What Landauer Limit? Ultra-low power electronics, and the minimum energy for computation

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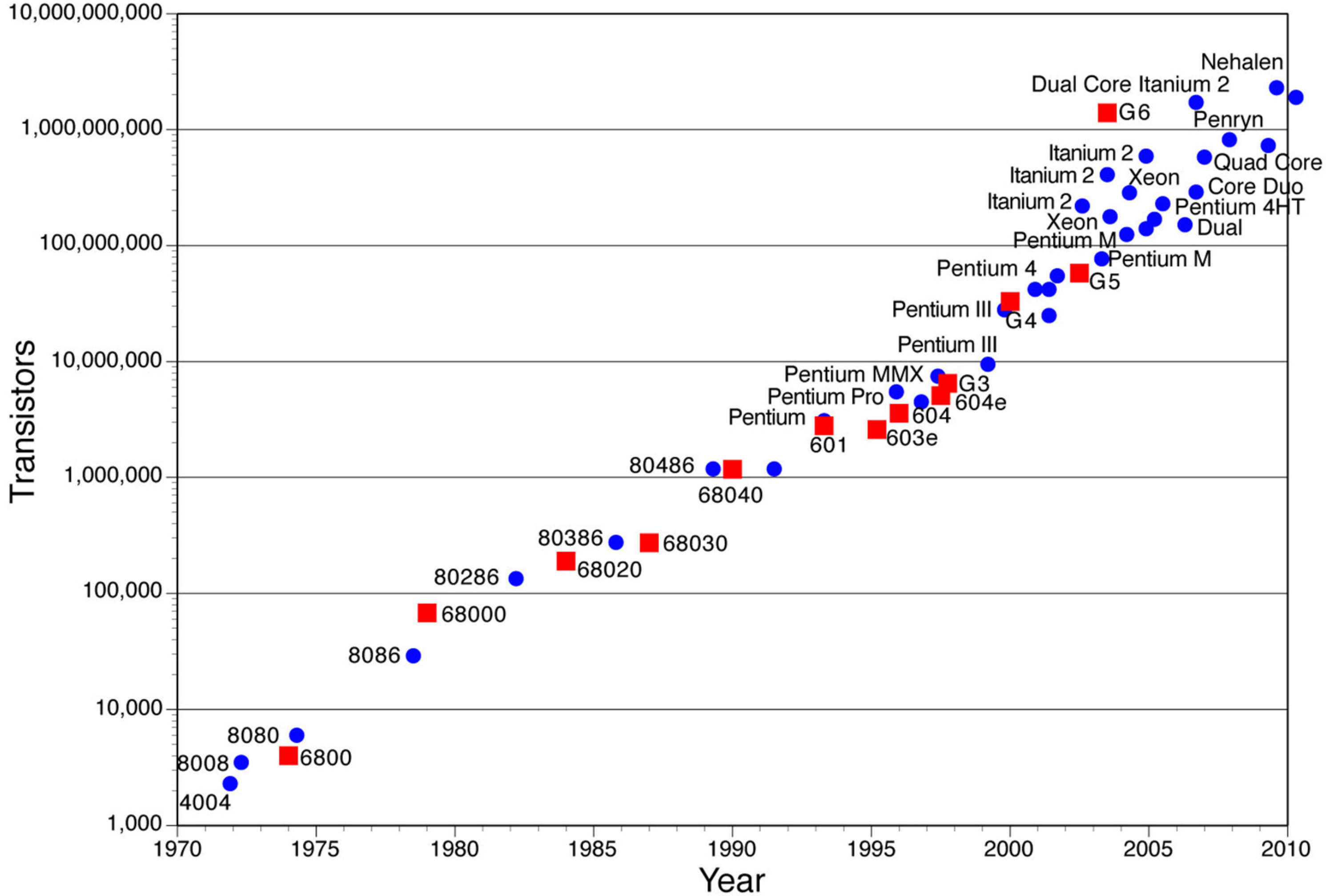
Outline

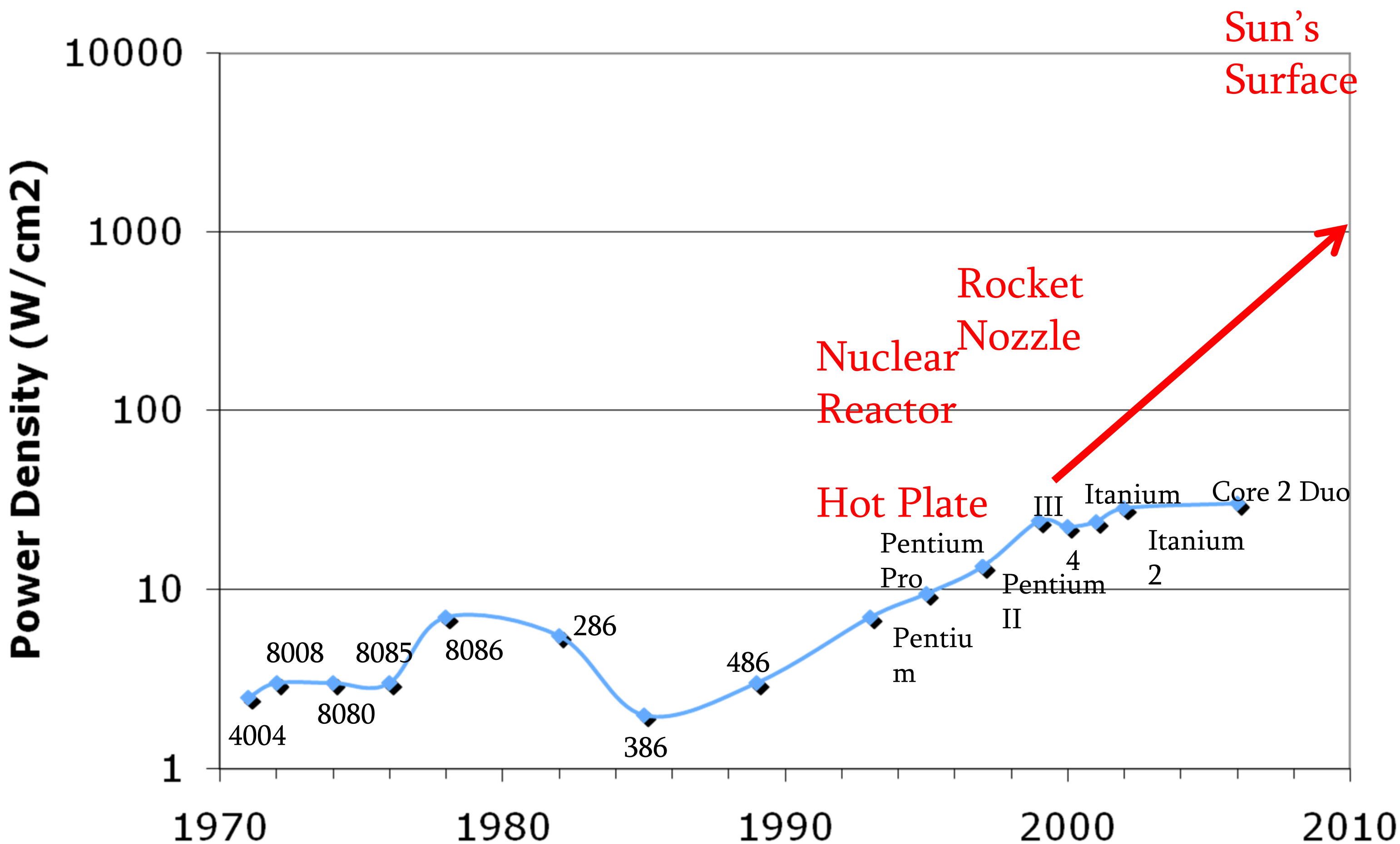
- The power dilemma and resulting limits
- The Landauer Principle
- A word about state variables
- Experiments
- Possible ways forward

Moore’ s Law



The number of transistors per chip doubles every 18 months

Power Density



Multi-core processors necessary to keep chips from melting

Is Heat Really a Problem?

Every Problem is an opportunity:

Bora Model G220

[front] [back] [colors] [more pictures]

- Heat Protection: ★★★☆☆
- Temperature Protection: *44°F*
- No-Slip Surfaces: *Front & Back*
- Sizing: *Fits Most Laptops*
- Wide-Screen Compatible: *Yes*
- Size (HxWxT): *11.0" x 16.0" x 0.5"*
- Weight: *13 oz*

Price: $24.95

Add to cart

Availability: In Stock

Benefits

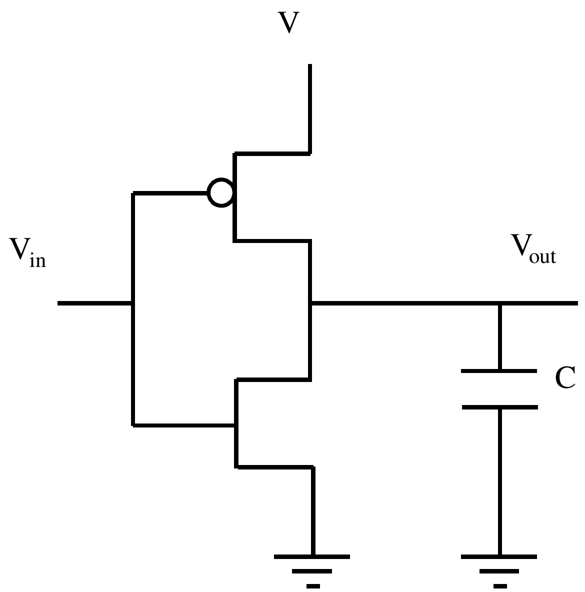
- Pays for itself in less than 1 week!
- Basic personal comfort and protection from laptop heat
- Rigid surface provides firm support underneath the laptop
- Made from durable materials that won't snag or tear
- Fits all laptop computers
- 1 year warranty

Applications for waste heat:

Home heating, Global warming, etc.

Power in Conventional Logic

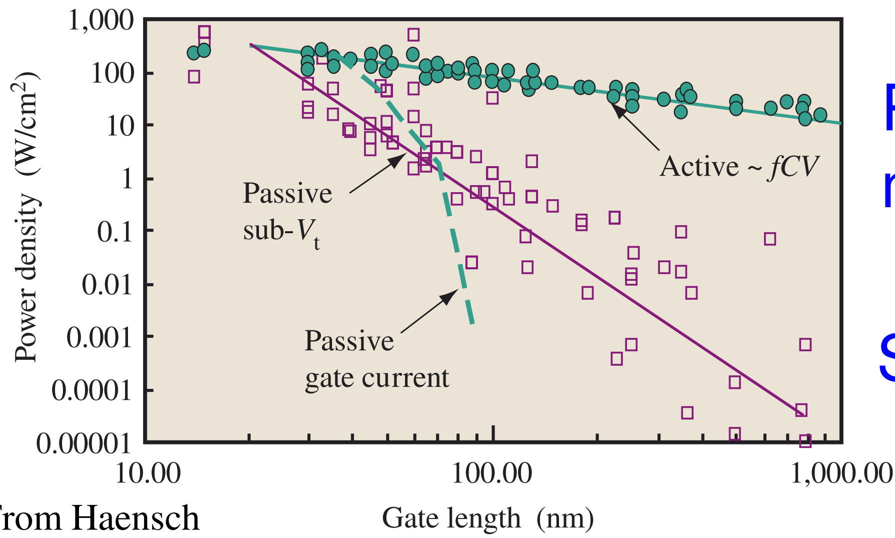
Conventional CMOS $P = N(\alpha \underbrace{CV^2}_{2E_{Bit}} f + \text{Passive Dissipation})$



How to reduce power?

- Reduce V
- Reduce C
- Reduce f (multi-core)
- Turn off parts of the circuit (α)
- Reduce passive power

Focus on Active or Passive Power?

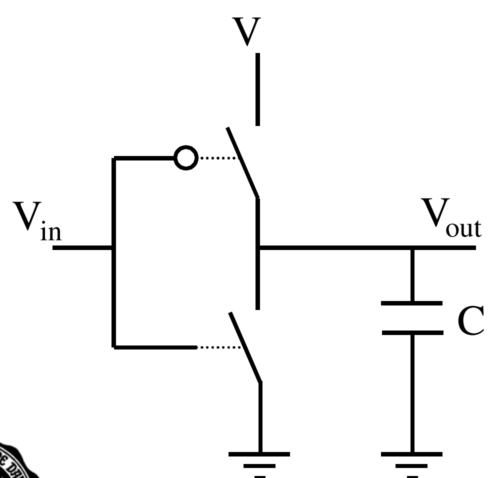


From Haensch
IBM J. Res. Dev. 2006

Passive Power seems the most threatening!

Solution: Improve the switch!

The Perfect Switch



You've fixed Static Power issue, but not the active power!

If E_{Bit} =100 k_BT, f=100 GHz, N=10^{11} cm^{-2}

P = 4 kW/cm^2

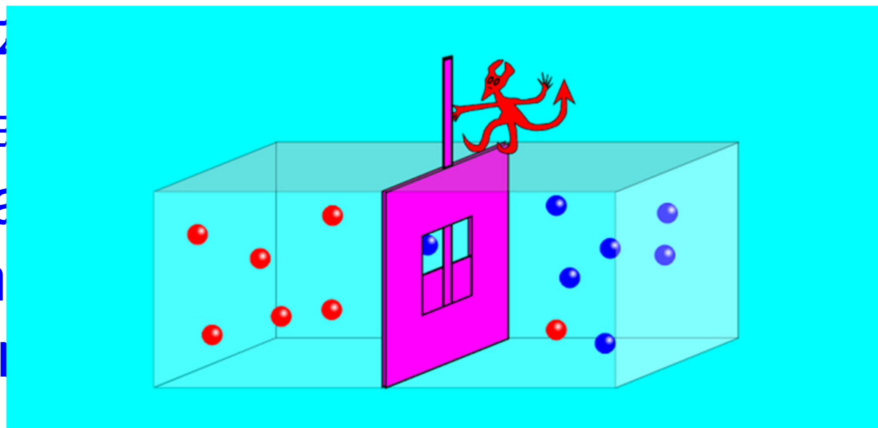
Fundamental limits for computation?

Is there a fundamental lower limit on energy dissipation per bit?

i.e. is there a minimum amount of heat that must be generated to compute a bit?

Minimum energy for computation

- Maxwell's demon (1875) – by first measuring states, could perform reversible processes to lower entropy
- Sz *measurement* causes k_B
- La *ruction* of information m 2) per bit (**Landauer's Pr**



Maxwell's Demon

- Bennett (1982): full computation can be done without erasure.

logical reversibility ⇔ physical reversibility

Still somewhat controversial.

The Debate

Exorcist XIV: The wrath of Maxwell's demon. Part I: From Maxwell to Szilard, Earman, J., & Norton, J. D., Studies in History and Philosophy of Modern Physics, 29, 435 (1998).

Exorcist XIV: The wrath of Maxwell's demon. Part II: From Szilard to Landauer and beyond, Earman, J., & Norton, J. D., Studies in History and Philosophy of Modern Physics, 30, 1 (1999).

Eaters of the lotus: Landauer's principle and the return of Maxwell's demon, Norton, J. D., Studies in History and Philosophy of Modern Physics, 36, 375 (2005).

The (absence of a) relationship between thermodynamic and logical reversibility, Maroney, O. J. E. Studies in History and Philosophy of Modern Physics, 36, 355 (2005)

The connection between logical and thermodynamic irreversibility, James Ladyman, Stuart Presnell, Anthony J. Short, Berry Groisman, Studies in History and Philosophy of Modern Physics, 38, 58 (2007).

Analysis of erasure process

Helpful to examine and contrast two cases:

- Erasure with a copy
  - Reversible logical operation (No Data Destroyed)
  - Key feature:

    The copy biases the system toward the state it's in
- Erasure without a copy
  - Irreversible logical operation (Data Destroyed)
  - Key feature:

    The system cannot be biased toward the state it's in, so there's an uncontrolled step

What About State Variables?

- Does the choice of a state variable affect this analysis?
- Isn't using charge as the state variable the real problem?
- If we use a different state variable like spin, the problem goes away, right?

A Little History

Beginning in 2003 Zhirnov, Cavin, and Hutchby from SRC have published a series of highly influential papers indicting charge as a state variable.

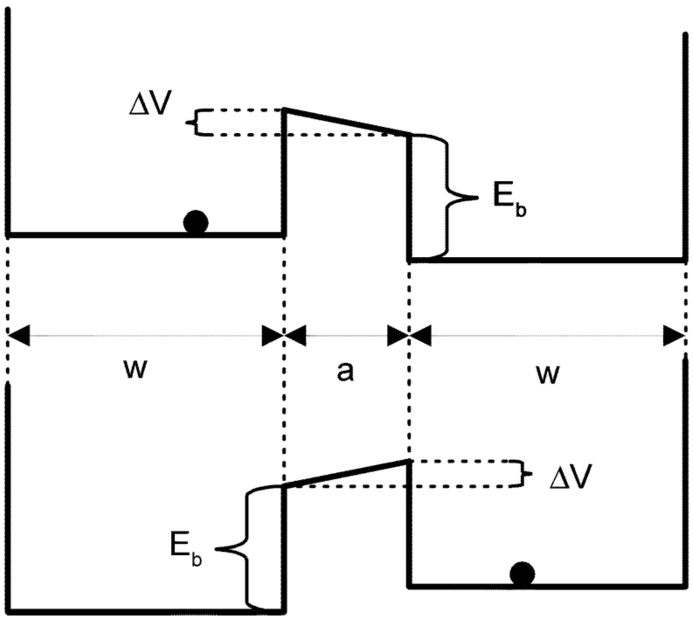


Fig. 1. Energy model for limiting device: w = width of left-hand well (LHW) and right-hand well (RHW); a = barrier width; E = barrier energy

Their conclusions:

- At least $k_B T \ln 2$ must be dissipated at each transition
- This result was generalized to all charge-based devices

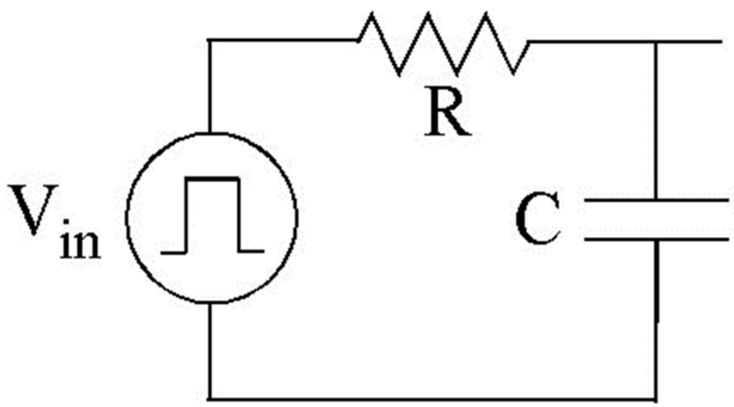
This is true for CMOS, but what about other charge based devices?

V.V. Zhirnov, et al., *Proceedings of the IEEE*, **91**, p. 1934-39, 2003.

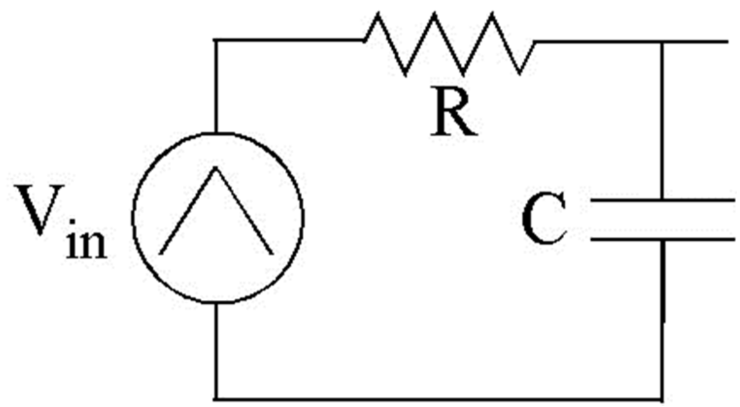
What About “Reversible” Computing?

Following Landauer, the idea is to avoid erasure of information.

A key technology in reversible computing is adiabatic charging and discharging of capacitors: recycle charge rather than throwing it to ground.



$$E_R = \frac{1}{2} C V^2$$



$$E_R < \frac{1}{2} C V^2$$

The SRC critique: Cavin’s Demon

Cavin's Demon

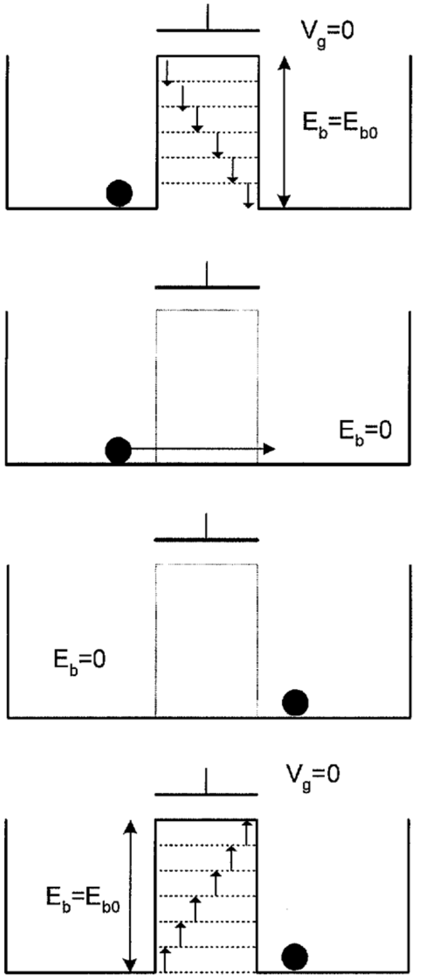
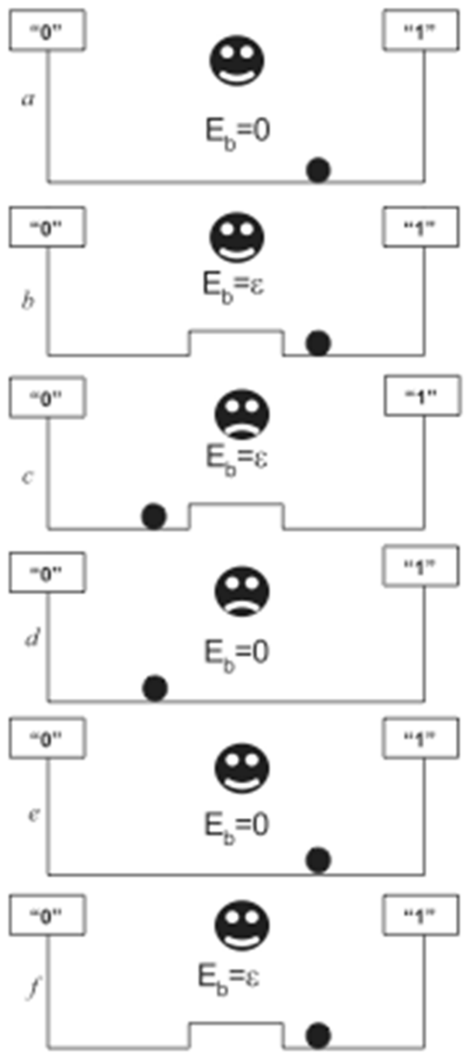


Figure 6.: Adiabatic barrier transitions

Assertion 1. Energy must be dissipated to make logic transitions.

Energy spent by the demon must be > $k_B T \ln 2$

Problem: Since there is no input this is really just creating a bit of information.



Fluct. and Noise Letters, Vol. **5**, pp. C29, 2005.

Proc. SPIE Vol. **5844**, pp. 1, 2005

Cavin's Demon

Assertion 2: Charging a capacitor requires at least $k_B T \ln 2$ of energy

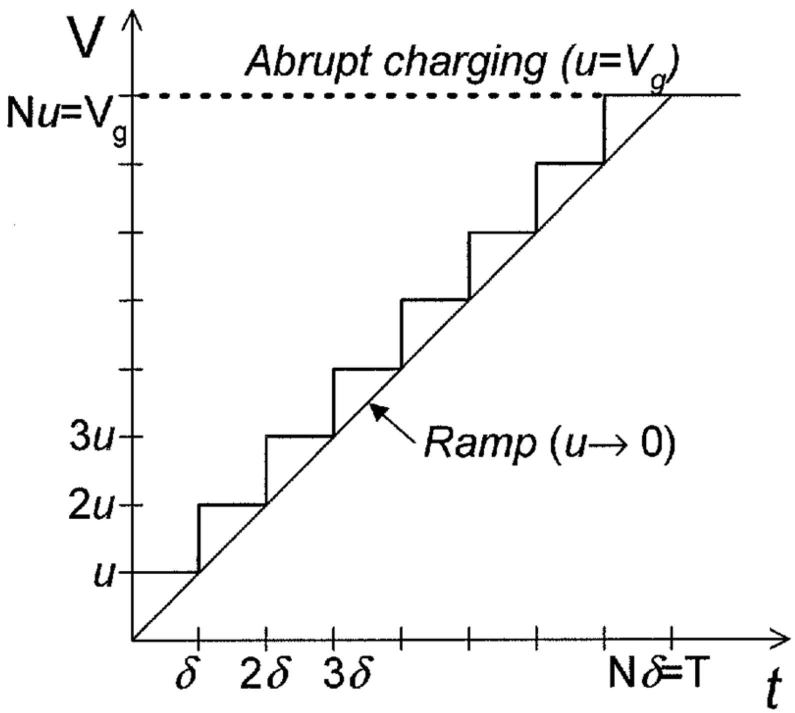


Figure 3: Signal forms for "non-adiabatic" and "adiabatic" charging

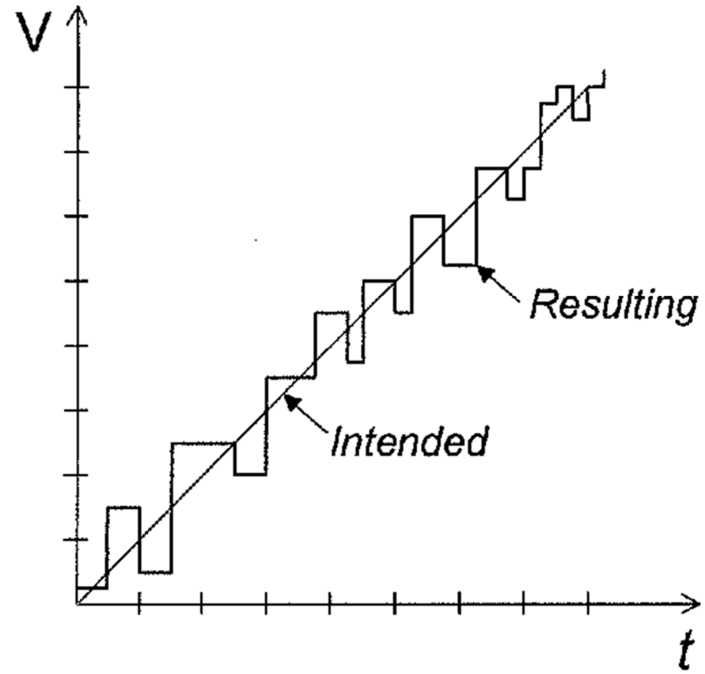


Figure 4: Due to the presence of thermal noise, the linear ramp is corrupted

Note I on adiabatic charging: The energy dissipated in RC circuit by adiabatic charging cannot be smaller than kTln2

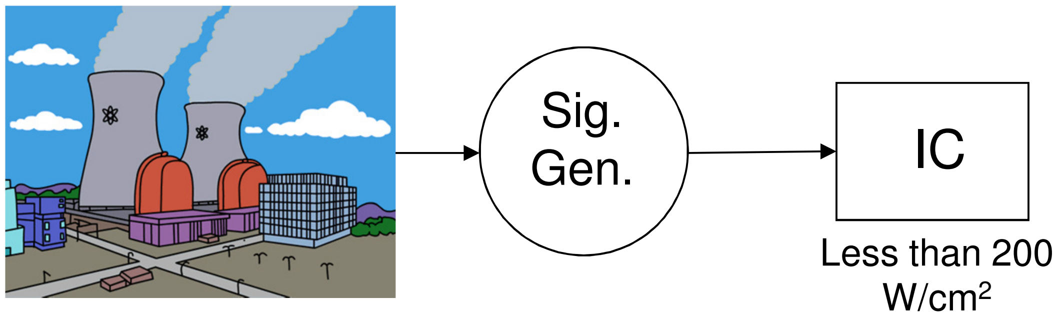
Cavin's Demon

Assertion 3: *Note II on "adiabatic charging": The total energy costs for "adiabatic charging" must include the energy dissipated by the signal generator and this is much larger than the energy dissipated in RC circuit by adiabatic charging:*

$$E_{ad}^{total} >> E_{ad}$$

This is a systems level assertion that depends on the signal generator. However, signal generators can scale differently than integrated circuits!

Worst case: Signal generator more easily cooled than and IC!

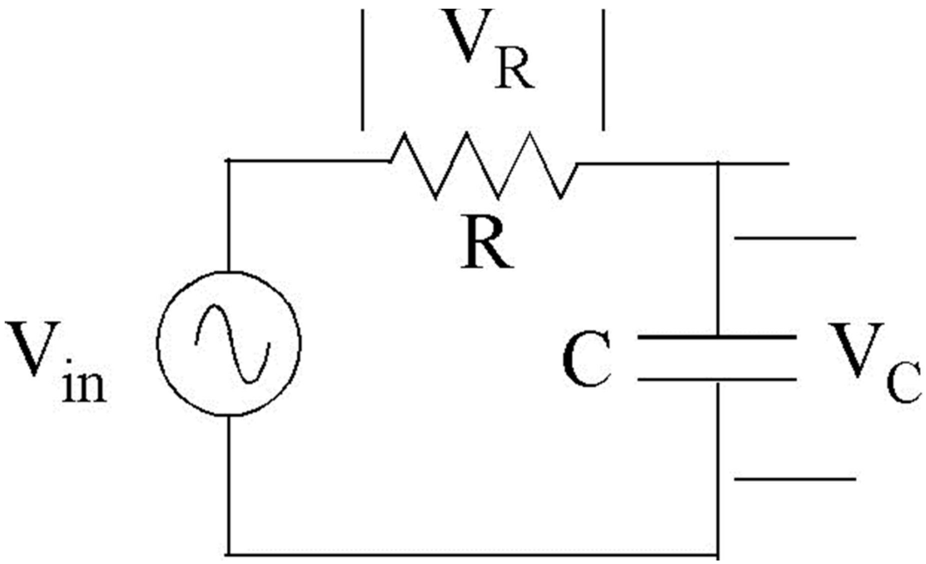


Signal generator concerns apply equally to the control signals for every state variable

SRC' s Conclusion: Charge is dead!

Is this Conclusion Correct?

Let's find out!

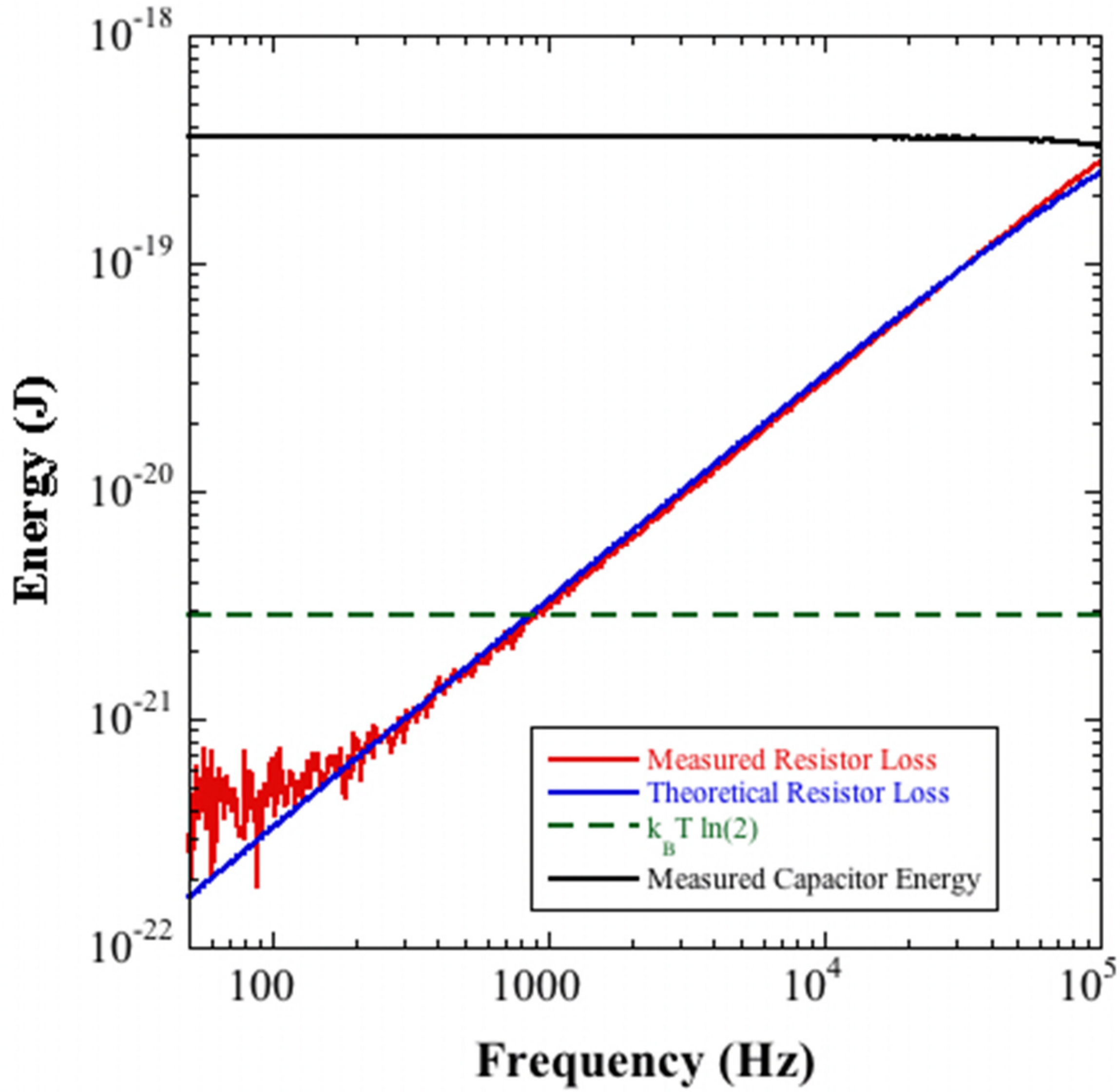


$$E_C(\omega) = CV_{in}^2\left[\frac{1}{1+\left(\omega/\omega_0\right)^2}\right]$$

$$E_R(\omega) = \frac{1}{2}\frac{V_{in}^2}{R}\frac{2\pi}{\omega}\left[\frac{\left(\omega/\omega_0\right)^2}{1+\left(\omega/\omega_0\right)^2}\right]$$

The challenge: $k_B T \ln 2$ at RT = 3 zJ!

Sanity Check



The Landauer Principle

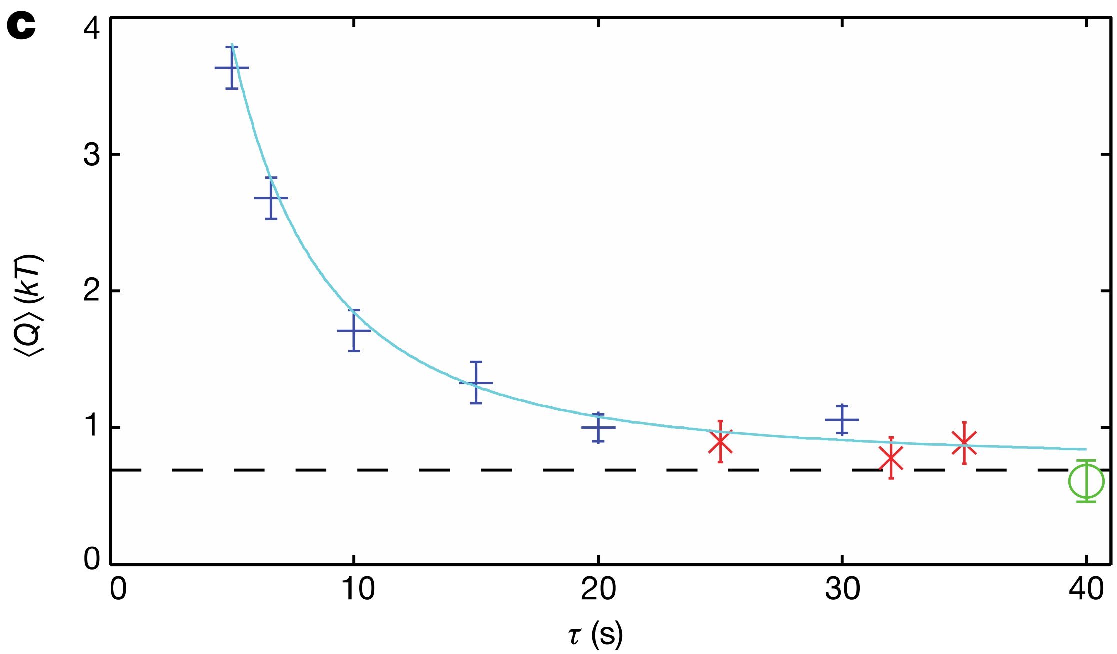
LETTER

doi:10.1038/nature10872

Experimental verification of Landauer's principle linking information and thermodynamics

Antoine Bérut[1], Artak Arakelyan[1], Artyom Petrosyan[1], Sergio Ciliberto[1], Raoul Dillenschneider[2] & Eric Lutz[3]†

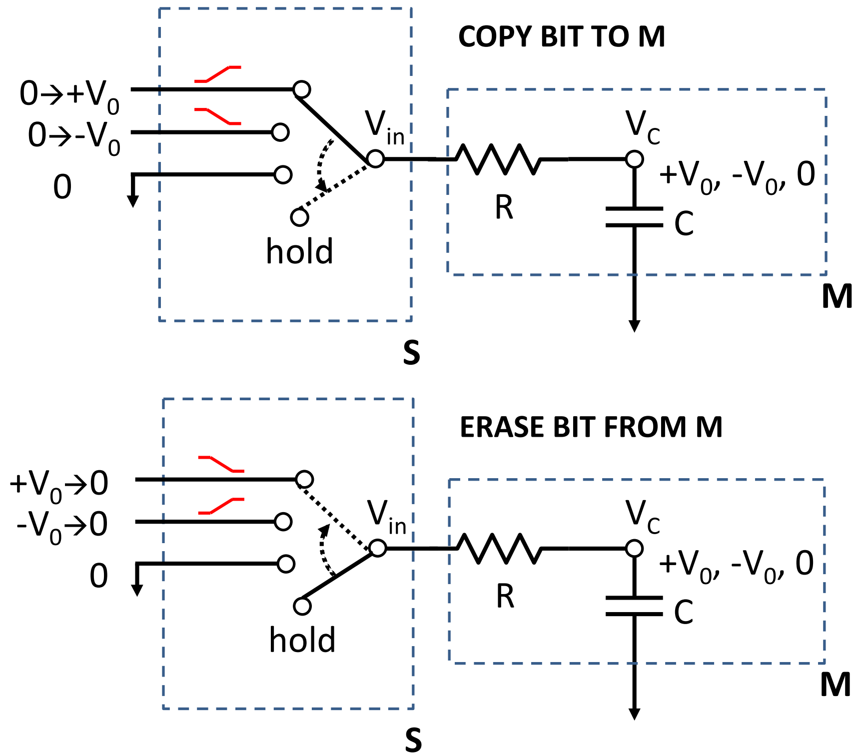
Nature **483**, p189, 2012

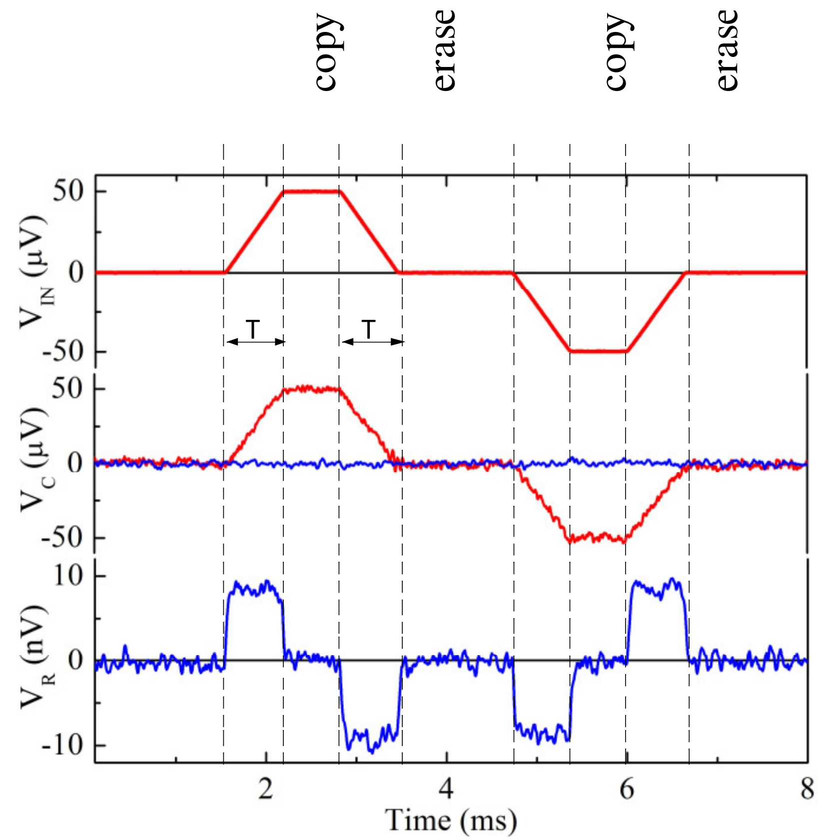


The Landauer Principle

The SRC group rejects the Landauer Principle, but can it be tested?

Room temperature operations on a 30 $k_B T$ bit of information



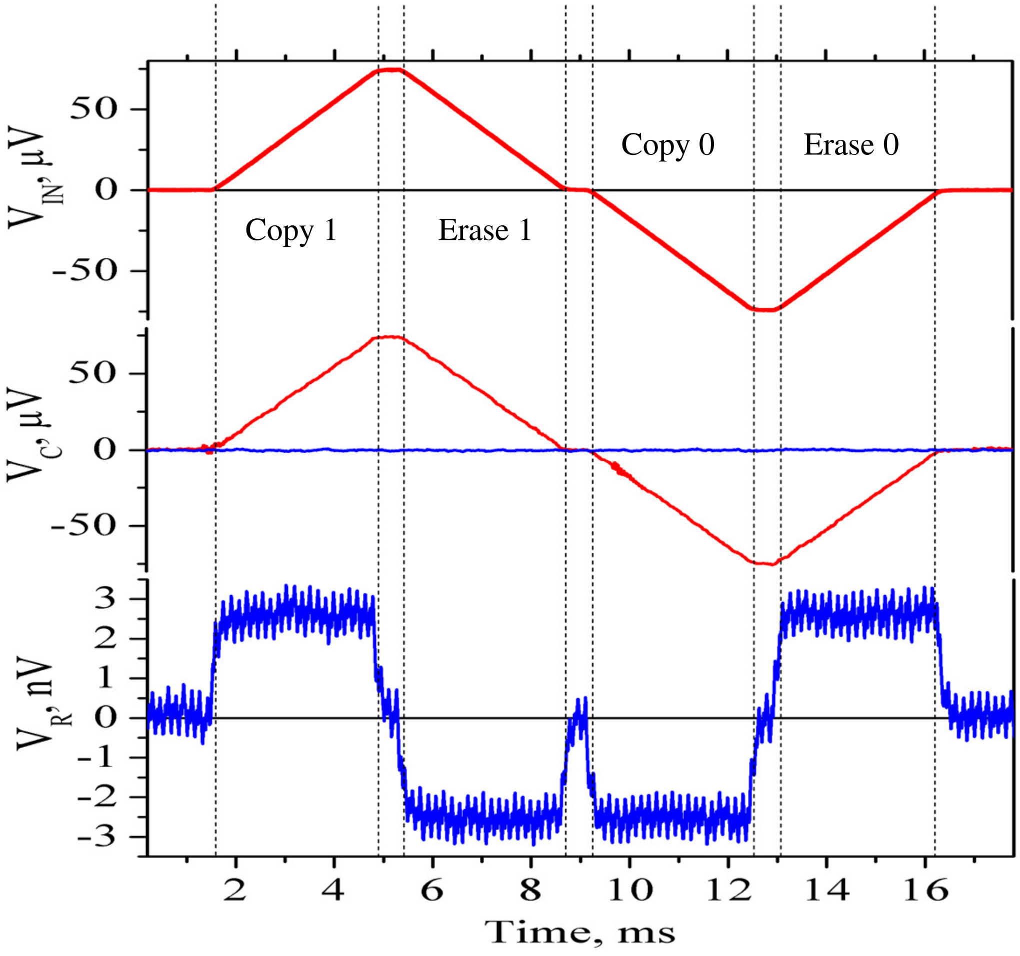


Dissipation was measured as low as 0.01 $k_B T$, confirming the Landauer Principle.

JJAP, **51**, pp. 06FE10, 2012.

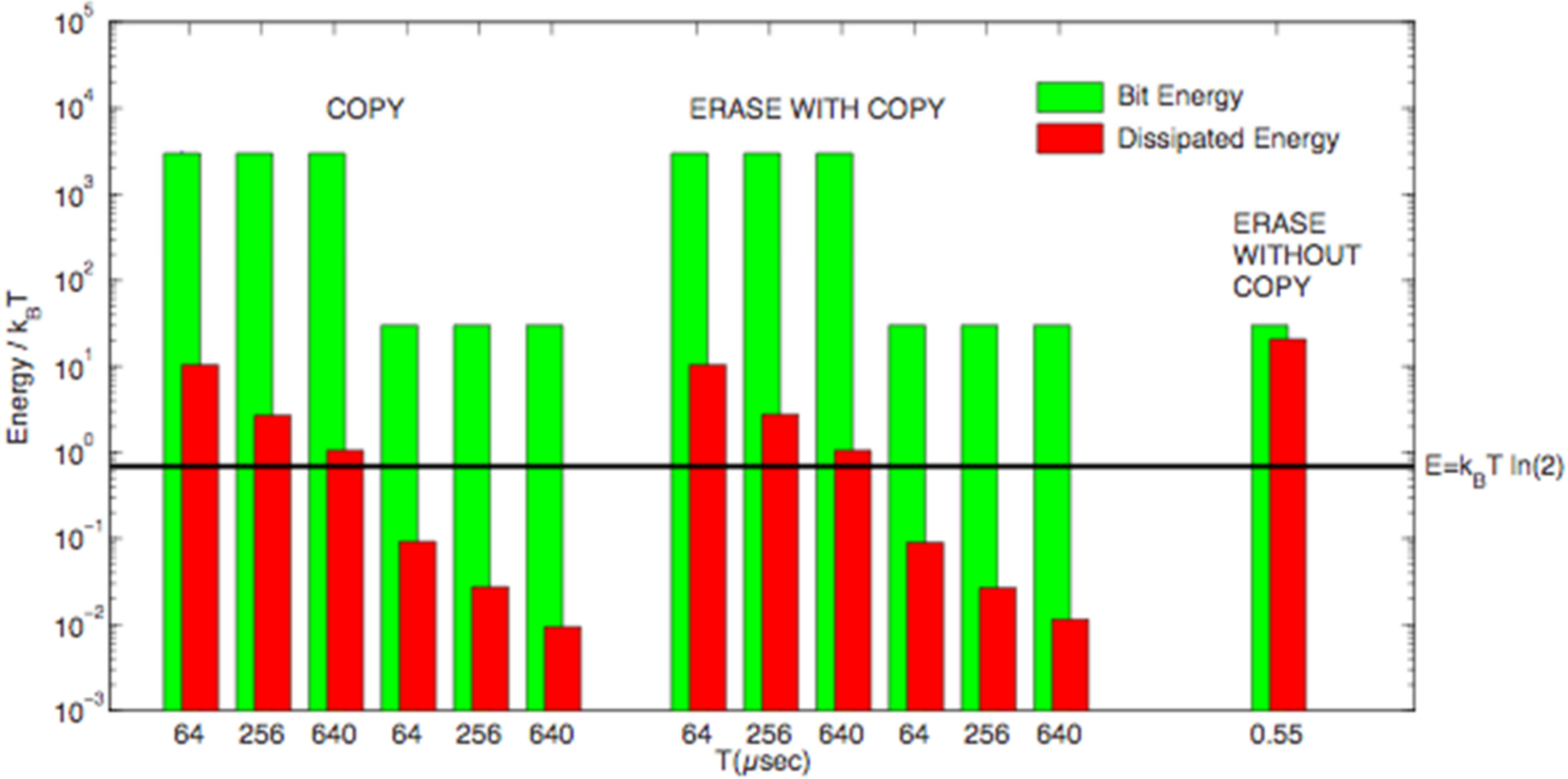
The Landauer Principle

Room temperature operations on a 73 k_BT bit of information



Measured dissipation was 0.005 k_BT (15 yJ).

Experimental Summary



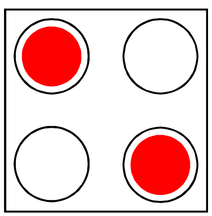
Is There Any Hope?

Yes, but transistors may not be the best way!

It is time to do something different.

Represent binary information by charge configuration!

Quantum-dot Cellular Automata



A cell with 4 dots

2 extra electrons

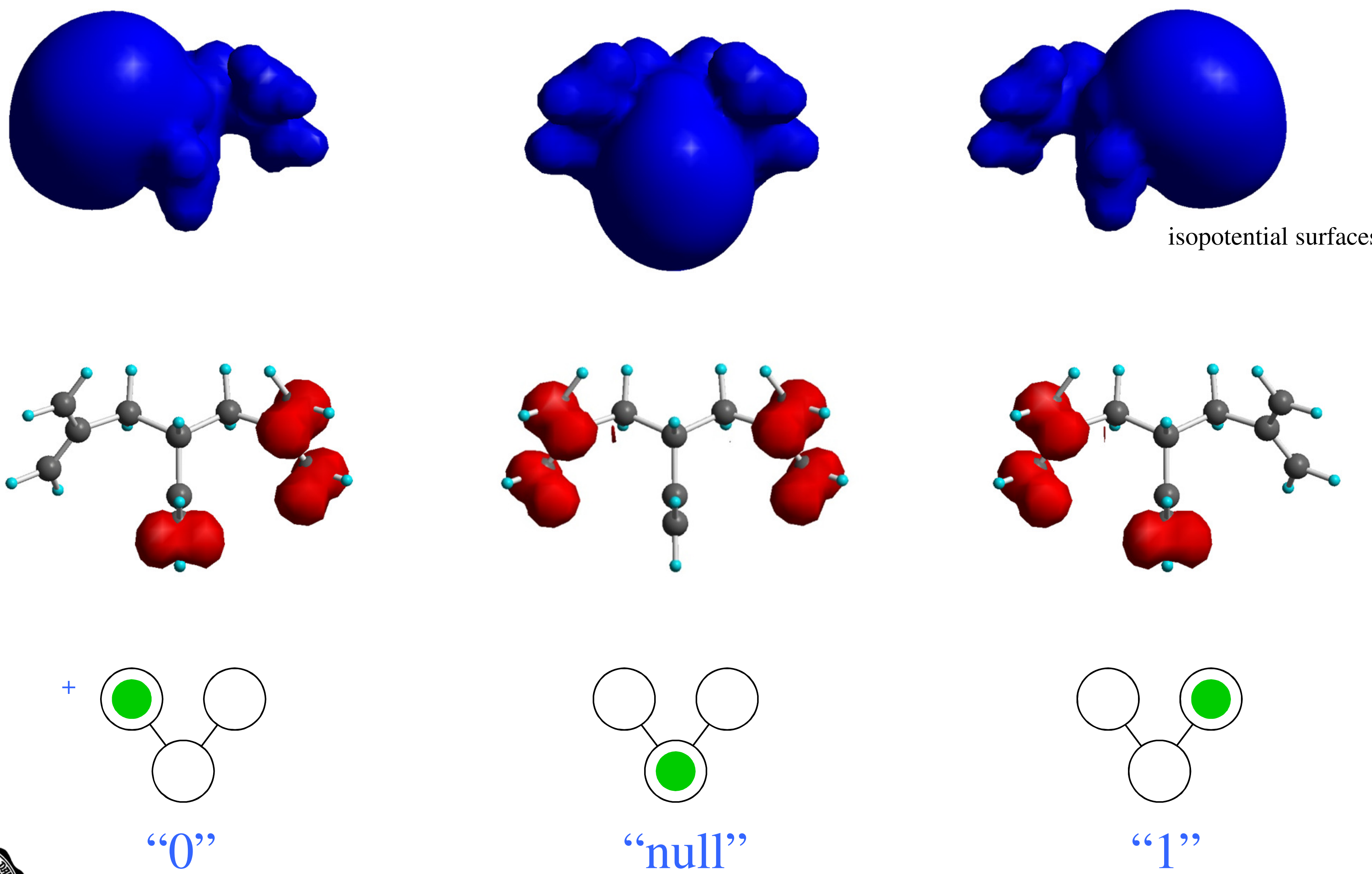
Tunneling between dots

Polarization P = -1

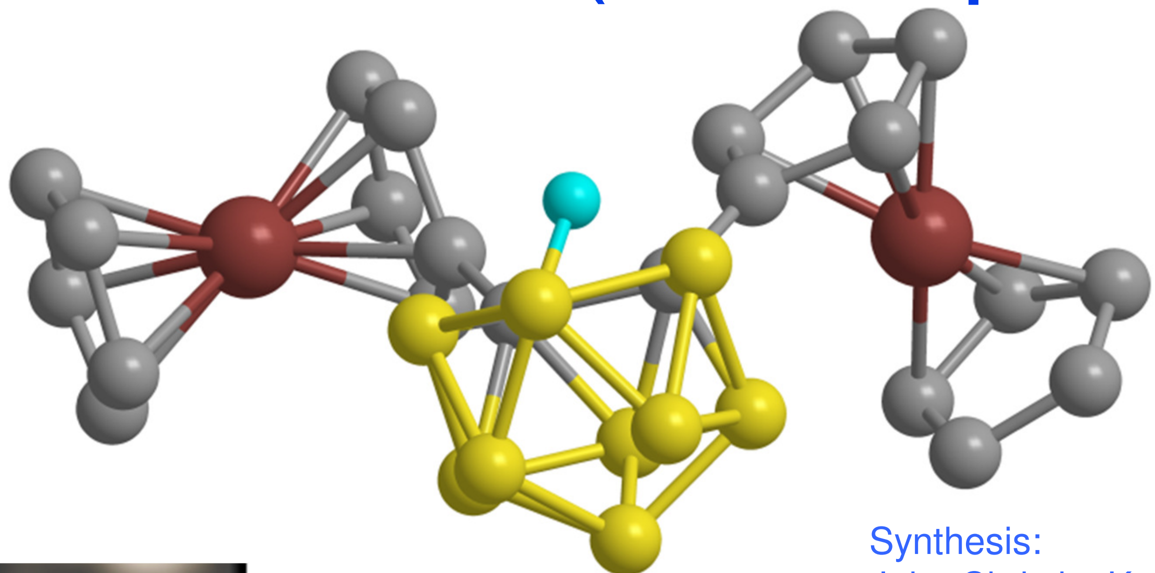
Bit value “0”

Developed in the early 90s by
Craig Lent
Wolfgang Porod
Gary Bernstein

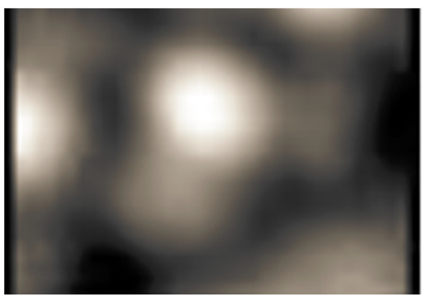
Charge configuration represents bit



Neutral mixed-valence zwitterion (self-doped)



Synthesis:
John Christie, Kenneth Henderson



Imaging:
Alex Kandel, Natalie Wasio, Rebecca Quardokas

Awitterionic mixed-valent nido-1,2-diferrocenyl-undecacarborane.

Conclusions

- Energy recycling can enable power reduction
- Charge is a viable state variable
- Alternative state variables face the same limits as charge
- There is no fundamental lower limit on the energy needed for computation – only practical ones
- The key is to trade speed for power, a trade-off that is already being made.
- Low energy dissipation key to implantable applications.