Future Paths for Components & Systems

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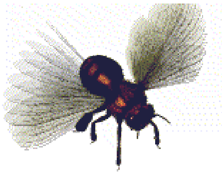
Summary

- Introduction: invent the future!
- Binary switch as key element of electronic computation & nano-CMOS vampire switch
- Future paths for components & systems:
  - Other ultra-low power electronic switches
  - Other materials: carbon electronics?
  - Energy efficient computing: from min energy switching to reversible computing & QCA
- Conclusion

Introduction (1)

- “The best way to predict the future is to invent it.” Alan Kay
- Possible barrier: “We see things not as they are but as we are.”
- Today nanolectronics = silicon technology and CMOS, predictions for the future of electronic components and systems are heavily influenced by this reality.

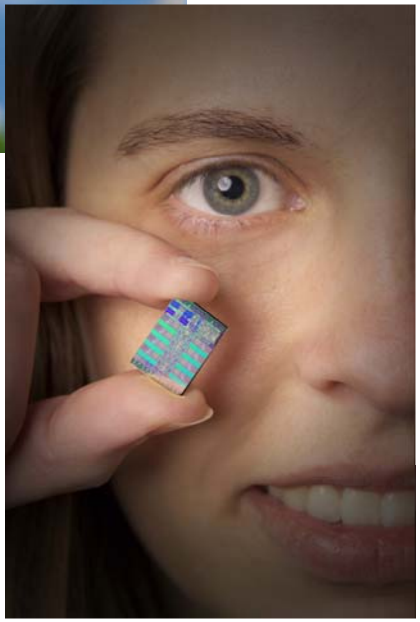


Introduction (2)

- Natural analog computation
  - Flies acrobatically
  - Recognizes patterns
  - Navigates
  - Communicates

Consumes: 10^{-15}J/op

- High-speed digital computation



Consumes: 10^{-7}–10^{-10}J/op

Binary switch as key element of electronic computation & nano-CMOS vampire switch

Paradigm of information encoding

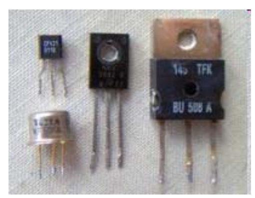
Konrad Zuse (1941) machine

– Use binary numbers to encode information
– Represent binary digits as on/off state of a current switch

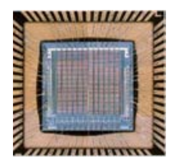
Problems with shrinking the switch:
- Difficult to obtain good on/off ratio
- Current becomes small, resistance high

Electromagnetic relay

Vacuum tube



Solid state transistors

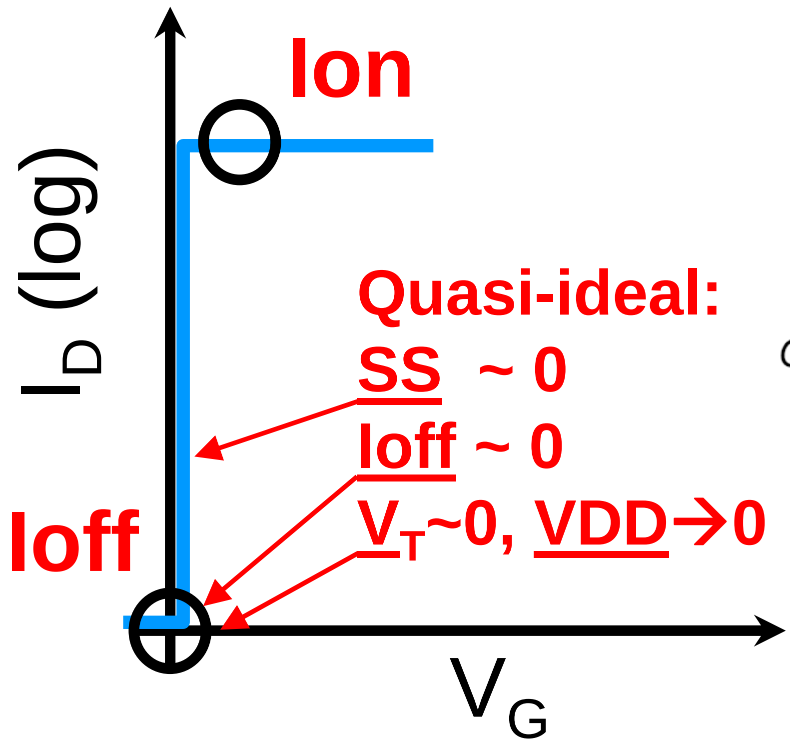


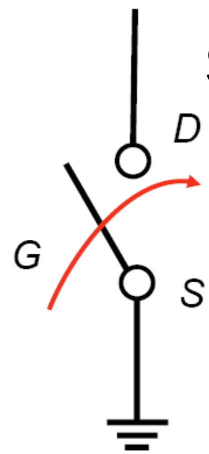
Integrated circuit

Molecule? Spin? Other?

New approaches to representing information required.

Quasi-Ideal Nanoelectronic Switch

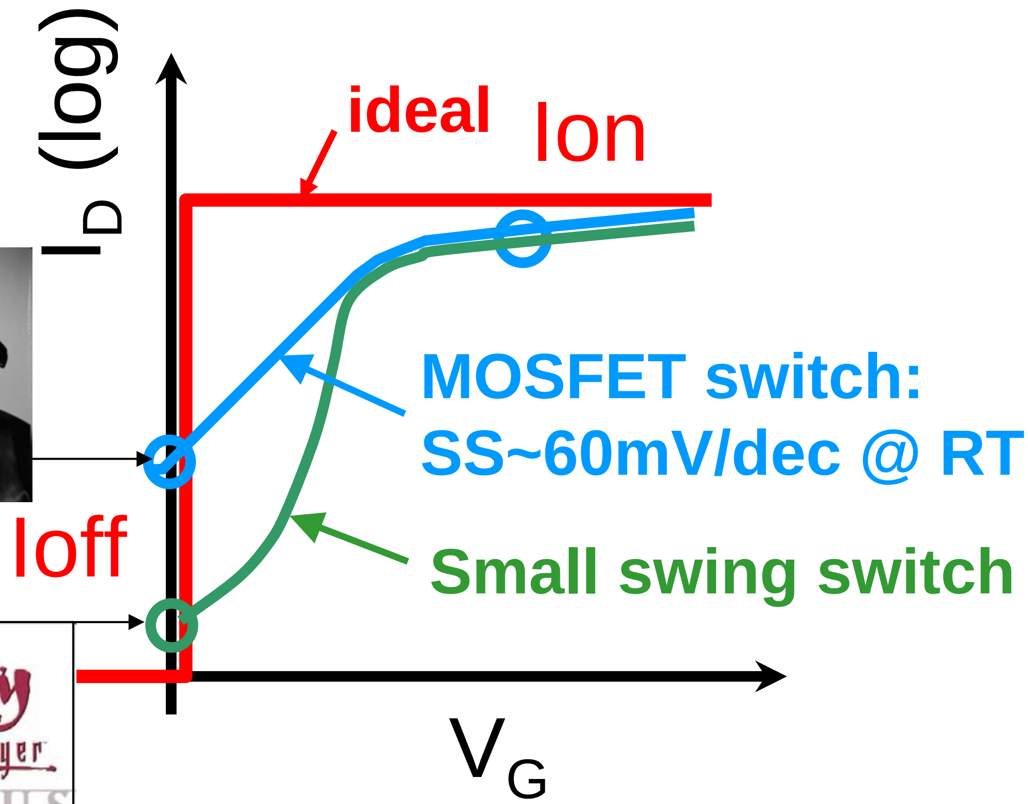


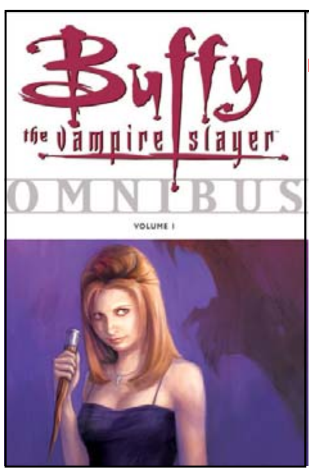


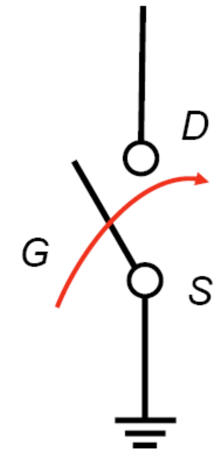
- Quasi-ideal binary switch, **what matters**:
  - 2 stable states (off, on)
  - Ion: as high as possible
  - Ioff: as low as possible
  - Ion/Ioff > 10^5
  - abrupt swing (mV/decade)
  - very fast (<ns)

A quasi-ideal nanoelectronic switch has **ZERO standby power** and offers the wanted on current! It should stay very fast!

What about nano-CMOS switch?





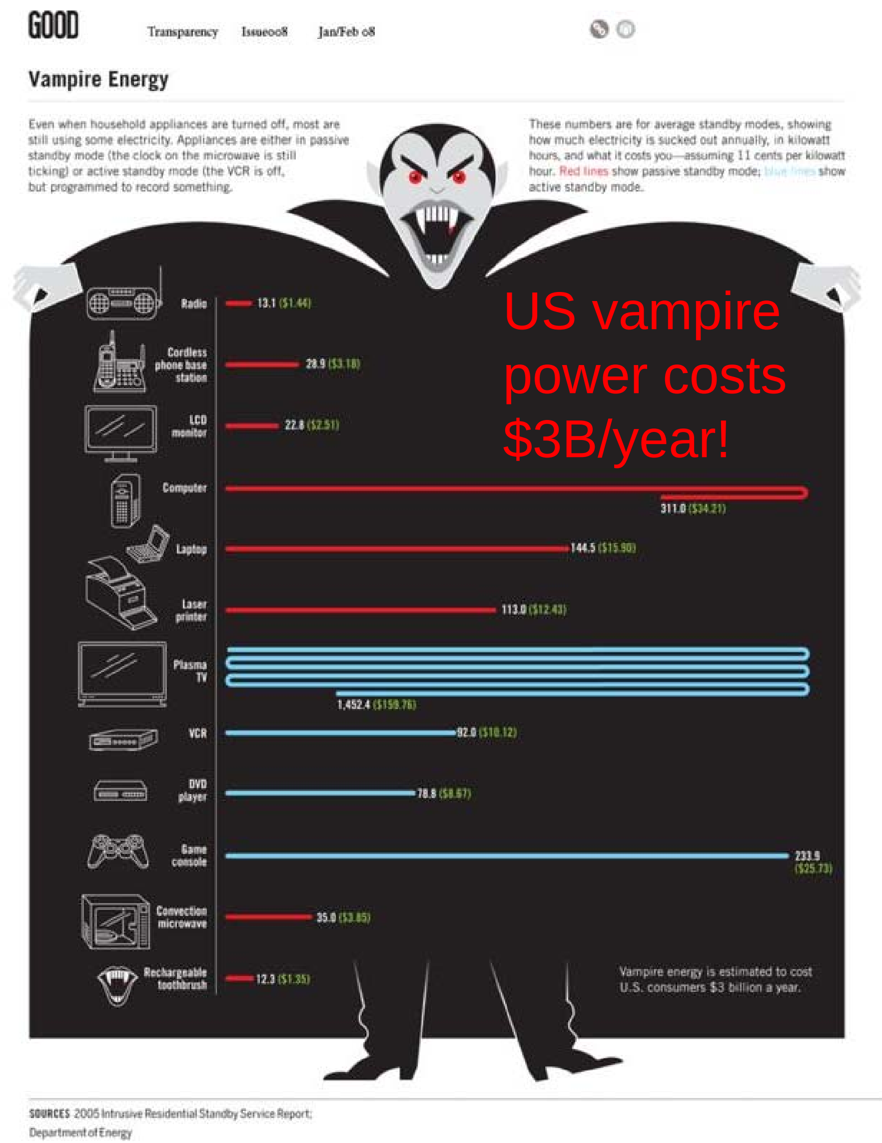


- **MOSFET is a vampire switch at nanoscale**
- New Small Swing Switch = New physics
- SSS: very low standby power (green switch)

General: critical standby electricity

- Standby electricity is the energy consumed by appliances when they are not performing their main functions or when they are switched off. Energy wasted: "standby loss" or "**vampire power**"

- Modern electrical and electronic appliances, even those having on/off switches, consume power for standby functions: standby loss in France is ~7% of the total residential electricity consumption



US vampire power costs $3B/year!

Future paths for components & systems

Steep swing switches = LSBP

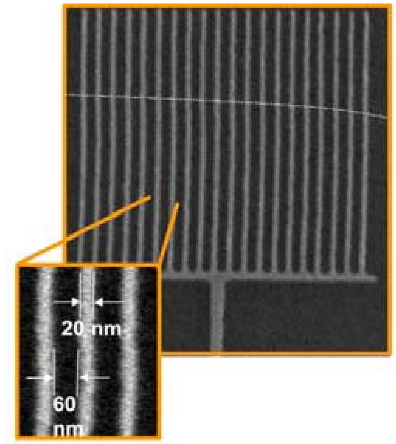
- Other device physics than MOSFET, new component-level architecture for low standby power:
  - **Tunneling devices**
  - **Impact ionization devices**
  - **Electro-mechanical devices**
  - **Ferroelectric devices**
  - **Other?**
- Co-integrate with high-performace silicon CMOS
- Materials not limited to silicon (III-V's, hetero, ferro)
- See program by DARPA: *Steep-Subthreshold-slope Transistors for Electronics with Extremely-Low Power (STEEP):* *http://www.darpa.mil/MTO/Programs/steep*

Emerging Research Device Technology Candidates Evaluated

- Determine which, if any, current approaches to providing a "Beyond CMOS" information processing technology(ies) is (are) ready for more detailed roadmapping and enhanced investment. (Jim Hutchby, ERD, ITRS)
- 7 technology candidates evaluated in July 2008:
  - **Nano-electro Mechanical Switches**
  - **Collective Spin Devices**
  - **Spin Torque Transfer Devices**
  - **Atomic Switch / Electrochemical Metallization**
  - **Carbon-based Nanoelectronics** **recommended**
  - **Single Electron Transistors**
  - **CMOL / Field Programmable Nanowire Interconnects**

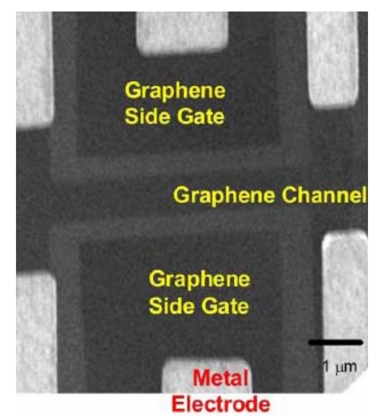
Carbon Electronics: potential

- **Potential**
  - Impact geometric scaling: alternate MOSFET structure
  - Provide a high mobility, high carrier velocity, MOSFET channel replacement material.
  - Provide a technology platform enabling a new “Beyond CMOS” information processing paradigm



- **Carbon nanotubes**
  - exceptionally long mean free path & mobility > 50,000 cm^2/Vsec at RT: ballistic FETs ~ 100 nm.
  - much lower capacitance of ~10 aF (for a diameter of CNT =1 nm, L = 10 nm).

- **Graphene**
  - ambipolar carrier conduction by electrical field and a high mobility ~100,000 cm^2/V.sec at RT (better than InSb).
  - wide variety of novel quantum transport phenomena and novel devices.



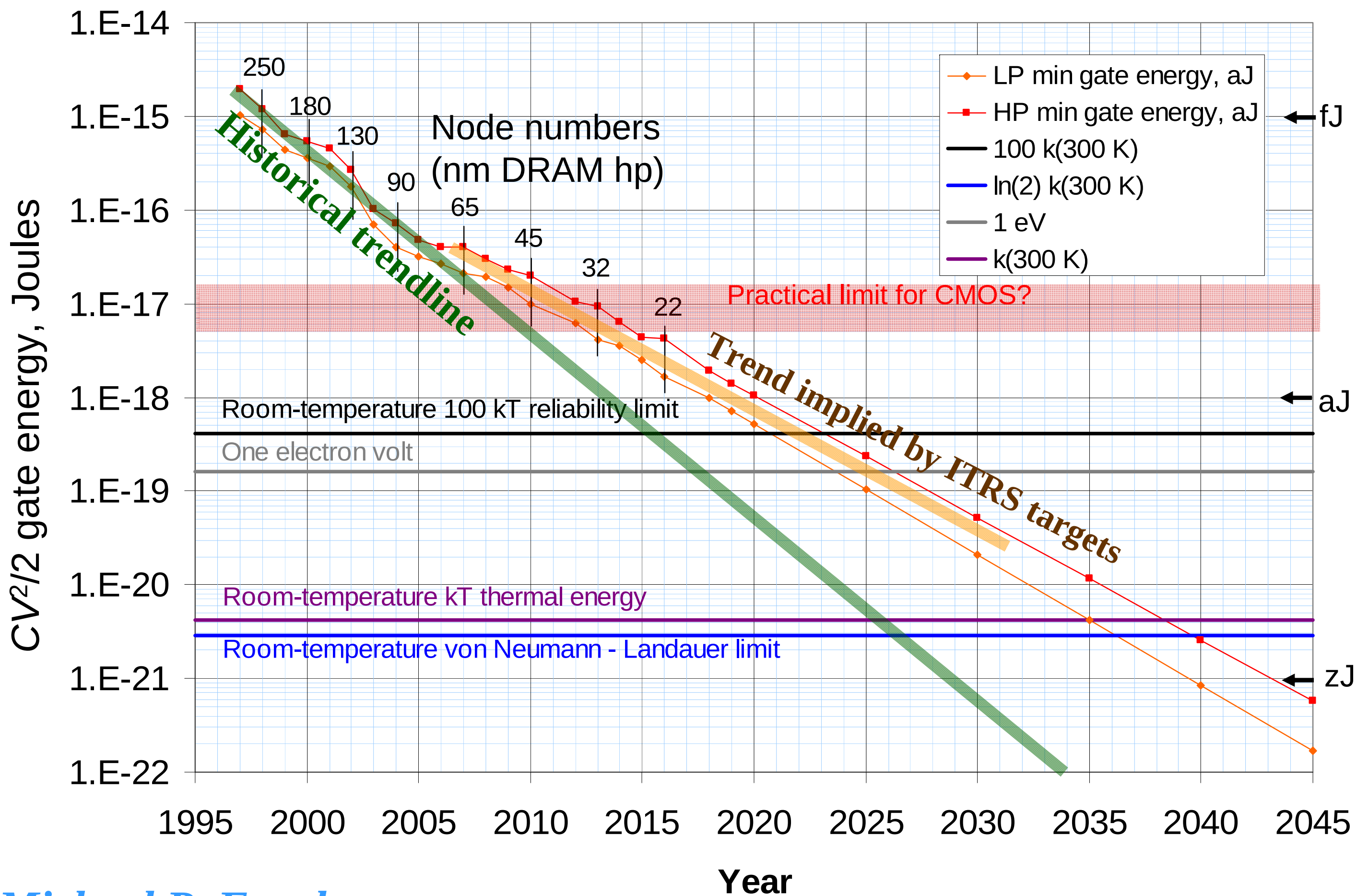
Carbon Electronics: Control!

- **Challenges for CNTs**:
  - **Control:** over the chirality and diameter of nanotubes (and the associated electronic bandgap)
  - **Densely packed arrays:** of nanotubes to achieve current levels comparable to silicon field-effect devices
- **Challenges for graphene**:
  - **Controlled growth**: methods to synthesizing, growing, or depositing high quality graphene film on a suitable insulating substrates for further device processing
  - **Edge control**: atomic precision of the physical and chemical structures of the edges, otherwise the electron transport would be dominated by the edge disorder of graphene nanostructures

Source: White Paper for ITRS ERD Working Group, 2008, P. Kim, Columbia.

Switching Energy @ Small Scale

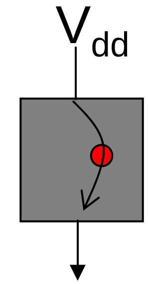
- Trend of min Transistor Switching Energy



Source: Michael P. Franck

Transistors at molecular densities

Suppose in each clock cycle a *single* electron moves from power supply (1V) to ground.



Power dissipation (Watts/cm^2)

Frequency (Hz)	10^{14} devices/cm^2	10^{13} devices/cm^2	10^{12} devices/cm^2	10^{11} devices/cm^2
10^{12}	16,000,000	1,600,000	160,000	16,000
10^{11}	1,600,000	160,000	16,000	1,600
10^{10}	160,000	16,000	1,600	160
10^{9}	16,000	1600	160	16
10^{8}	1600	160	16	1.6
10^{7}	160	16	1.6	0.16
10^{6}	16	1.6	0.16	0.016

ITRS: 9nm gate length, 10^9 logic transistors/cm^2 @ 3×10^{10} Hz for 2016

Source: Craig S. Lent, University of Notre Dame

The von Neumann-Landauer (VNL) bound & reversible computing

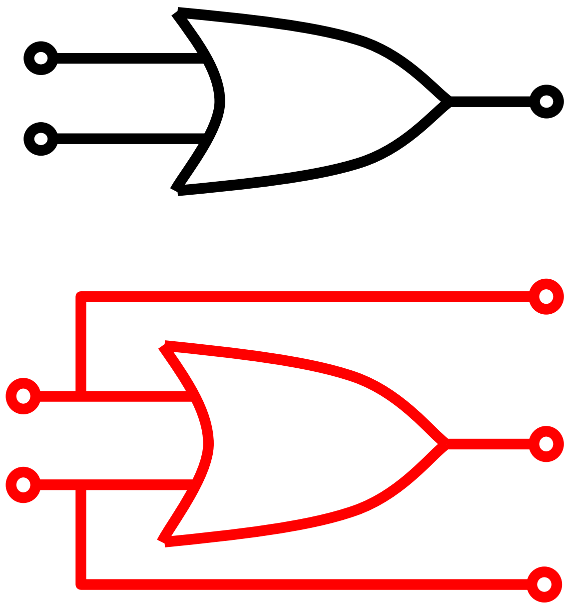
- To lose, obliviously erase, or otherwise irreversibly forget 1 bit's worth of known information involves/requires the eventual **dissipation of at least $k_B T \ln 2$ amount of free energy** to an environment at some temperature T.
- **Reversible computing**: A paradigm for digital information processing in which all (or most) of the digital operations performed (logic, communication, and storage) carry out **logically reversible (functionally invertible) transformations of the local digital state**.
  - **don't lose any logical information**.
  - **VNL bound does not apply**.
  - **careful engineered implementations able to have $E_{diss} << kT \ln 2$.**

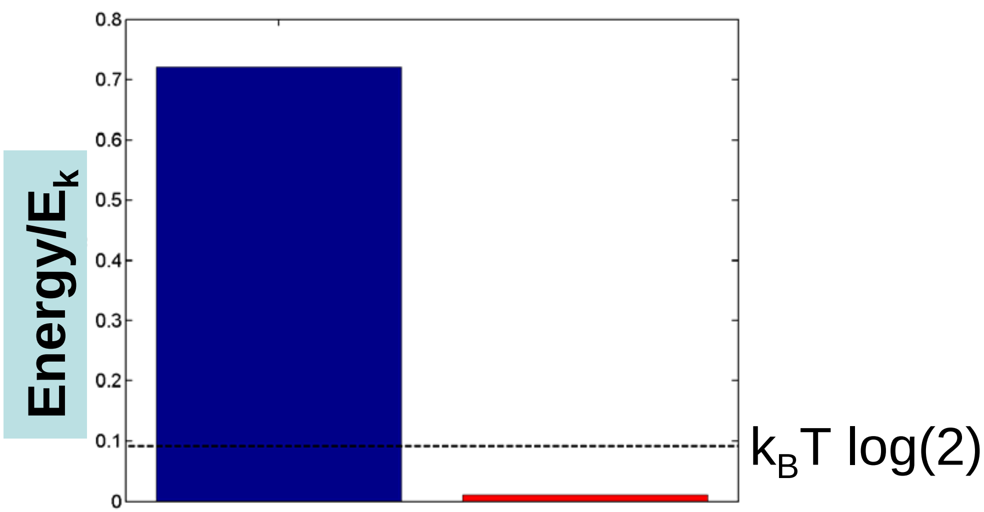
Minimum energy for computation

- **Question**: Is there a fundamental lower limit to the amount of energy that must be dissipated to compute a bit?
- **Answer**: **NO -- Landauer (1961)**
- Bennett (1982): full computation can be done without erasure.

logical reversibility ⇔ physical reversibility

Quantum Cellular Automata: reversible/irreversible





Direct time-dependent calculations with QCA logic shows that logically reversible circuit can dissipate less than k_BT log(2).

Source: Craig S. Lent, University of Notre Dame

Conclusion

- Possible future paths for Components & Systems:
  - **Power & Performance**: Low standby power by steep swing switches on high-performance CMOS platforms.
  - **Higher Performance**: Carbon electronics.
  - **Long term dense computing**: Energy efficient computing. Reversible computing?


Thank you!