It's time for Adiabatic Computing

Gregory Snider
Department of Electrical Engineering
University of Notre Dame

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Question: How fast do you run a circuit?

Answer: As fast as you can!!

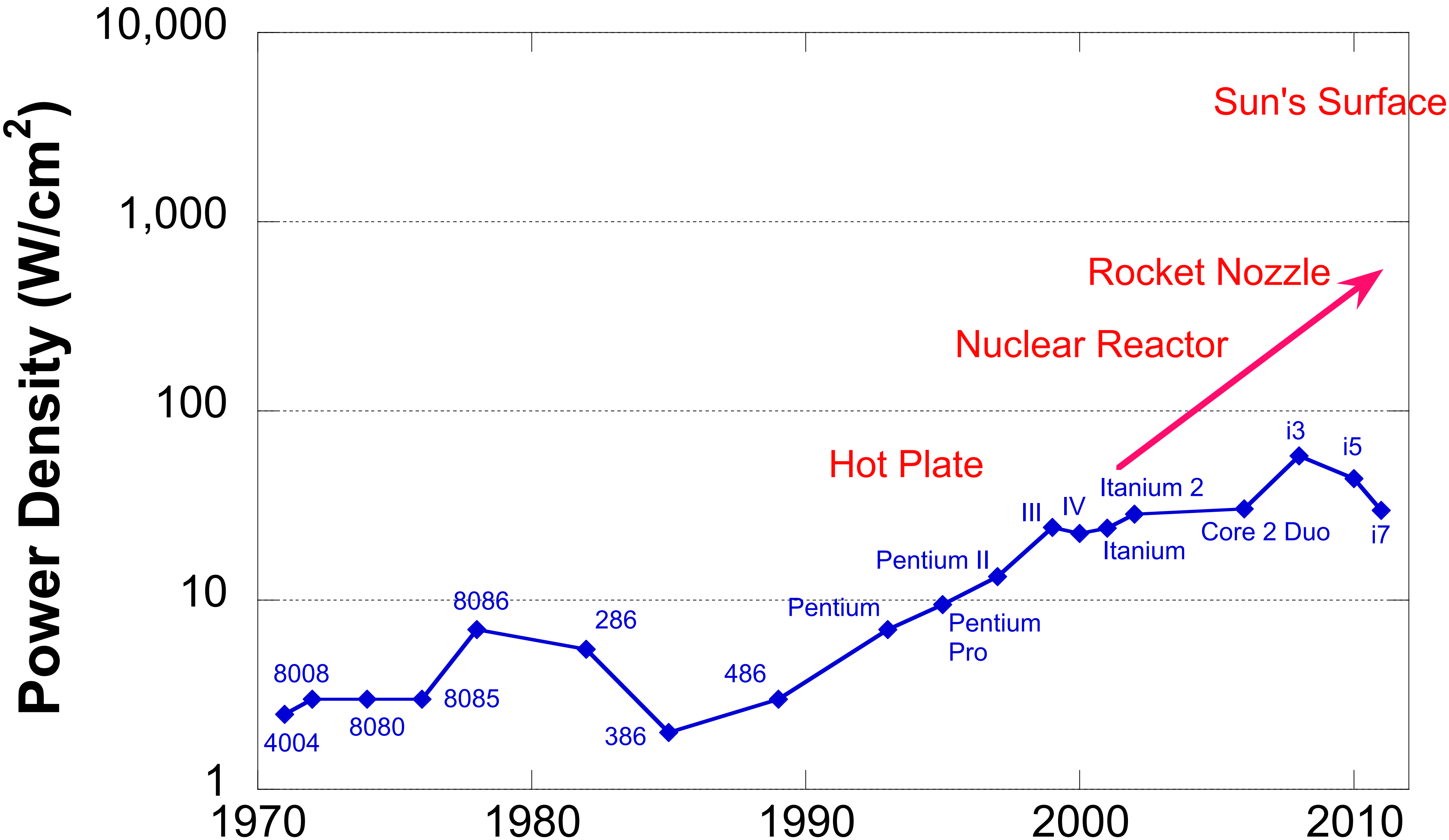
Question: How fast is that?

Answer: It depends.

Constraints

- Inherent speed, RC time constant
- Thermal budget
- Energy budget

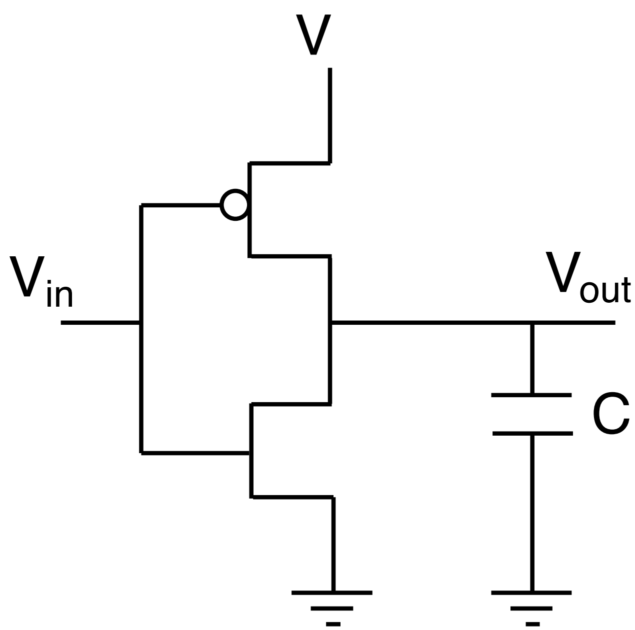
Power Density



What is the underlying cause of this power dissipation?

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

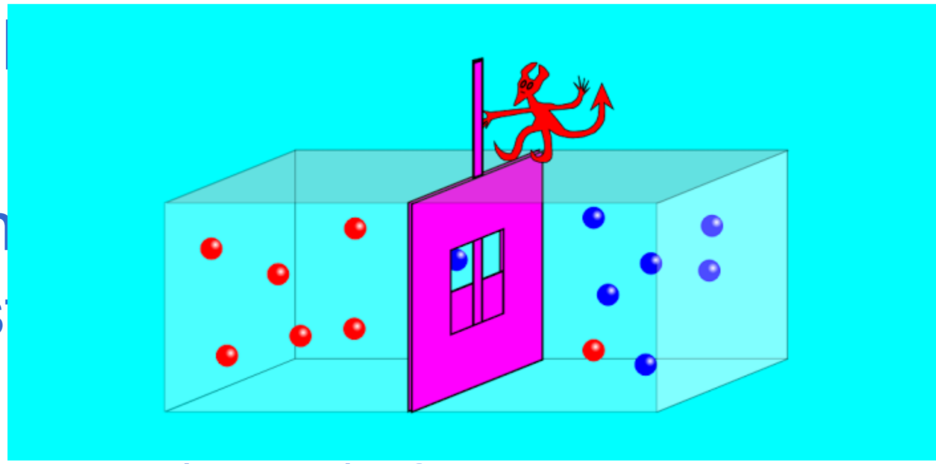
How low can you go?

If E_{Bit} =100 $k_B T$ (400 zJ), f=100 GHz, N=10^{11} cm^{-2}

$P = 8\ kW/cm^2$

Minimum energy for computation

- Maxwell's demon (1875) – by first measuring states, could perform reversible processes to lower entropy
- Szi *easurement* causes per bit.
- Lan *ction* of information must per bit (**Landauer's**



Maxwell's Demon

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

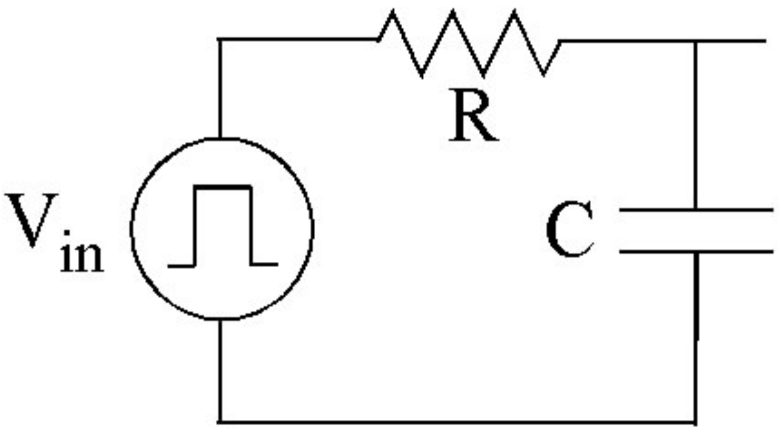
logical reversibility ⇔ physical reversibility

Still somewhat controversial.

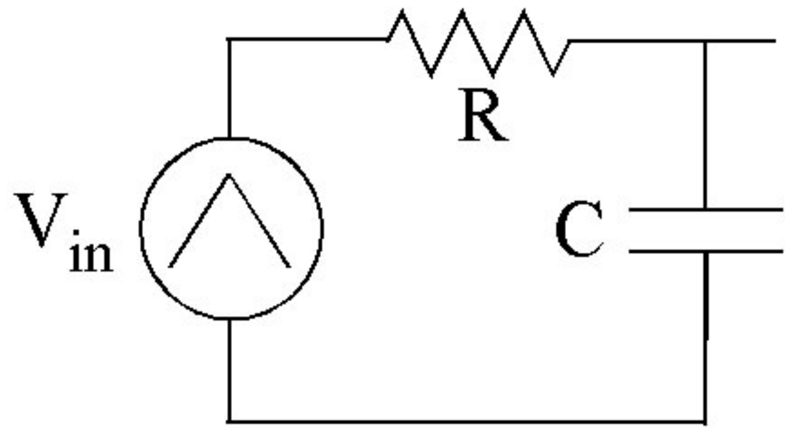
"Adiabatic" Computing

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 Landauer Principle

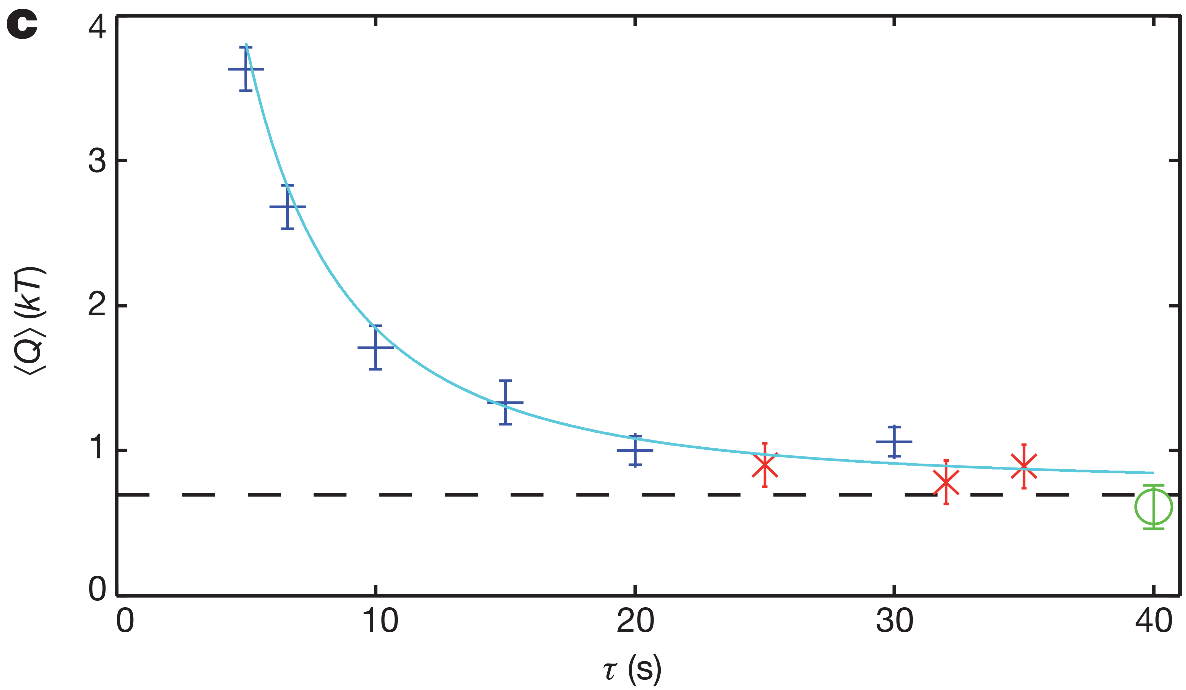
LETTER

doi:10.1038/nature10872

Experimental verification of Landauer's principle linking information and thermodynamics

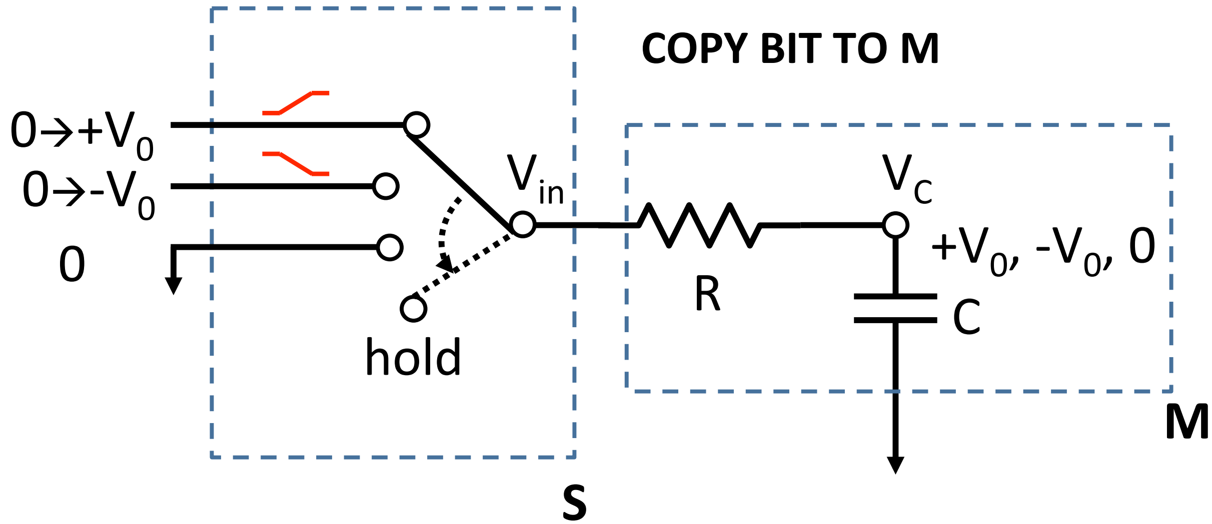
Antoine Bérut[1], Artak Arakelyan[1], Artyom Petrosyan[1], Sergio Ciliberto[1], Raoul Dillenschneider[2] & Eric Lutz[3]†

Nature **483**, p189, 2012

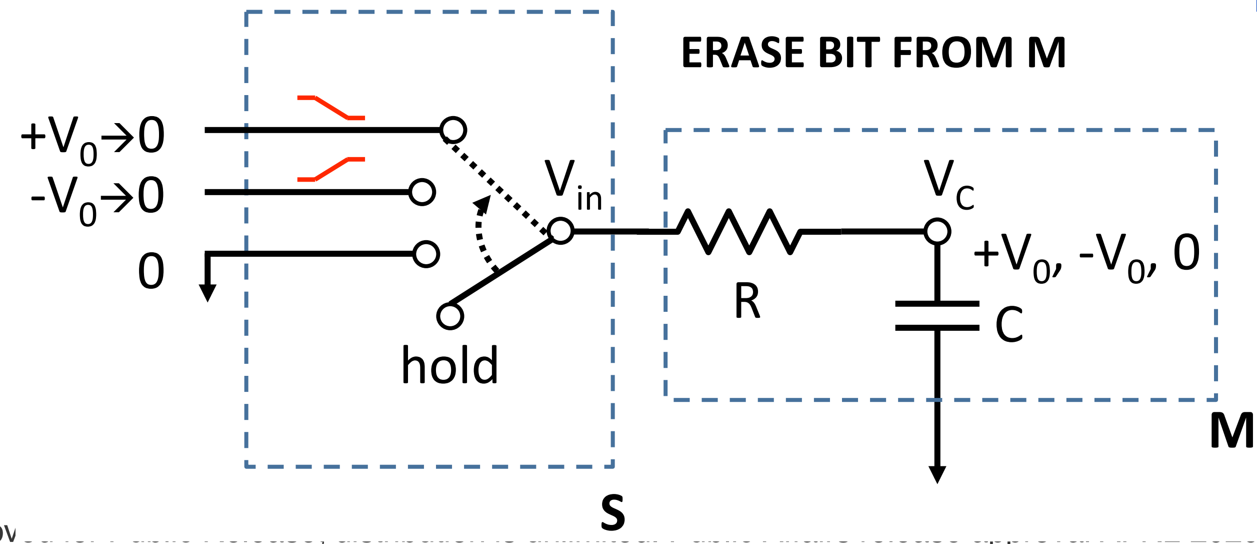


The Landauer Principle

Can the real implications of the Landauer Principle be tested?

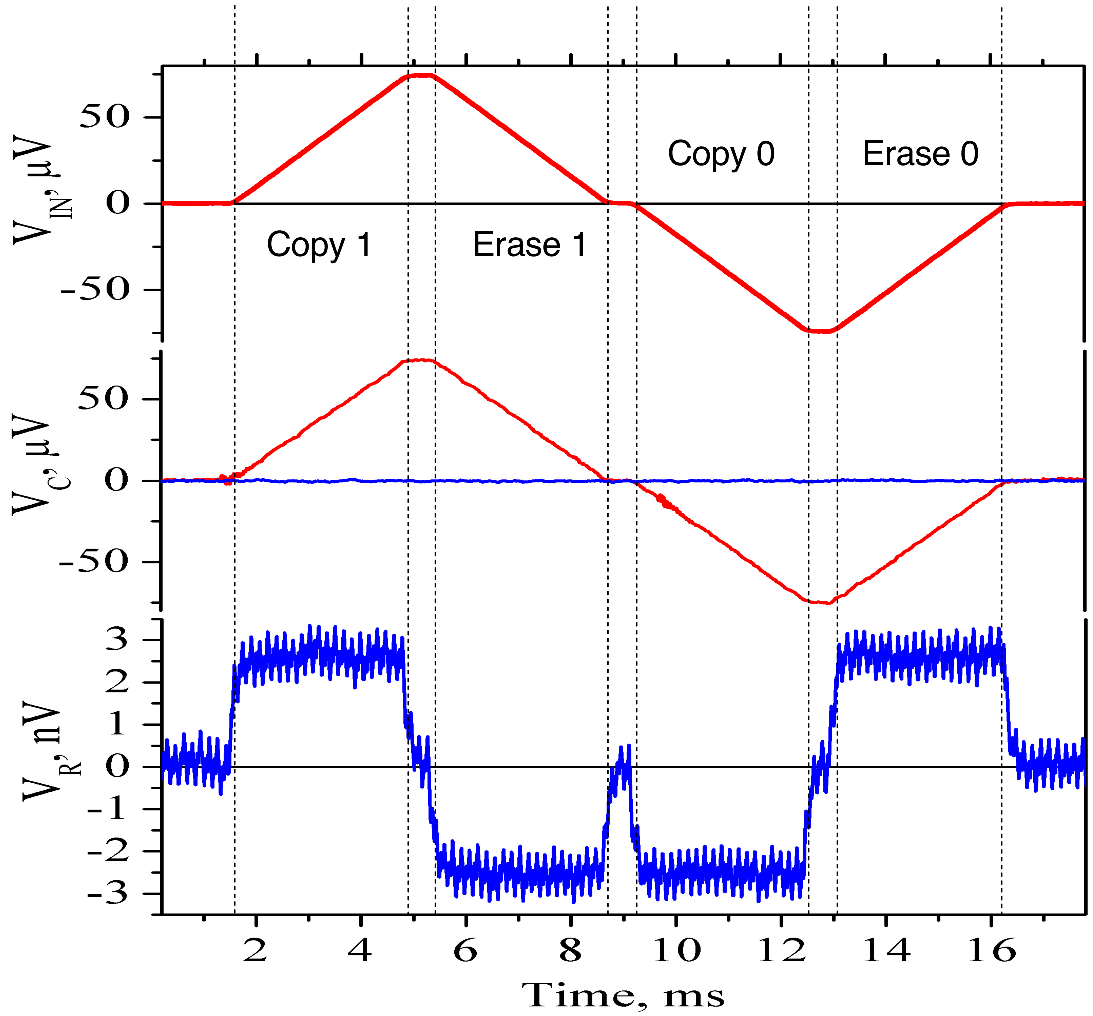


JJAP, **51**,
pp. 06FE10, 2012.



The Landauer Principle

Room temperature operations on a 73 $k_B T$ bit of information

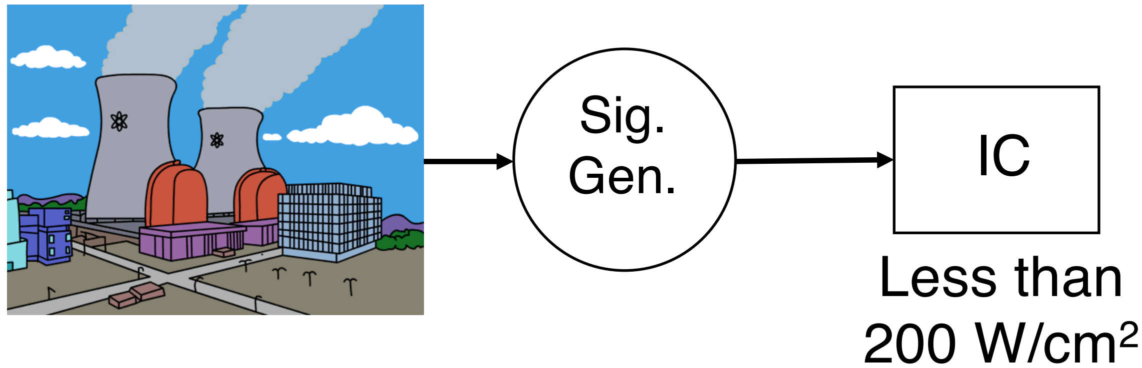


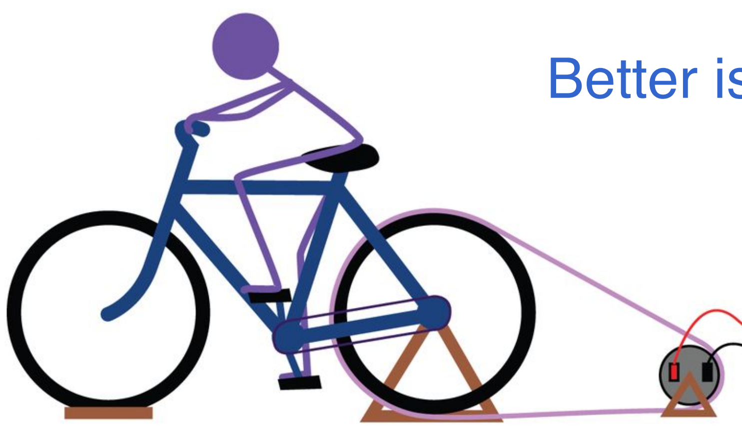
Measured dissipation was 0.005 $k_B T$ (15 yJ).

Energy Recovery for Computation

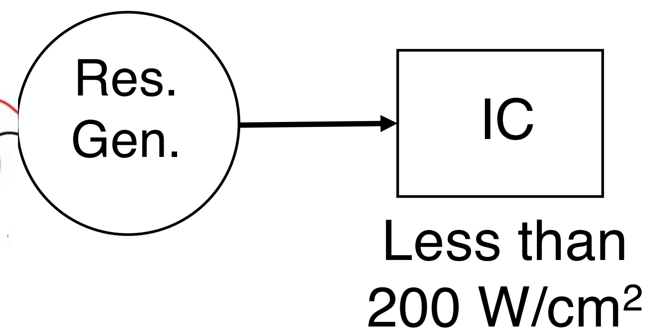
Reversible logic allows you to recover the bit energies, but then what do you do?

Worst case: You burn the bit energies in the clock generator. These can be cooled more easily than a chip.





Better is a resonant clock generator that can recover and reuse energy



MEMS resonators can do this with higher Q than conventional circuits!

When Does Energy Recovery Make Sense?

Goal in any computation: Minimize the use of space, time, and energy.

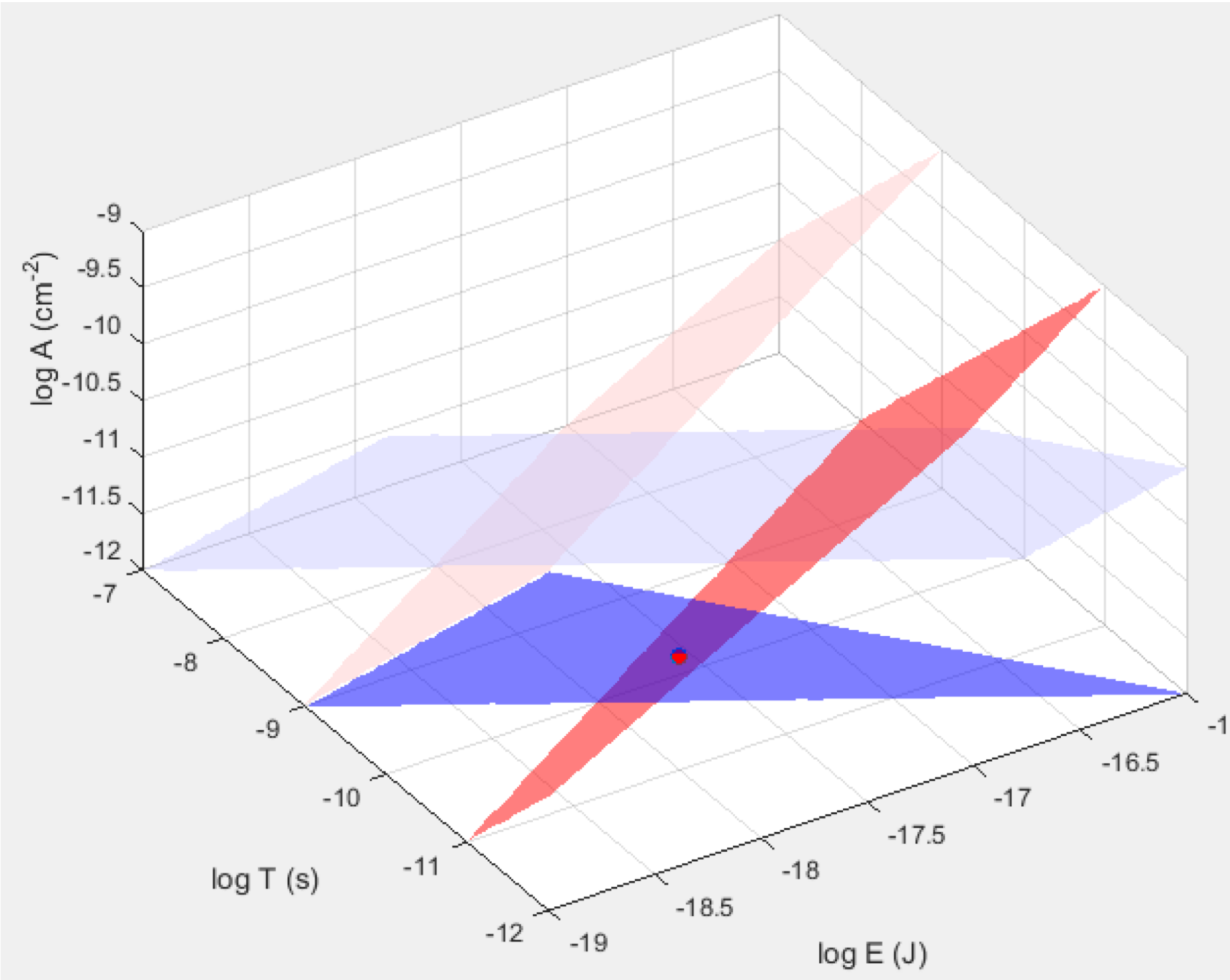


Figure of Merit: EDA

The logic technology determines an intrinsic performance:

E_o

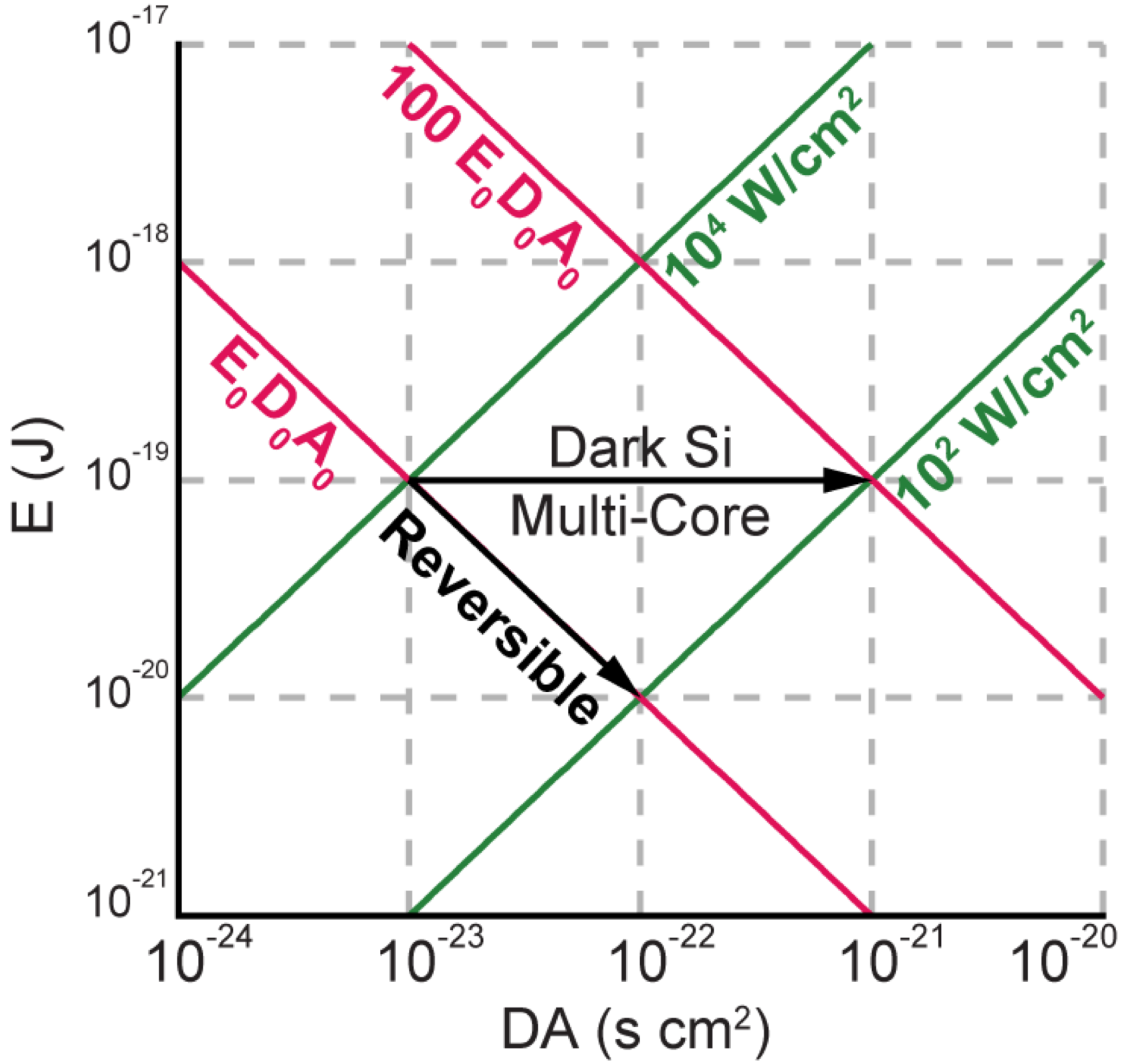
D_o

A_o

Can you run at full capacity?

What if Power Density is Constrained?

Example $E_o = 1$ aJ, $D_o = 10$ ps, $A_o = 10^{-11}$ cm^2



Performance must be sacrificed!

Multi-Core: $EDA = E_o\ CD_o\ A_o$

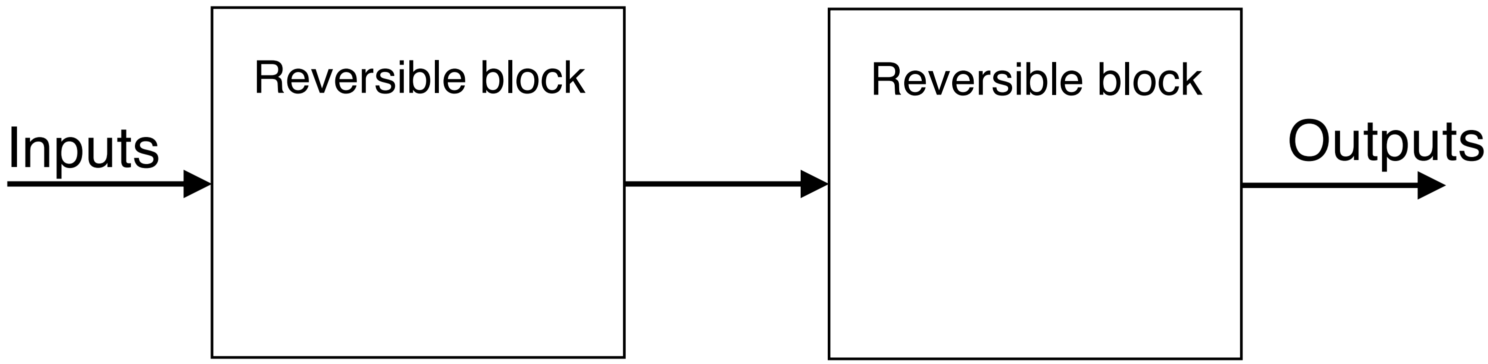
Dark Si: $EDA = E_o\ D_o\ CA_o$

Reversible: $EDA = E_o/C\ CD_o\ A_o$
$= E_o\ D_o\ A_o$

Reversible computing makes the best use of limited resources!

Future of Computation?

- No Matter what your state variable, you have to worry about E_{bit}
- Does that mean you have to go fully reversible?
- Are new devices necessary?



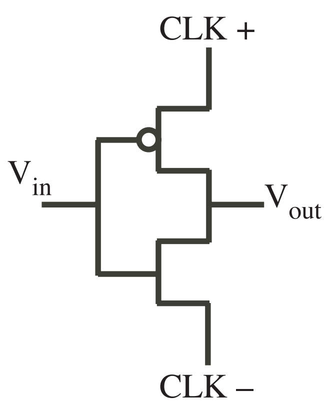
What are the trade-offs?

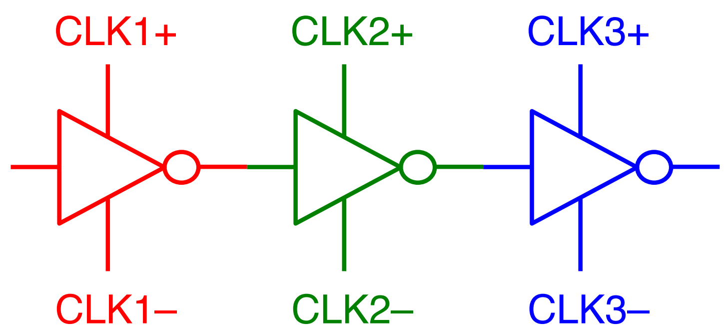
- Speed
- Complexity

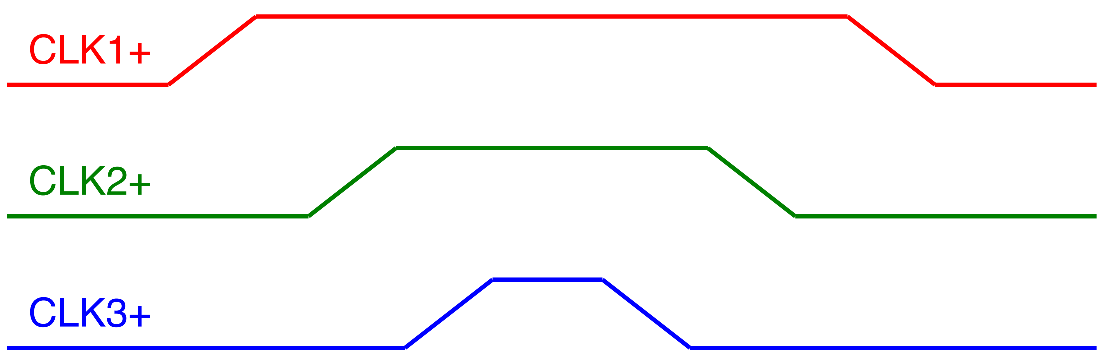
Adiabatic CMOS with Bennett Clocking

- Reversible computation always has some associated overhead

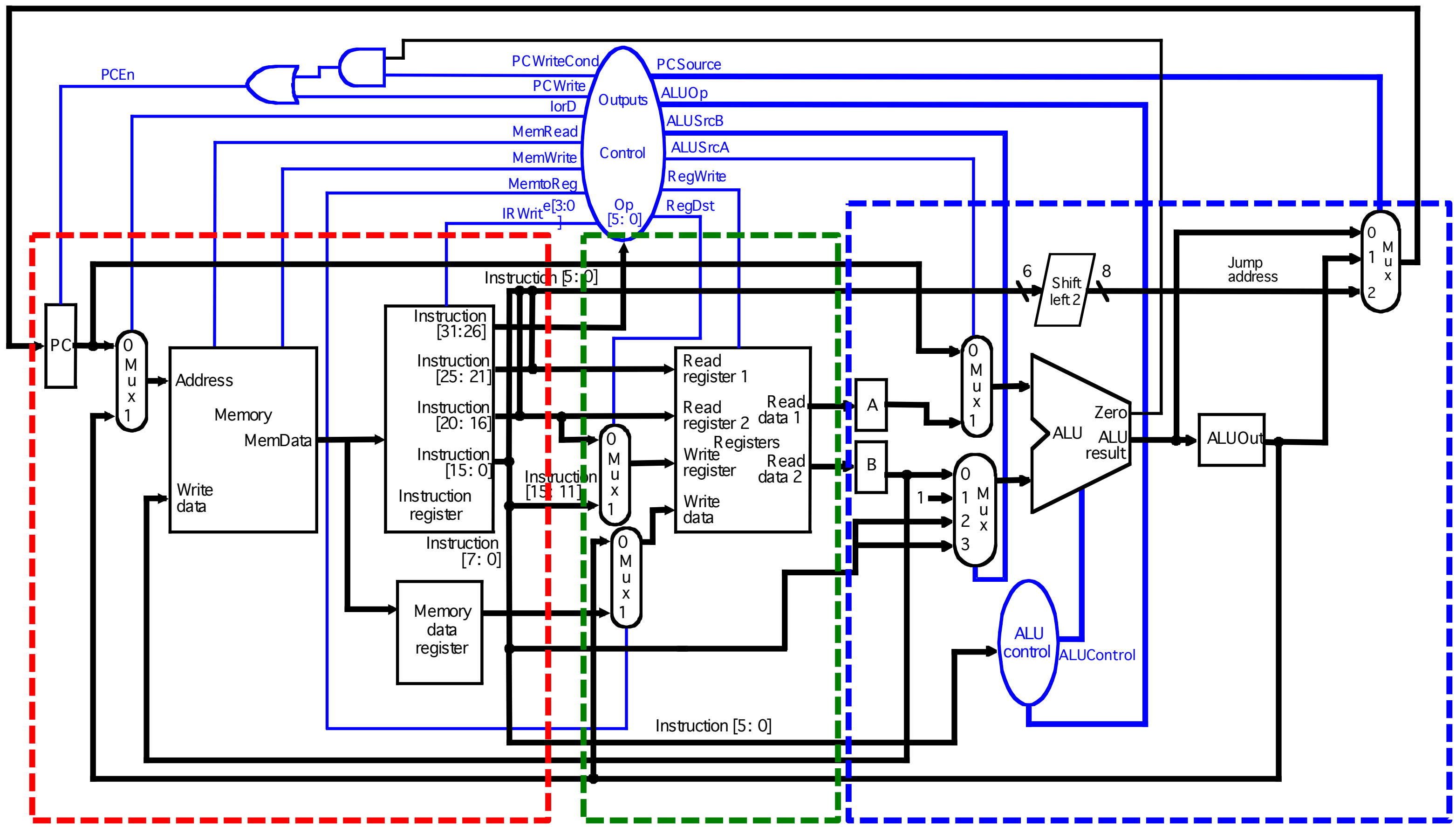
Bennett Clocking (retractile cascade) combined with split-level logic







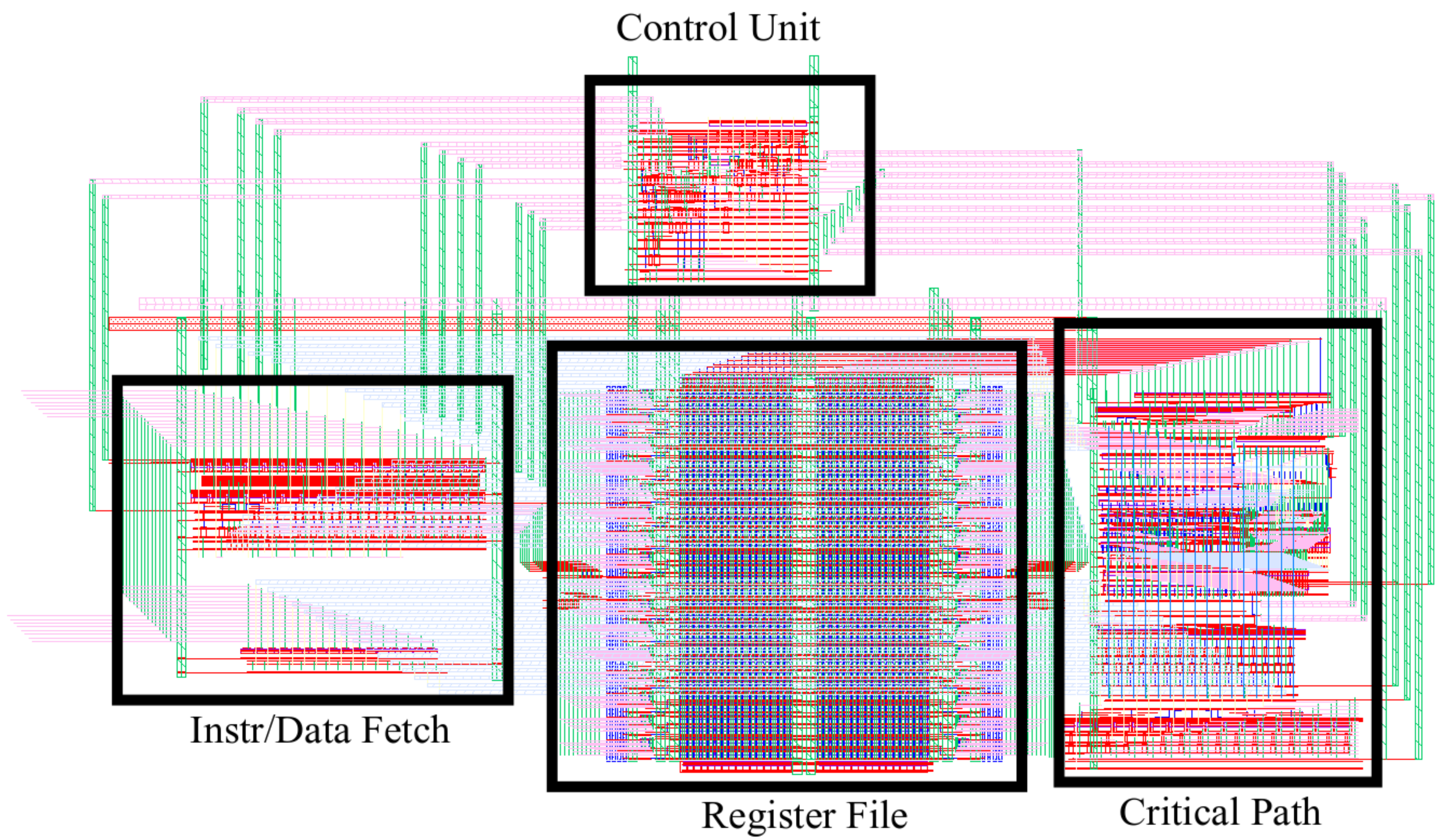
MIPS Microprocessor



Three Bennett zones of 12 phases, no pipelining

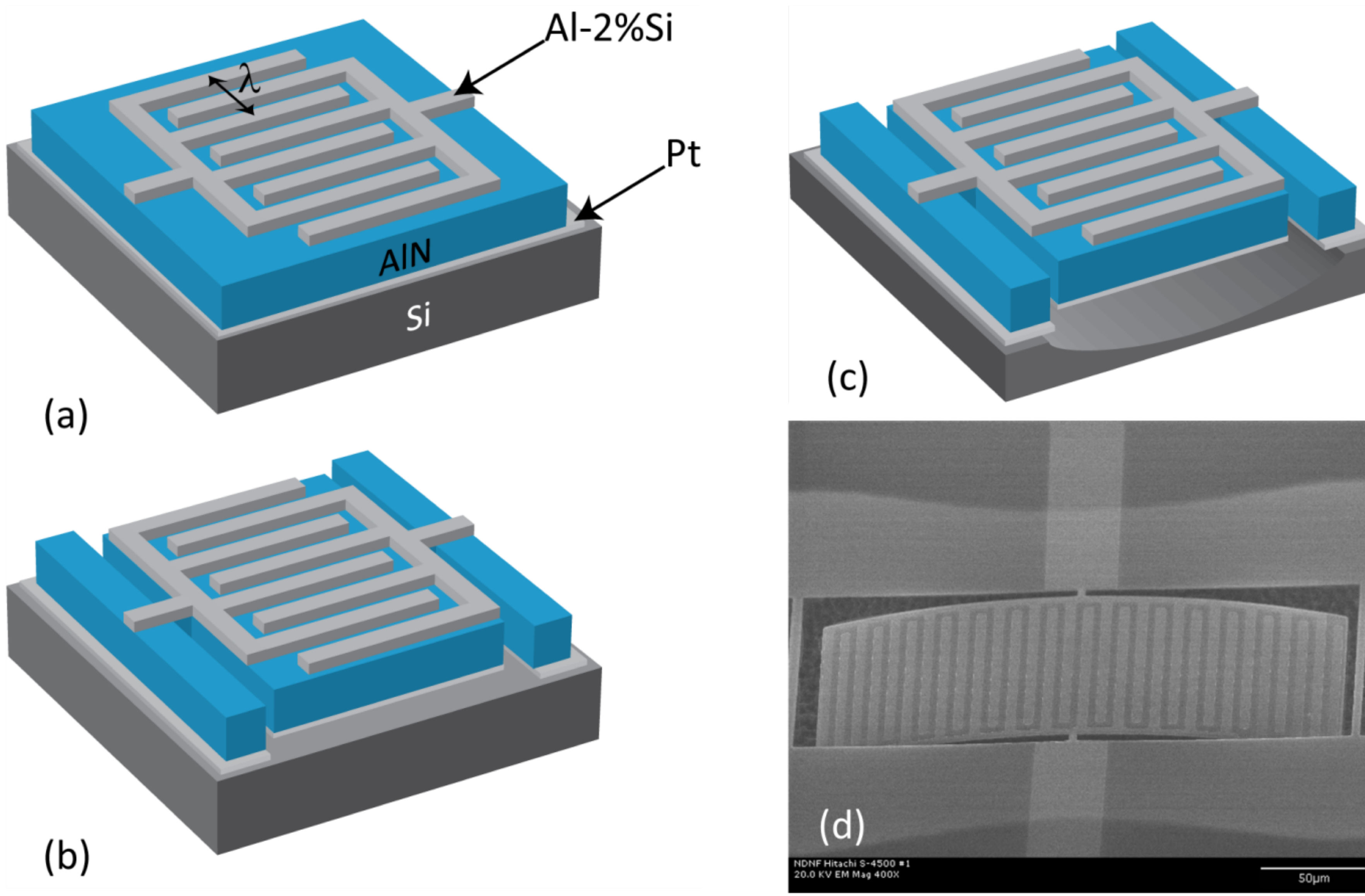
From Weste and Harris, Addison-Wesley

16 bit MIPS Microprocessor



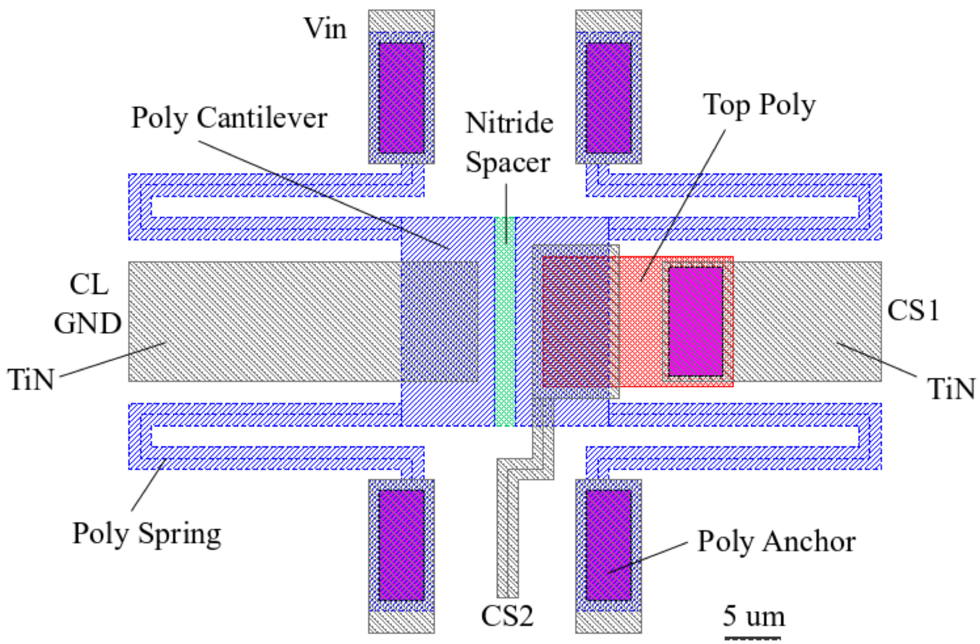
Supported by the US Air Force Research Laboratory

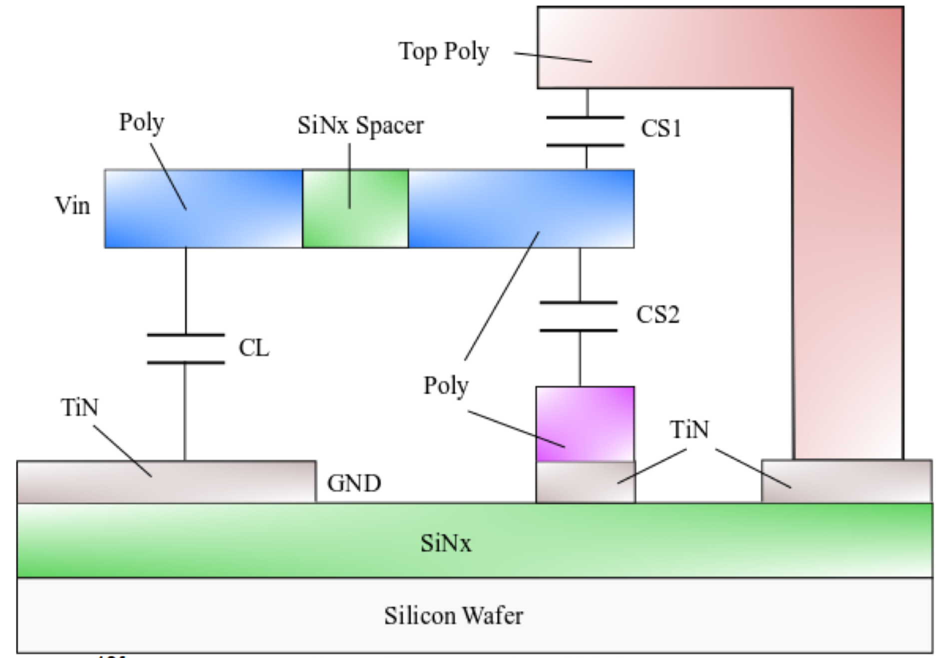
Resonant Power Clocks

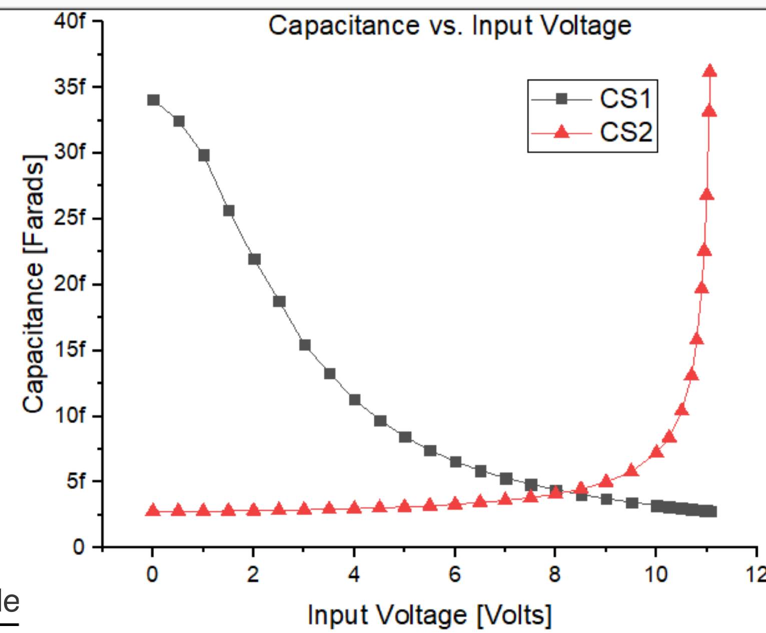


Are New Devices Necessary?

Adiabatic Capacitive Logic

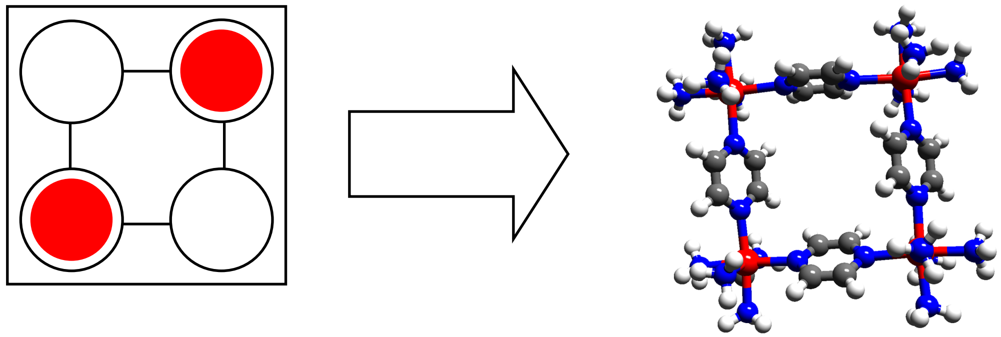




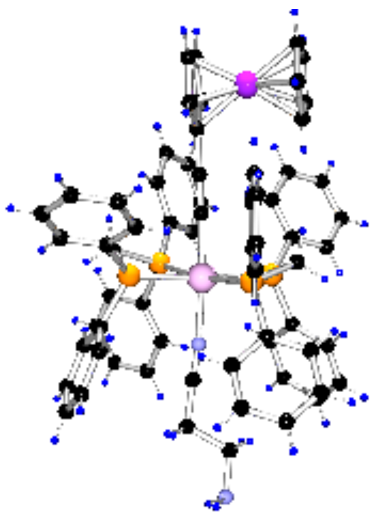


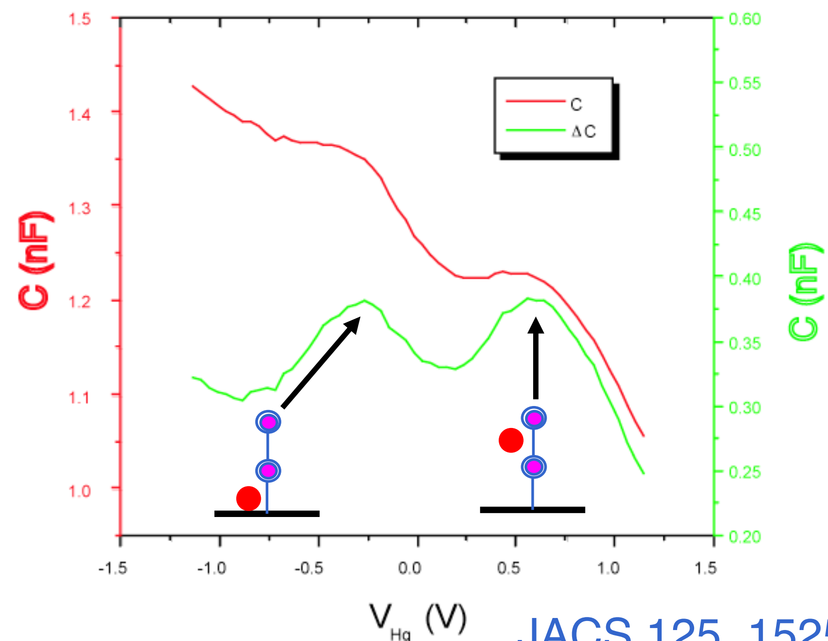
Use MEMs Relay-like devices as variable capacitors

Quantum-dot Cellular Automata



Molecular Dots





JACS 125, 15250, 2003

QCA maps well onto adiabatic reversible architectures

Conclusions

- Future progress in computation requires energy recycling
- 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
- A MIPS-based microprocessor was designed and will be fabricated
- Beyond-CMOS devices can truly reap the benefits of adiabatic processing

Acknowdgements

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