alone ... do not explain the warming in the second half of the century”**

Stott et al, Science 2000

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

# FLOPS Increases for Global Climate

	Issue	Scaling
1 Zettaflops	Ensembles, scenarios 10×	Embarrassingly Parallel
100 Exaflops	Run length 100×	Longer Running Time
1 Exaflops	New parameterizations 100×	More Complex Physics
10 Petaflops	Model Completeness 100×	More Complex Physics
100 Teraflops	Spatial Resolution $10^4\times (10^3\times-10^5\times)$	Resolution
10 Gigaflops	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

**Best-Case Logic**

**Microprocessor Architecture**

**Physical Factor**

**Source of Authority**

$2 \times 10^{24}$  logic ops/s

Expert Opinion	100 Exaflops	800 Petaflops
	← 125:1 →	
Estimate	25 Exaflops	200 Petaflops
	4 Exaflops	32 Petaflops
	1 Exaflops	8 Petaflops

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

80 Teraflops

40 Teraflops

Reliability limit 750KW/(80k <sub>B</sub> T)	Esteemed physicists (T=60°C junction temperature)
Derate 20,000 convert logic ops to floating point	Floating point engineering (64 bit precision)
Derate for manufacturing margin (4x)	Estimate
Uncertainty (6x)	Gap in chart
Improved devices (4x)	Estimate
Projected ITRS improvement to 22 nm (100x)	ITRS committee of experts
Lower supply voltage (2x)	ITRS committee of experts
Red Storm	contract

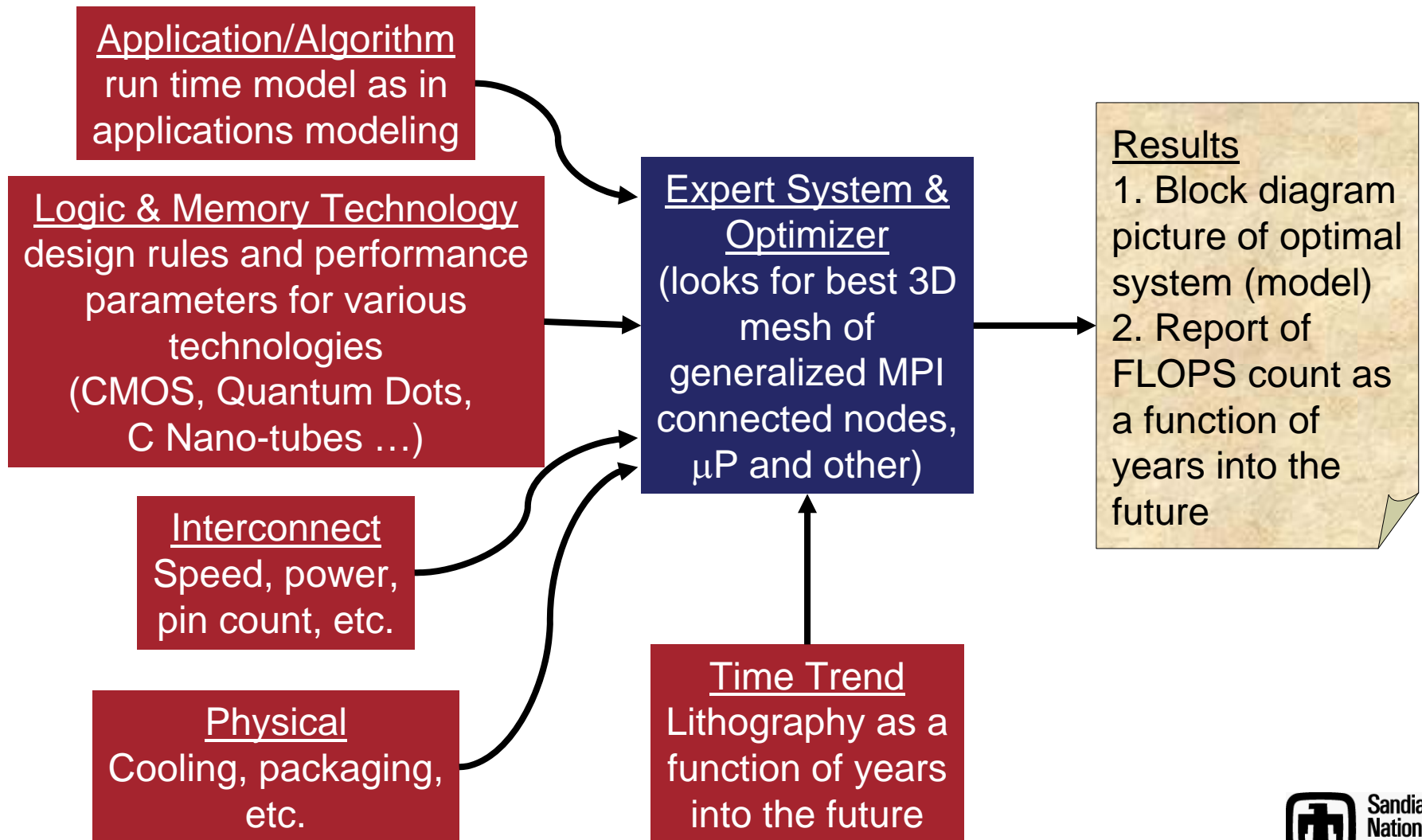


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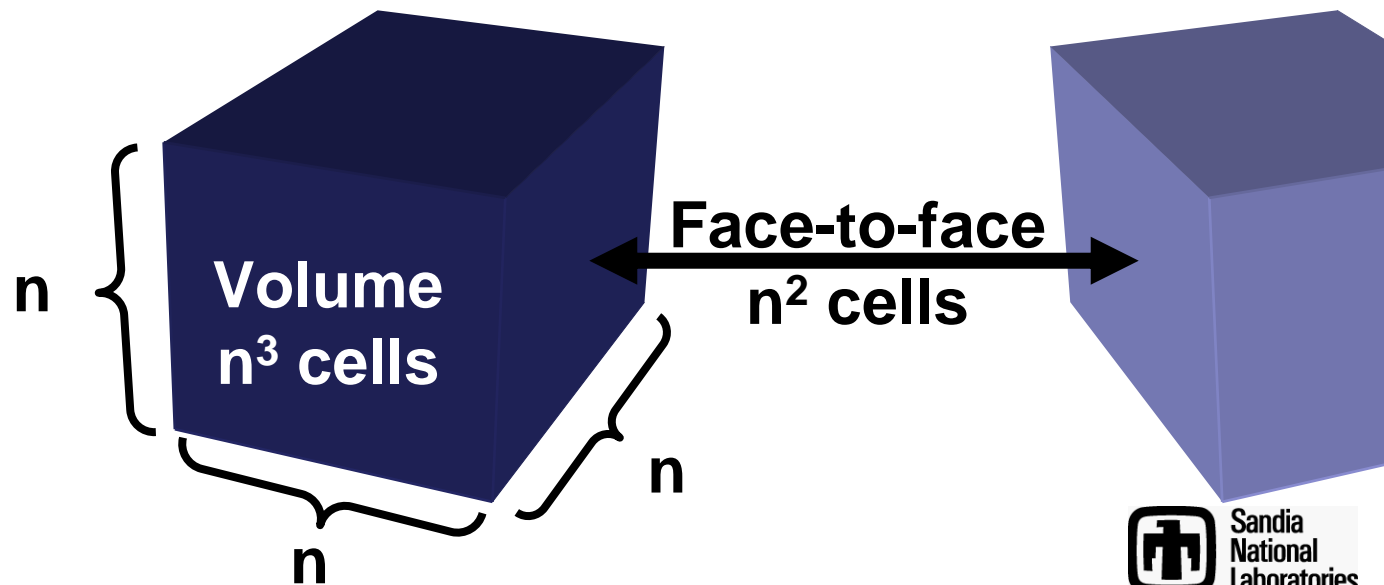
# Supercomputer Expert System



# Sample Analytical Runtime Model

- Simple case: finite difference equation
- Each node holds  $n \times n \times n$  grid points
- Volume-area rule
  - Computing  $\propto n^3$
  - Communications  $\propto n^2$

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





# Expert System for Future Supercomputers

---

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

- Use “Expert System” To Calculate:

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

- Report:

Floating operations

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

and illustrate “design”



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# The Big Issue

- Initially, didn't meet constraints



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



# ITRS Device Review 2016 + QDCA

Technology	Speed (min-max)	Dimension (min-max)	Energy per gate-op	Comparison
CMOS	30 ps-1 $\mu$ s	8 nm-5 $\mu$ m	4 aJ	
RSFQ	1 ps-50 ps	300 nm- 1 $\mu$ m	2 aJ	Larger
Molecular	10 ns-1 ms	1 nm- 5 nm	10 zJ	Slower
Plastic	100 $\mu$ s-1 ms	100 $\mu$ m-1 mm	4 aJ	Larger+Slower
Optical	100 as-1 ps	200 nm-2 $\mu$ m	1 pJ	Larger+Hotter
NEMS	100 ns-1 ms	10-100 nm	1 zJ	Slower+Larger
Biological	100 fs-100 $\mu$ s	6-50 $\mu$ m	.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



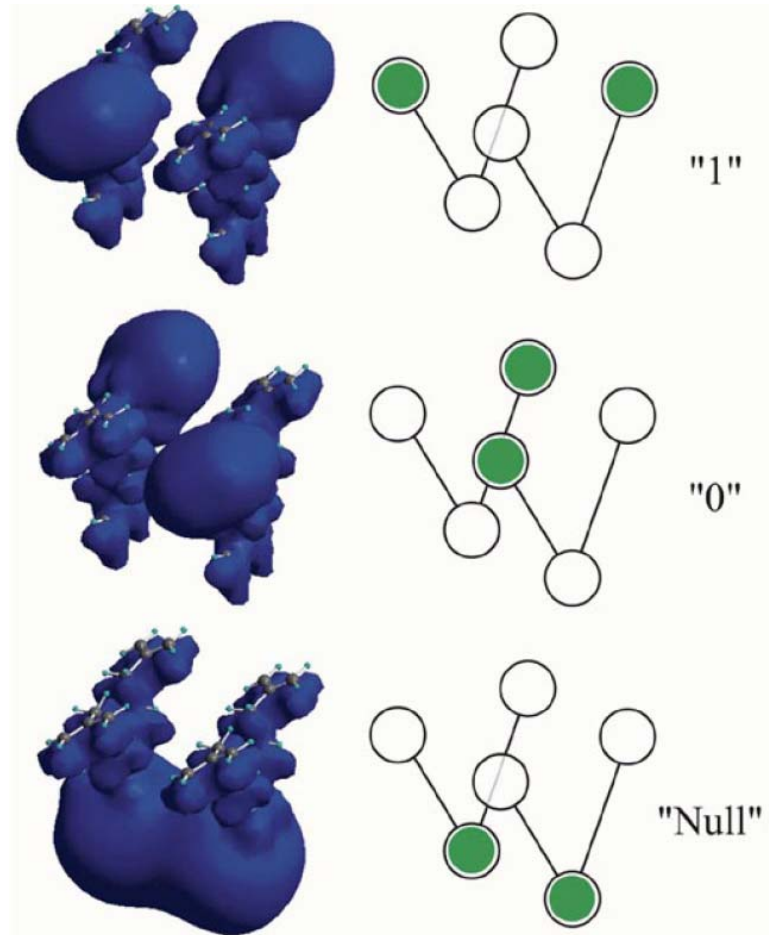
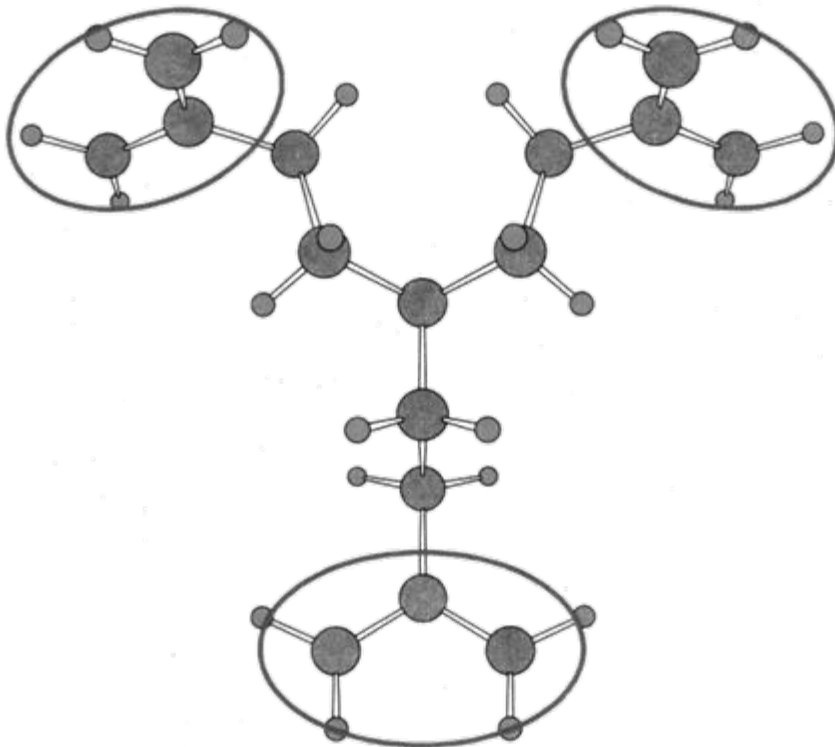
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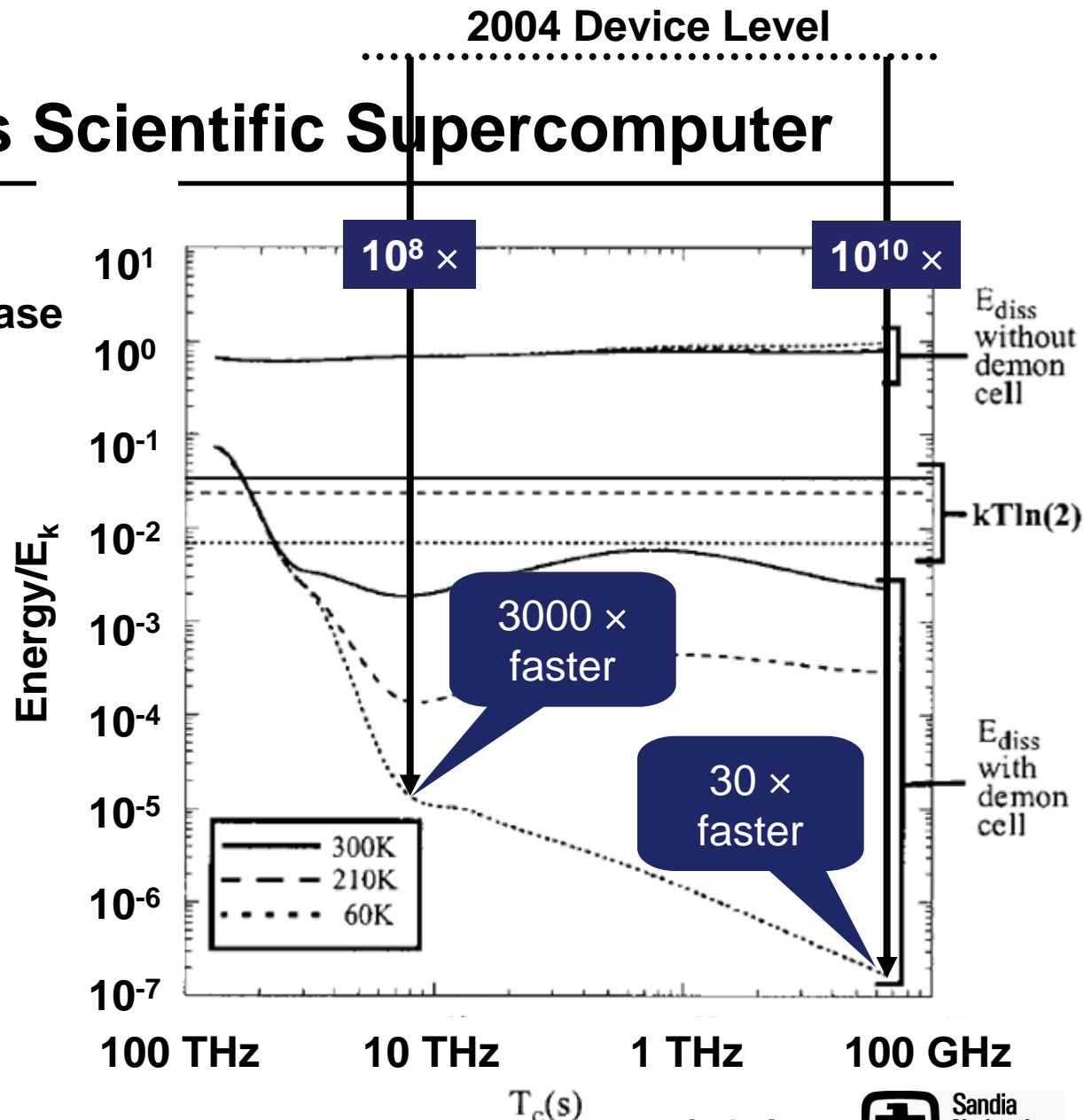
# An Exemplary Device: Quantum Dots

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



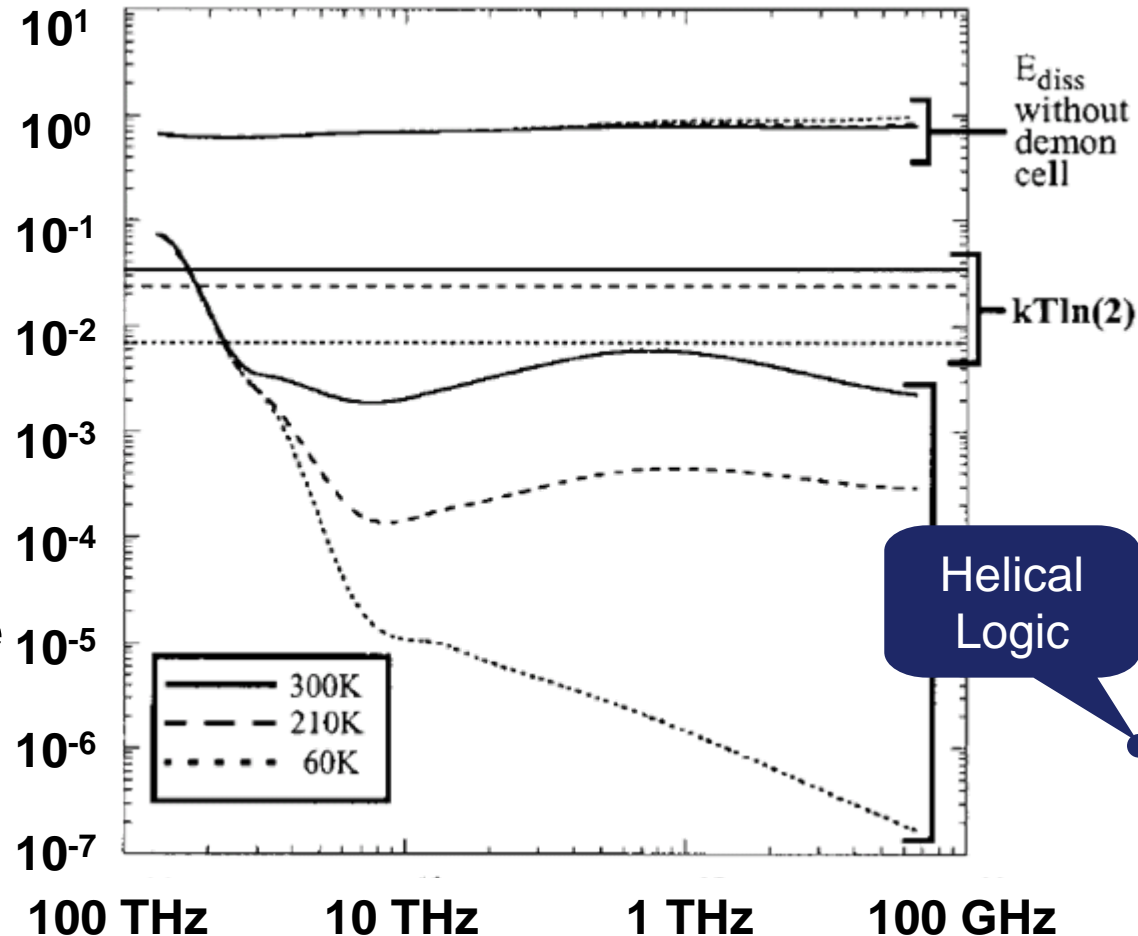
# 1 Zettaflops Scientific Supercomputer

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



# 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 Timmer 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 $\times$  circuit density of CMOS at same  $\lambda$
- Applies to various devices
  - Metal dot 4.2 nm<sup>2</sup>
  - Molecular 1.1 nm<sup>2</sup>

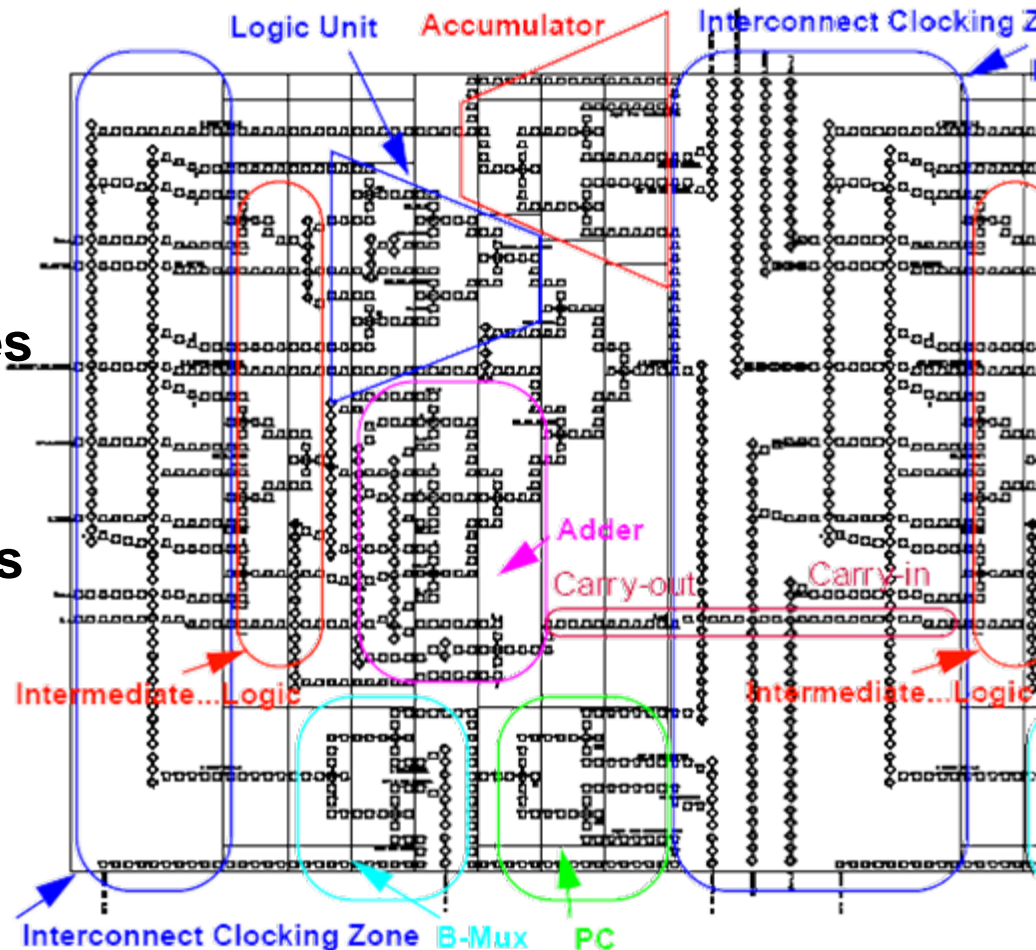
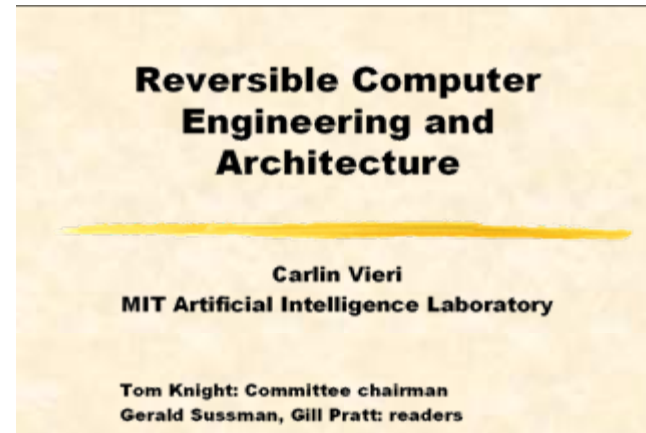


Figure 4.6. A 2-bit QCA Simple 12 ALU with Logic Circuits

# 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 =



**Pendulum Reversible  
Processor**

- ⌘ 200,000 Transistors
- ⌘ 18 Instructions
- ⌘ 3-phase SCRL
- ⌘ 50 mm<sup>2</sup> in HP14
- ⌘ 180 Pins
  - ⌘ 32 power supplies
- ⌘ 2 Person years for schematics and layout

Pendulum Chip

5/7/99 Ph.D. Thesis Defense 4

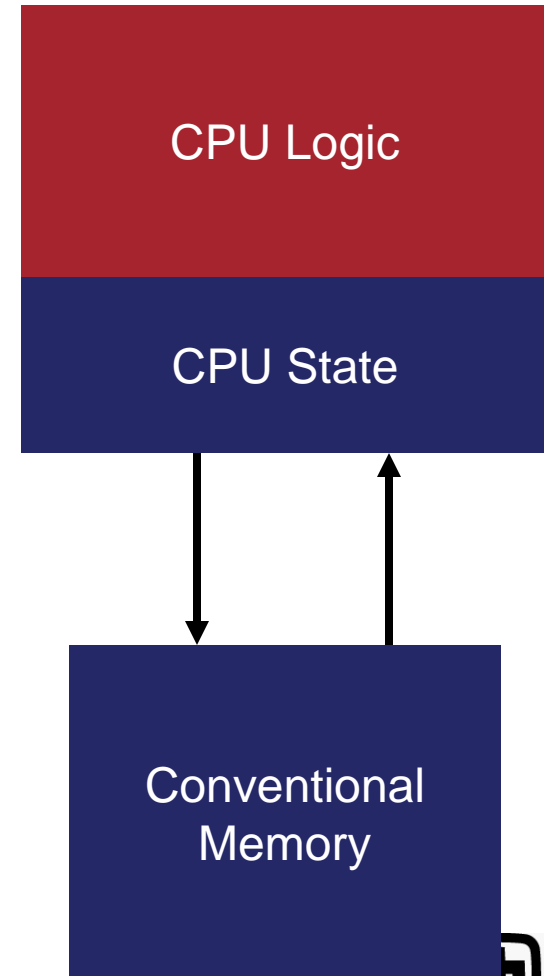


# CPU Design

- **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**

Reversible  
Logic

Irreversible  
Logic





# Atmosphere Simulation at a Zettaflops

Supercomputer is 211K chips, each with 70.7K nodes of 5.77K cells of 240 bytes; solves  $86T=44.1K \times 44.1K \times 44.1K$  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.

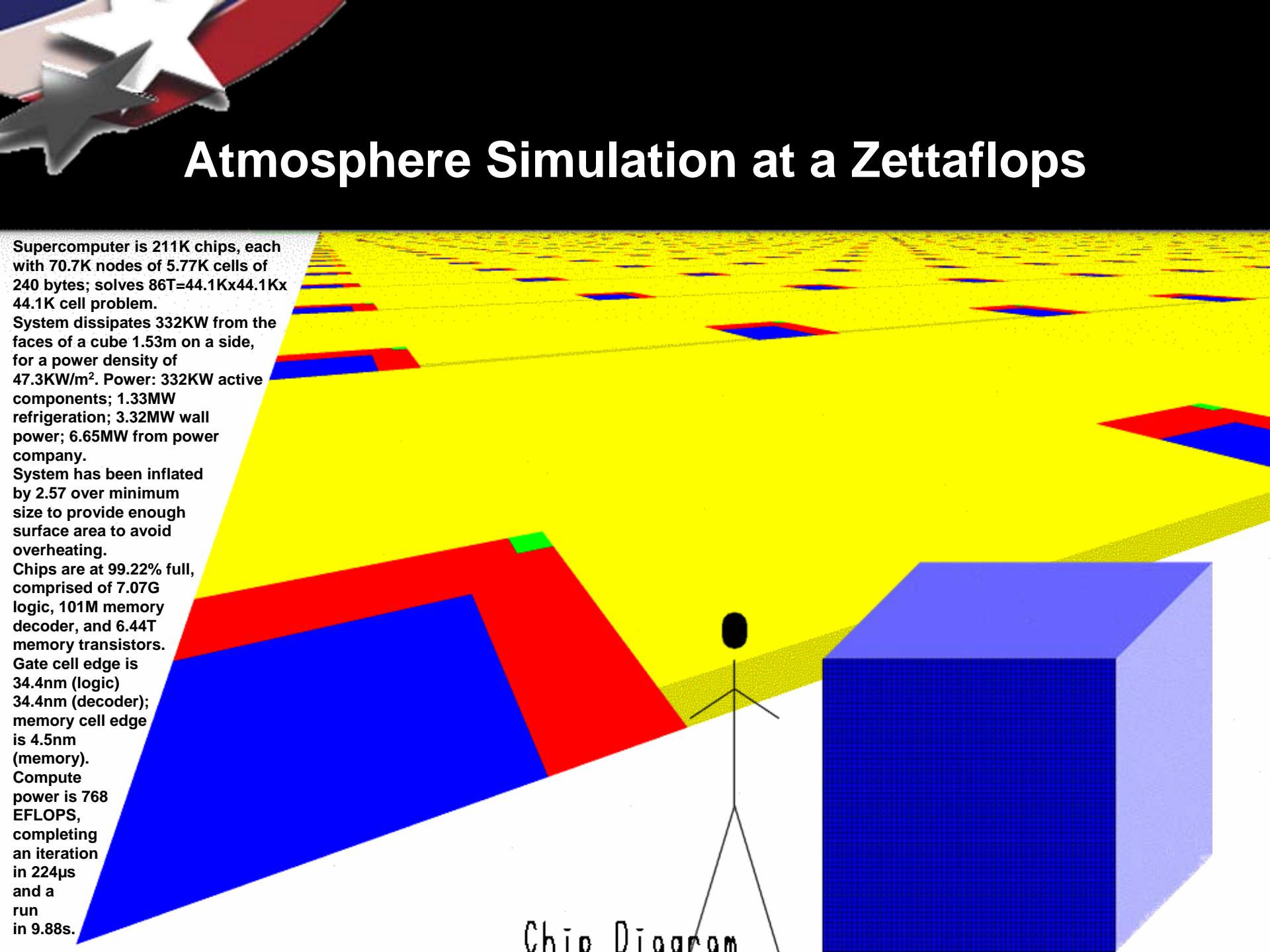
System has been inflated by 2.57 over minimum size to provide enough surface area to avoid overheating.

Chips are at 99.22% full, comprised of 7.07G logic, 101M memory decoder, and 6.44T memory transistors.

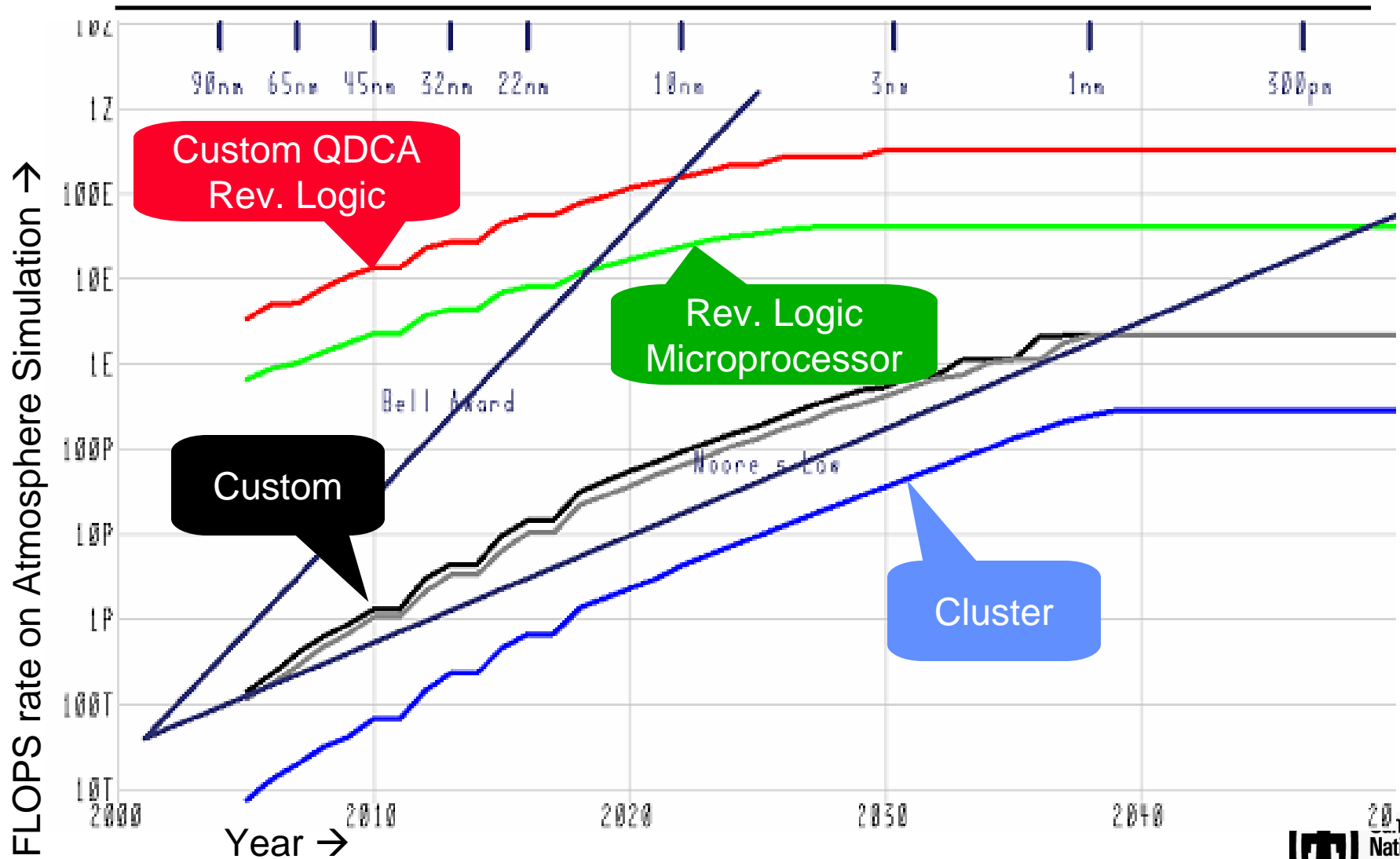
Gate cell edge is 34.4nm (logic)  
34.4nm (decoder);  
memory cell edge is 4.5nm (memory).

Compute power is 768 EFLOPS, completing an iteration in  $224\mu s$  and a run in 9.88s.

Chip Diagram



# Performance Curve





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# Conclusions

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- **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- $k_B T$
  - Molecular scales
- **Software and Algorithms**
  - Must be much more parallel than today
- **With all this, just barely works**
- **Conclusions appear to apply generally**



# Backup

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# \*\*\* This is a Preview \*\*\*

**Best-Case Logic**

**Microprocessor Architecture**

**Physical Factor**

**Source of Authority**

$2 \times 10^{24}$  logic ops/s

Expert Opinion	100 Exaflops	800 Petaflops
	← 125:1 →	
Estimate	25 Exaflops	200 Petaflops
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Assumption: Supercomputer is size & cost of Red Storm: US\$100M budget; consumes 2 MW wall power; 750 KW to active components

80 Teraflops

40 Teraflops

Reliability limit 750KW/(80k <sub>B</sub> T)	Esteemed physicists (T=60°C junction temperature)
Derate 20,000 convert logic ops to floating point	Floating point engineering (64 bit precision)
Derate for manufacturing margin (4x)	Estimate
Uncertainty (6x)	Gap in chart
Improved devices (4x)	Estimate
Projected ITRS improvement to 22 nm (100x)	ITRS committee of experts
Lower supply voltage (2x)	ITRS committee of experts
Red Storm	contract



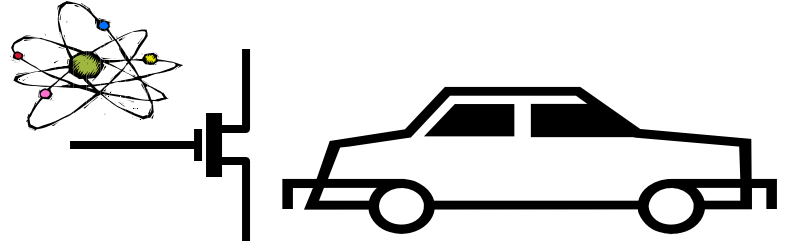
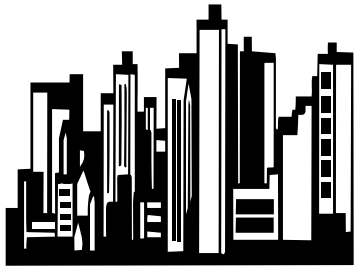
# Metaphor: FM Radio on Trip to in USA

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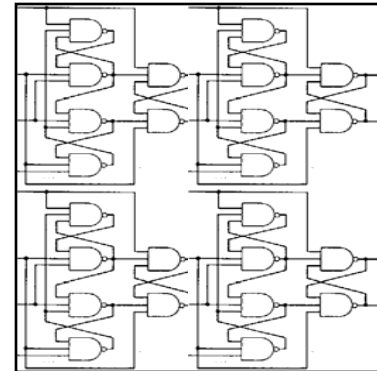
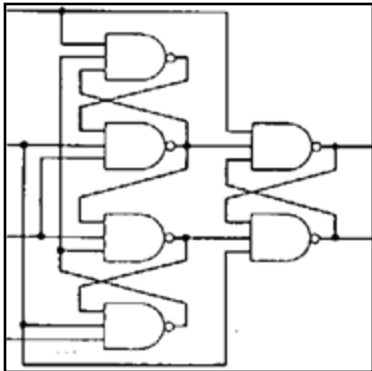
- You drive to a distant listening to FM radio
- Music clear for a while, but noise creeps in and then overtakes music
- Analogy: You live out the next dozen years buying PCs every couple years
- PCs keep getting faster
  - clock rate increases
  - fan gets bigger
  - won't go on forever
- Why...see next slide

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

# FM Radio and End of Moore's Law



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



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