NSF-NNI Workshop: Design and Manufacture of Integrated Nanosystems

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Future Directions of Nanoelectronic Systems: A Nanomorphic Cell

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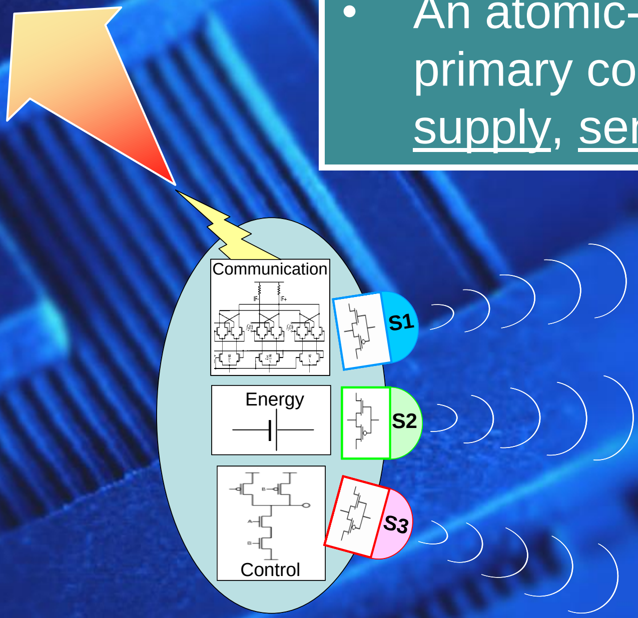
Semiconductor Research Corporation

Arlington, Virginia, March 2-3, 2011

Prototypical Example of an Extremely Scaled Microsystem

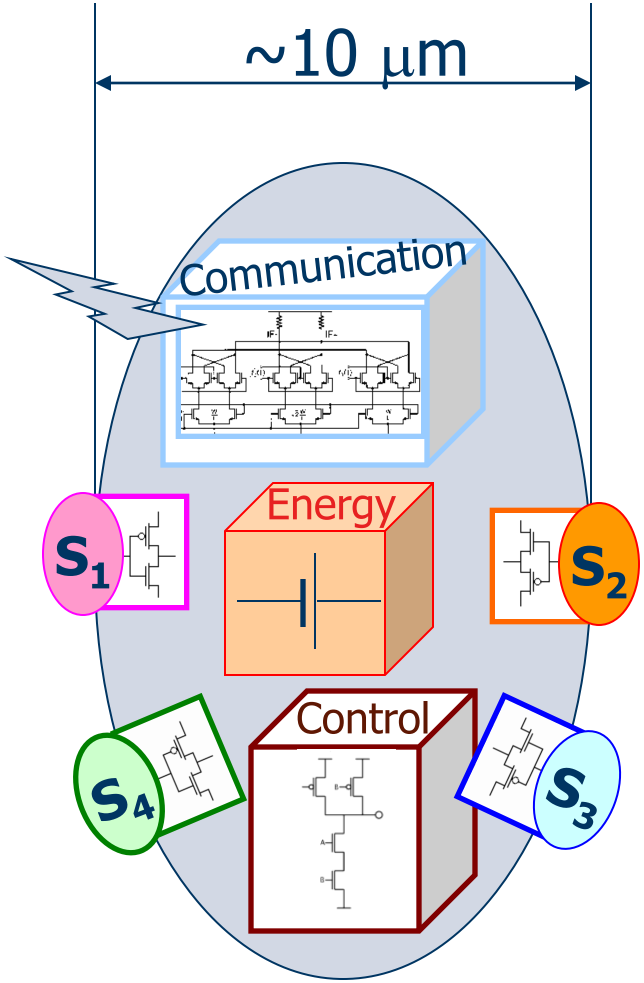
- **Nanomorphic Cell:** A model system, designed to analyze the physical scaling limits of electronic systems,
- Postulated to be confined within a 10μm×10μm×10μm cube.
- An atomic-level integrated, self-sustaining microsystem with **six** primary components: computation, communication, energy supply, sensing, and actuation.



Benchmark: Living cell
***In carbo* system**

"Microsystems for Bioelectronics: The Nanomorphic Cell",
by Victor V. Zhirnov and Ralph K. Cavin (*Elsevier*, 2010)

Electronic Cell



Major functional blocks:

Sensing
Communication
Control
Energy

Technology Convergence

Constraints and Trade-offs:

Very limited space needs to by divided between

sensors
power supply
electronic components

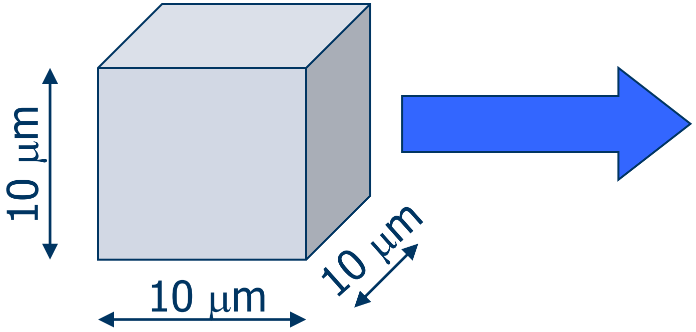
Scaling Limits need to be Understood

Extreme scaling needed

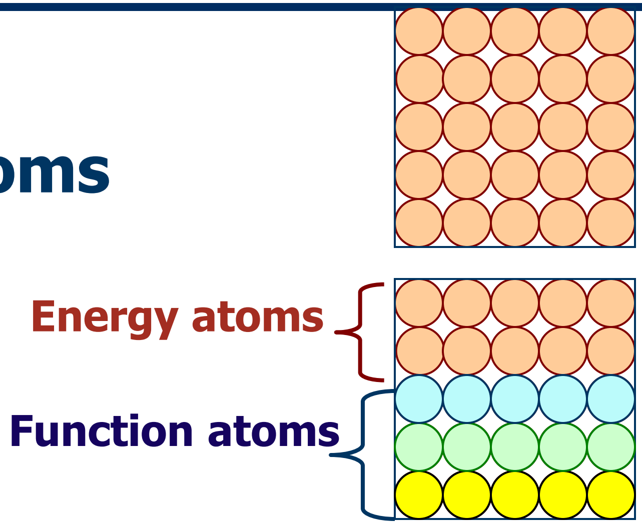
Layout:

3D microcircuits

Atomistic View of System Integration



$5x10^{13}$ atoms



Energy atoms
- ● **Energy**

Function atoms
- ● **Communication**
- ● **Logic Control**
- ● **Sensing**

At this scale, we are literally designing with atoms

1. ENERGY IN THE SMALL

Physics behind:

- **Galvanic &Fuel cells Source: Avogadro’s Law**
- **RF energy transmission/harvesting: EM theory/Maxwell’s equation**
- **Thermoelectric conversion: Carnot Law (=The Second Law)**
- **Nuclear batteries**

Energy sources candidates

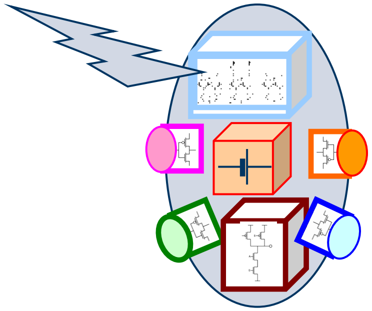
- Electrochemical cell
  - Galvanic cell
  - Fuel cell
  - Integrated Supercapacitors
- Radio-isotope energy sources

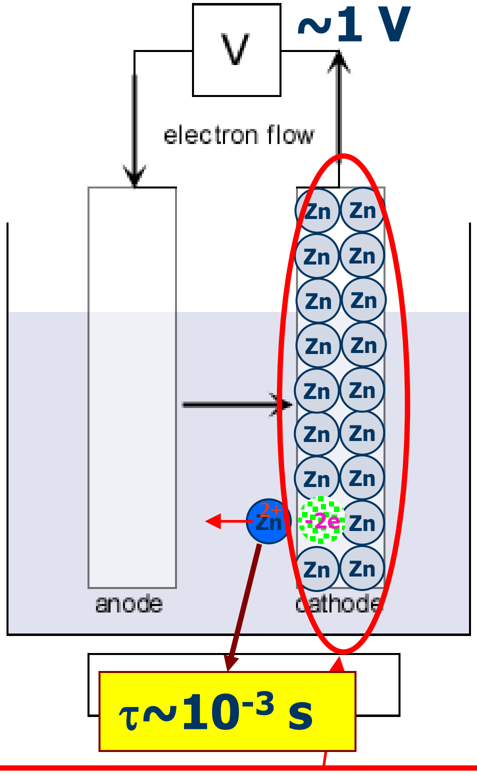
Size-energy-power trade-offs

- ‘Harvesting’ concepts
  - Don’t appear to offer benefits compared to the major energy sources
  - Omitted in this discussion

Integrated Micro-scale Power Sources

Choice and scaling limits of micro-batteries





The galvanic cell consumes *atomic fuel* to produce electricity

Example:

What occurs in a electro-chemical cell?

For every 1-2 electrons that flow through the external connection, on the electrolyte side a metal atom must go into solution as a Me^+ ion

Characteristic reaction time $\tau \sim 10^{-3}$ s

Because the typical chemical bonding energy per electron is ~eV, the typical emf ~1V

$Li \rightarrow Li^+ + e^-$

$Zn \rightarrow Zn^{2+} + 2e^-$

$Cd \rightarrow Cd^{2+} + 2e^-$

$Fe \rightarrow Fe^{2+} + 2e^-$

$Pb \rightarrow Pb^{2+} + 2e^-$

…

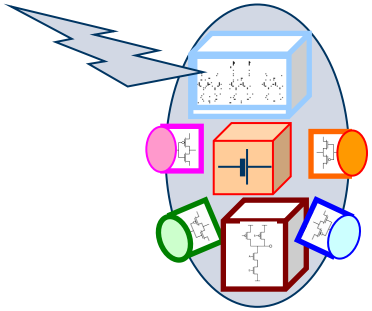
H_2

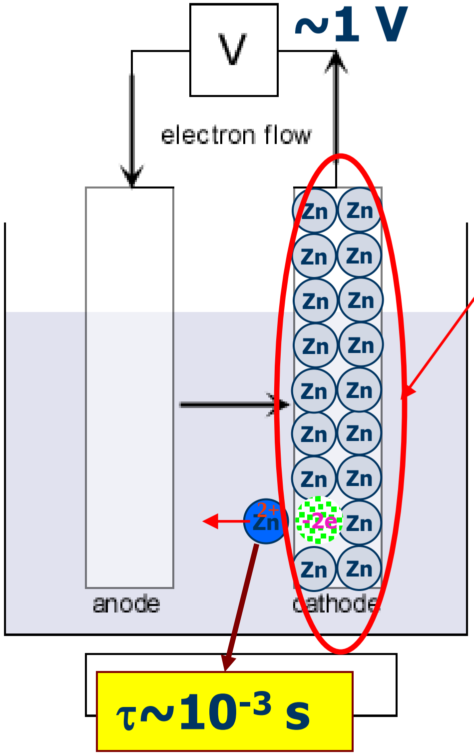
1-2 electrons

~ 0.5-3 Volts

Integrated Micro-scale Power Sources

Choice and scaling limits of micro-batteries





τ~10^{-3} s

The galvanic cell consumes *atomic fuel* to produce electricity

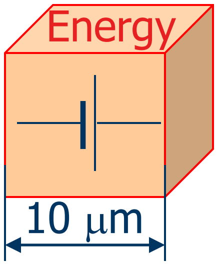
ε ~ **1eV/atom**

The energy output is limited by the *number of atoms*

$$E = \varepsilon \cdot N$$

Number of atoms in cathode electrode

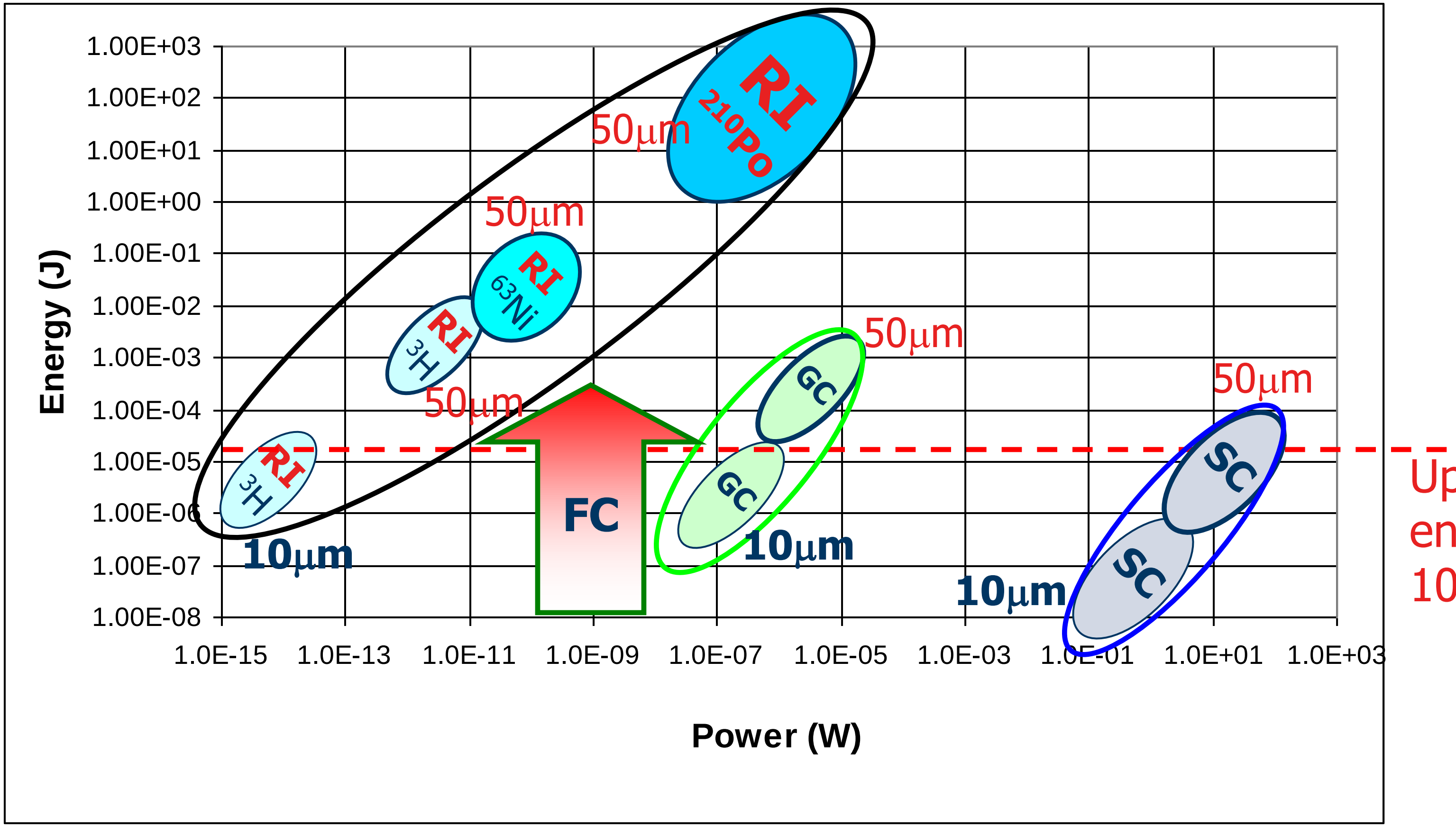
$$E_{\max} \sim eN_A \cdot 1V = 1.6\times10^{-19} \cdot 6\cdot10^{23} \sim 10^5 \frac{J}{mole} \sim 10^4 \frac{J}{cm^3}$$



$$E \sim (10^{-3} cm)^3 \cdot 10^4 \sim 10^{-5} J$$

$$P \sim \frac{\varepsilon N_s}{\tau} \sim 10^{-6} W$$

Energy vs. Power Delivery

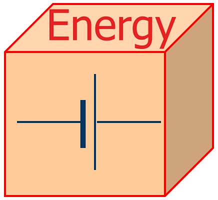


Upper bound for energy stored in 10 µm cube

RI	**-Radioisotopes**	**10^{-5} J/ 10^{-14} W**
GC	**-Galvanic cells**	**10^{-5} J/ 10^{-6} W**
FC	**-Fuel cells**	***sustainable*/ 10^{-8} W**
SC	**-Supercapacitors**	**10^{-7} J/ 1 W**

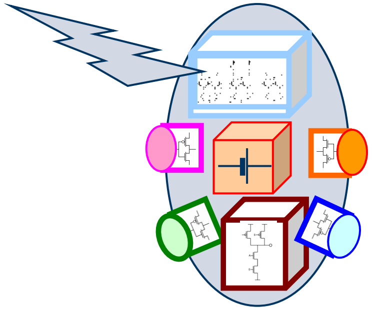
~10 µm size of energy source

Energetics of an Autonomous Micron-Scale System Drives System Design



TOTAL

$$E \sim (10^{-3}\, cm)^3 \cdot 10^4 \sim 10^{-5}\, J$$



Control

?

Communication

?

Sensing

?

2. MINIMAL LOGIC ELEMENT

Scaling limits: The binary switch

Boltzmann-Heisenberg relations

We think that all devices operating in an equilibrium with thermal environment are governed by these relations, no matter what state variables are chosen!

$$\Pi_{error} = \exp\left(-\frac{E_b}{k_B T}\right)$$

$$\Delta x \Delta p \geq \hbar$$

$$\Delta E \Delta t \geq \hbar$$

“Boltzman constraint” on minimum switching energy

$\Pi_{error} = 0.5$

Nanoscale Devices

“Heisenberg constraints” on device size and speed

$$x_{\min} = \frac{\hbar}{\sqrt{2mkT\ln 2}}$$

$$E_b^{\min} = k_B T \ln 2$$

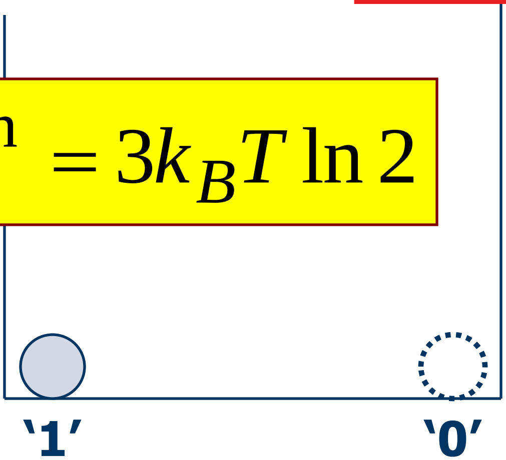
~10^{-21} J

$$E_{sw}^{\min} = 3k_B T \ln 2$$

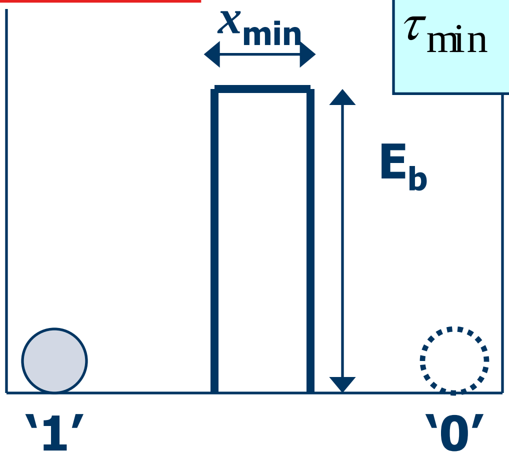
~1.5 nm

$$\tau_{\min} = \frac{\hbar}{kT\ln 2}$$

~40 fs

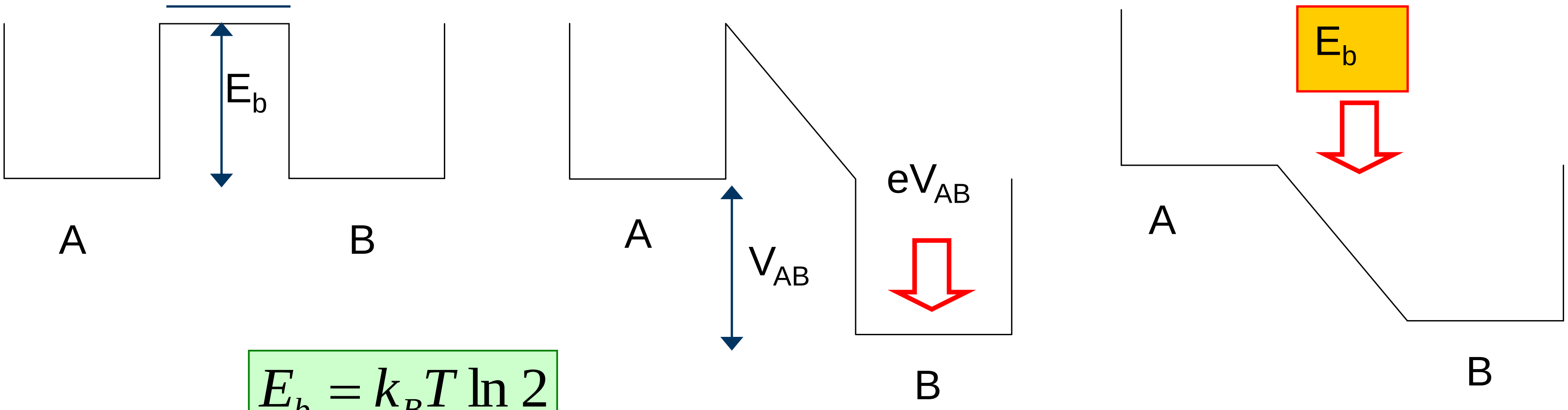


This structure cannot be used for representation/processing information



An energy barrier is needed to preserve a binary state

Creating Barrier Asymmetry also requires energy



$$E_b = k_B T \ln 2$$

$$E_W = k_B T \ln 2 \times N$$

N – the number of electrons

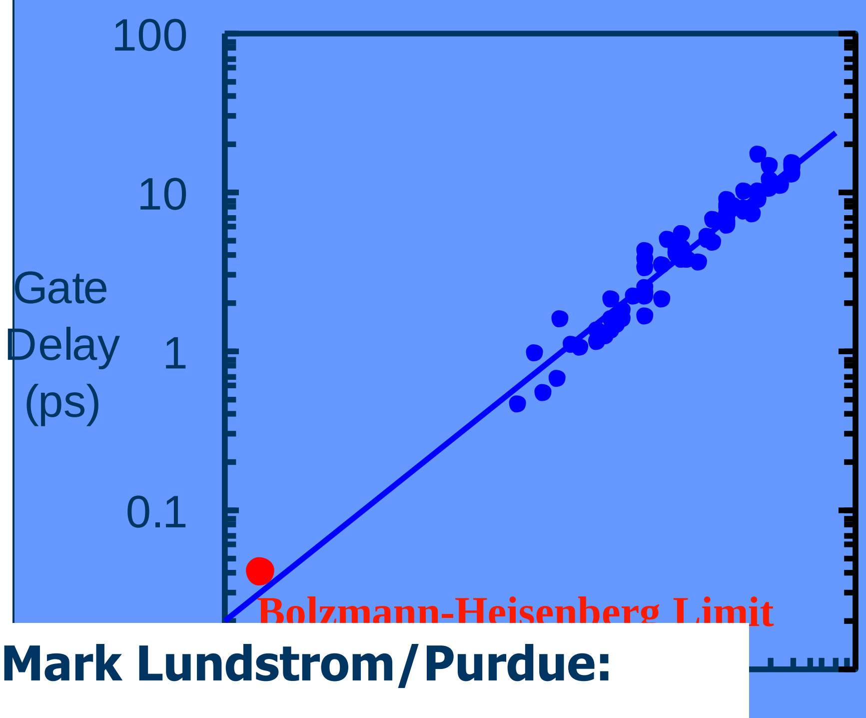
$$E_{sw} = 2E_b + NE_w = (N+2)k_B T\ln 2$$

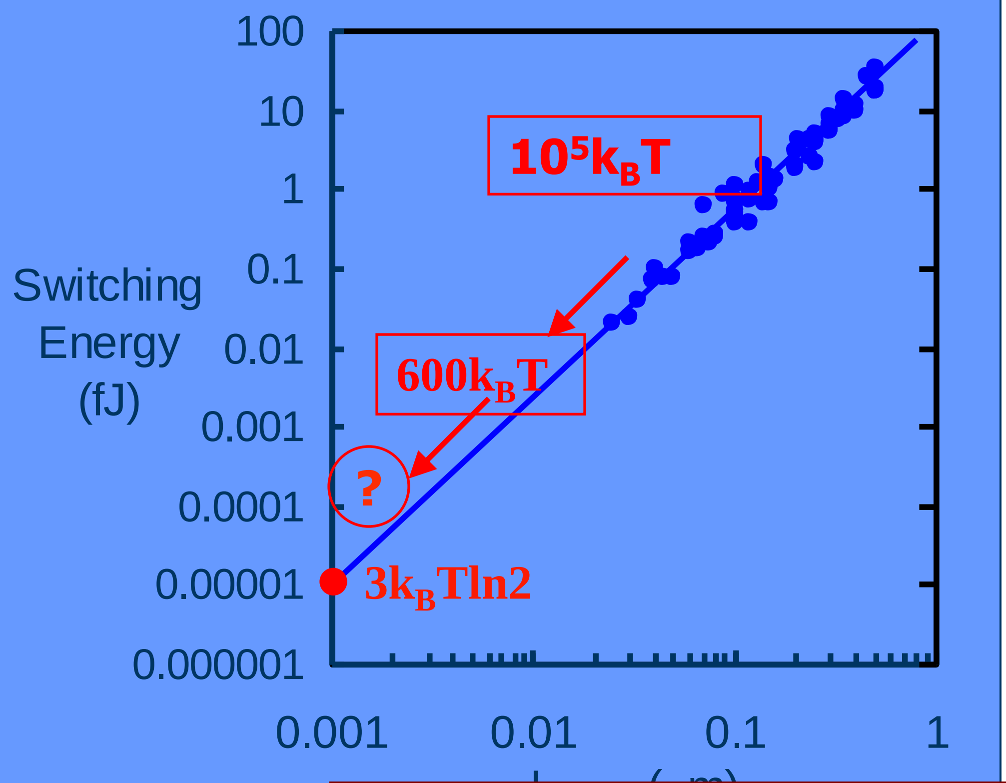
N=1

$$E_{sw} = 2E_b + E_w = 3k_B T\ln 2$$

CMOS scaling on track to obtain physical limits for electron devices

George Bourianoff / Intel





Mark Lundstrom/Purdue:

Why do we still operate so far above the fundamental limit: Why $10^5\, k_BT\ln2$ and not $3k_BT\ln2$?

$$E \sim N \cdot E_b = N \cdot e \cdot V_{dd}$$

Answer:

1) System reliability costs
2) Communication costs
3) Fan-Out costs

System Level Energetics I: *Reliable Switching*

Computation at $\Pi_{err}=0.5$, and hence at $E_b=k_BT\ln 2$ is impossible

In useful computation, Π_{err} <<0.5, hence barrier height larger than $k_B ln2$ is needed (larger <u>total</u> power consumption)

Question: How Much Larger?

If we assume switches operate independently

$$\Pi_{syst}=\left(1-\Pi_{err}\right)^N$$

The probability that all N switches in a circuit work correctly

N↑→L↓→Π_{err}↑

(Heisenberg)

Π_{err}↓ →E↑

(Boltzmann&Heisenberg)

System Constraint on Minimum Energy per Bit

$$\Pi_{syst} = \left(1 - \Pi_{err}\right)^{N}$$

The probability that all N switches in a circuit work correctly

$$\Pi_{syst} > \Pi_{crit}$$

e.g.,
- **0.5** – **lower boundary**
- **0.99** – **a "reasonable" boundary**

$$\Pi_{err} = 1 - \Pi_{crit}^{\frac{1}{N}}$$

$$\Pi_{err} = f(E_b)$$

$$\boxed{E_{b_{\min}} = f(N)}$$

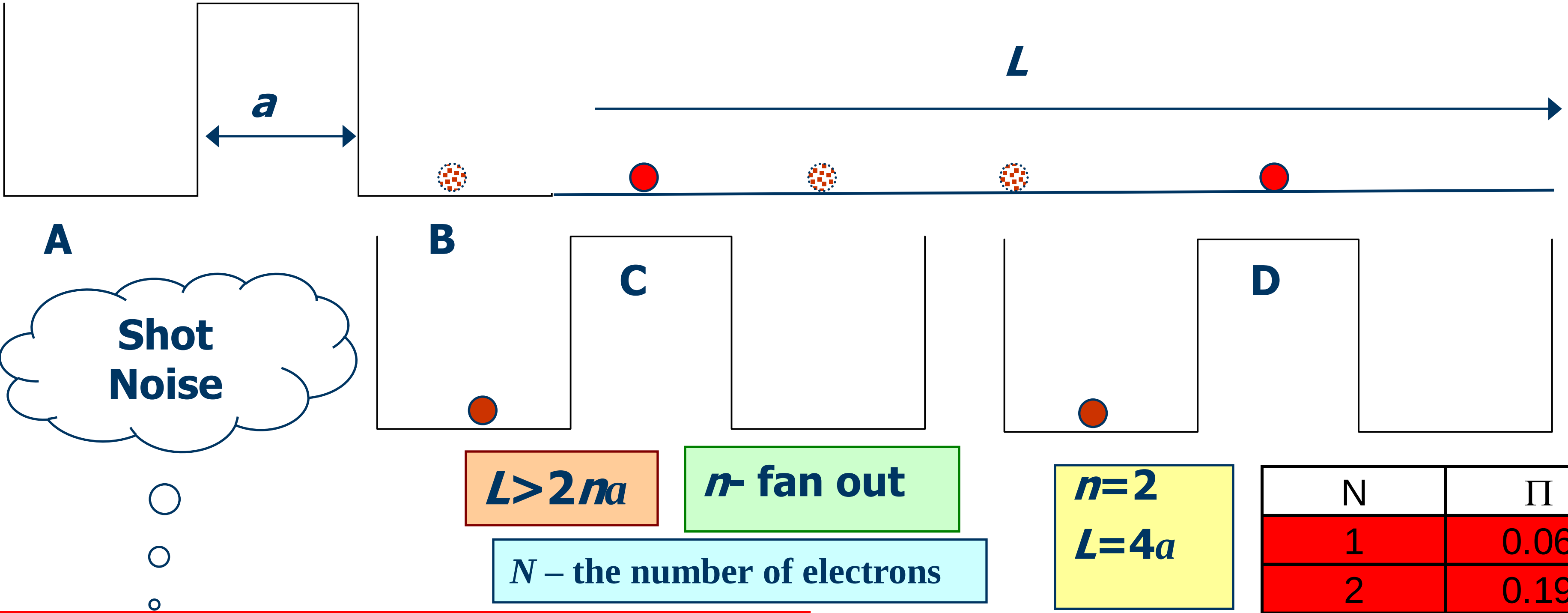
$$\boxed{N_{\max} \sim \frac{1}{a^2}}$$

Boltzmann **Heisenberg**

$$\Pi_{err} = \boxed{\exp\left(-\frac{E_b}{kT}\right)} + \boxed{\exp\left(-\frac{2\sqrt{2m}}{\hbar} a\sqrt{E_b}\right)}$$

Connecting Binary Switches via Wires in 2D (*L*>2*na*, *N electrons*)

For logic operation, a binary switch needs to control at least two other binary switches



L*>2*na

***n*- fan out**

N – the number of electrons

***n*=2**
L*=4*a

$$\Pi_{C\&D} = \Pi_C \times \Pi_D = \left(1-\left(1-\frac{a}{L}\right)^N\right)^2$$

$N_{min}=5$

N	Π
1	0.06
2	0.19
3	0.33
4	0.47
5	0.58
6	0.68

Minimum switching energy for connected binary switches

$$E_{sw}=2E_b+NE_b=(N+2)E_b$$

FO2

n=2 *L*=4*a*

$$N_{min}=5$$

$$E_{sw}=7k_BT\ln 2$$

FO4

n=4 *L*=8*a*

$$N_{min}=14$$

$$E_{sw}=16k_BT\ln 2$$

Communication between logic switches takes more energy than information processing (switch operations)

N	Π
1	0.00
2	0.00
3	0.01
4	0.03
5	0.06
6	0.09
7	0.14
8	0.19
9	0.24
10	0.29
11	0.35
12	0.41
13	0.46
14	0.51
15	0.56
16	0.60
17	0.65
18	0.68

Operational reliability vs. Number of Electrons

- In interconnects, the number of electrons needs to be sufficient to guarantee successful communication between binary switches

Typical fan out (n=4) for logic

L=8a

N electrons	**Operational reliability**
14	50%
20	75%
42	99%

We need many electrons for reliable communication

More electrons means more energy…

Mark Lundstrom/Purdue:

Why do we still operate so far above the fundamental limit:
Why $10^5\ k_BT\ln 2$ and not $3k_BT\ln 2$?

We need a significant number of electrons for branched communication between binary switches

$$E \sim N \cdot E_b = N \cdot e \cdot V_{dd}$$

At the limits:

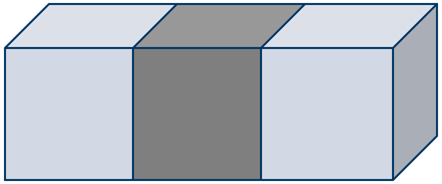
$$E \sim 22 \cdot 1.6 \cdot 10^{-19} \cdot 0.7 = 2.5 \cdot 10^{-18} J = 600\, k_BT$$

Roadmap:

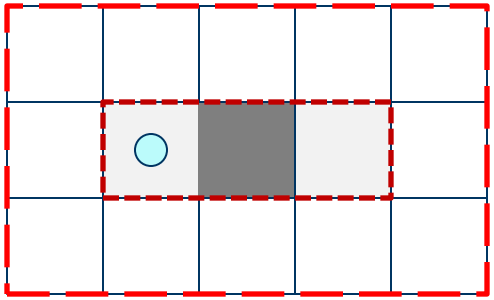
Year	Node	MPU gate	N electron	E_{bit}/k_BT
2003	100	45	1215	5.63E+04
2004	90	37	812	3.76E+04
2005	80	32	532	2.26E+04
2006	70	28	439	1.87E+04
2007	65	25	360	1.53E+04
2008	57	22	331	1.28E+04
2009	50	20	280	1.08E+04
2010	45	18	245	9.47E+03
2012	35	14	155	5.39E+03
2013	32	13	134	4.66E+03
2015	25	10	77	2.37E+03
2016	22	9	69	2.12E+03
2018	18	7	40	1.07E+03
2020	14	5	22	6.05E+02

Minimal 3D Electronic Logic Switch: Volume bounds

3D tiling



NRI is looking for new radical solutions



$a_{\min}$**~5 nm**

(Limited by the mass of electron)

$$n_{3D} \sim \frac{1}{(3a\times 3a\times 5a)} = \frac{1}{45a^3} \sim 10^{17}\ \frac{bit}{cm^3}$$

n_{LOGIC}**~10^{17} cm^{-3}**

(Limited by the mass of electron)

$$E \sim 10^{-5}\ J$$

Max number of processed bits

E_{bit}~$2.5\text{x}10^{-18}$ J

N_{max}=$4\text{x}10^{12}$ bits

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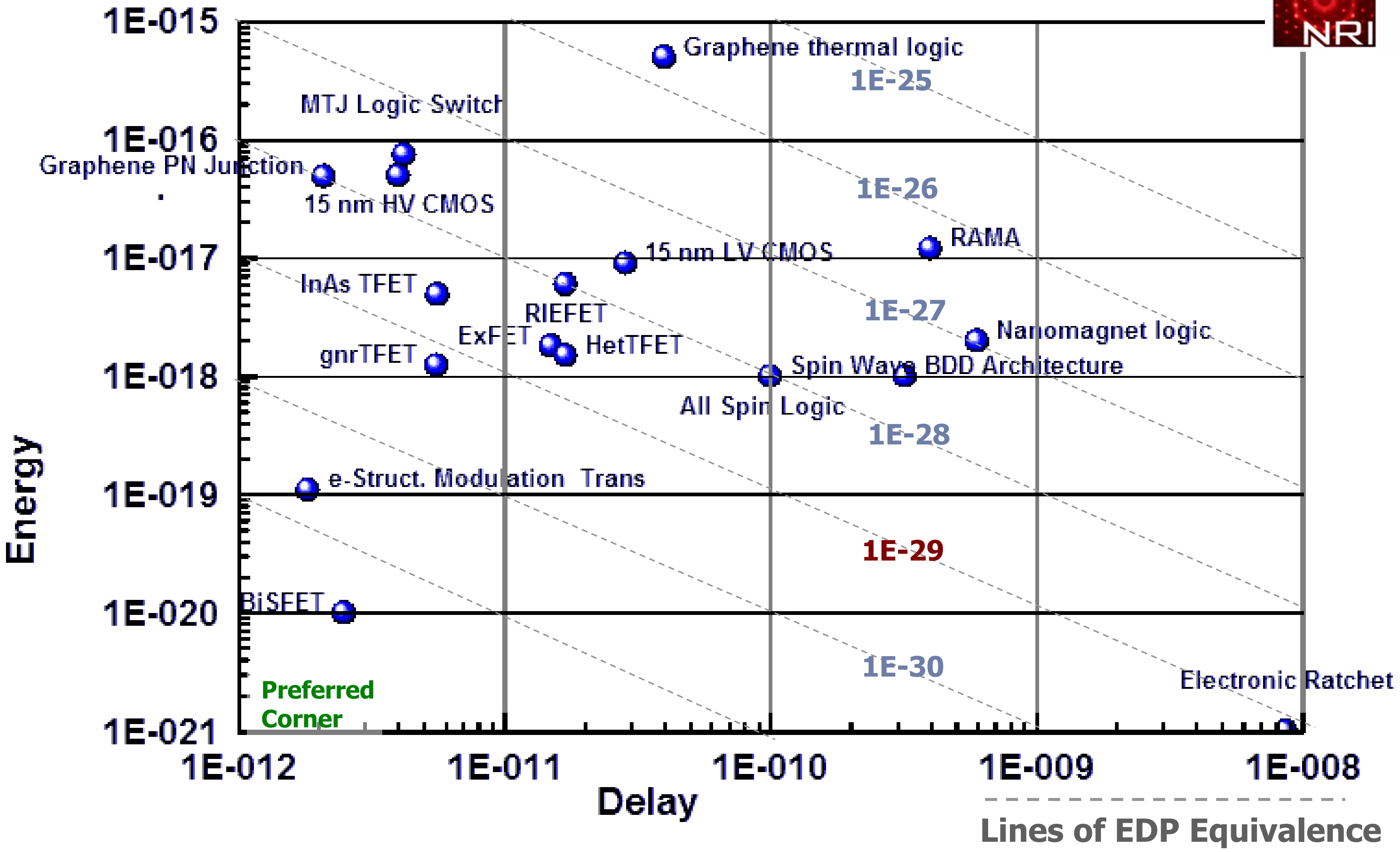
The Quest for a Better Switch

The SRC Nanoelectronics Research Initiative

NRI Switch Candidates

- 15 nm HV CMOS
- 15 nm LV CMOS
- Excitonic FET
- MTJ Logic Switch
- All Spin Logic
- Graphene PN Junction
- Electronic Ratchet
- Graphene thermal logic
- BDD Architecture
- Nanomagnet logic
- gnrTFET
- InAs TFET
- e-Struct. Modulation Trans
- RAMA
- BiSFET
- RIEFET
- HetTFET
- Spin Wave
- MTJ/STT
- Spin Torque Amplifiers
- Mag Domain Wall Logic
- Graphene spin transport
- MOTT Device
- Spin-Inj Hall Effect
- Few Spin Device

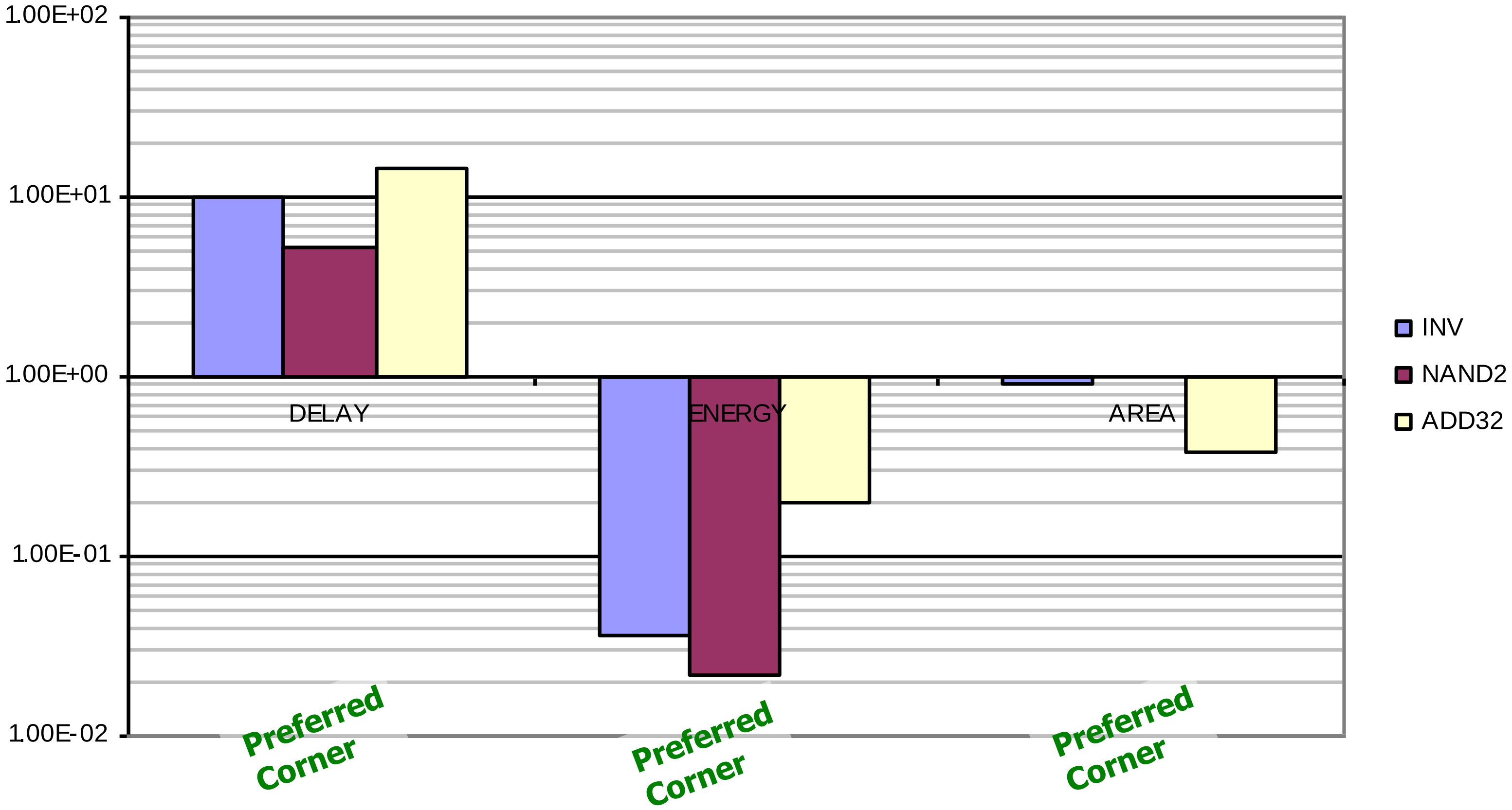
NAND2 Delay vs Energy



A potential Delay-Energy minima exists at approximately 1E-29

Normalized Data

NRI Median Switch Characteristics



All 3 metrics responding consistently – energy and area superiority.

3. MINIMAL MEMORY ELEMENT

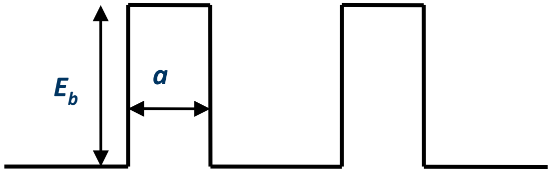
(Nonvolatile case)

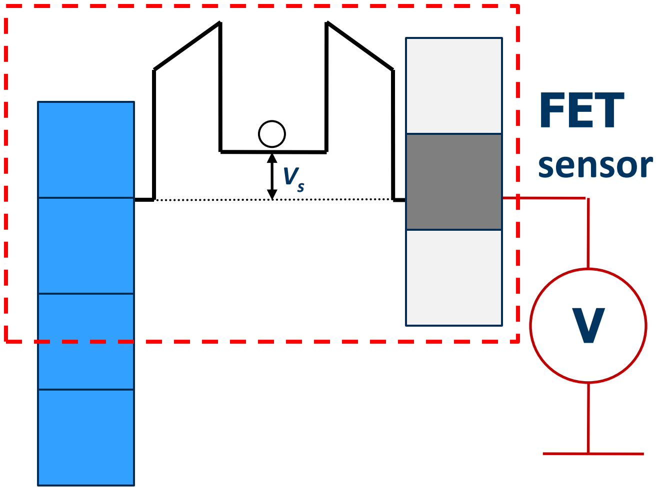
What is the smallest volume of matter needed for memory?

Al Fazio, Intel Fellow (ITRS ERD meeting, April 2010)

Three essential components of a Memory Device

- **Storage** element
  - Two-barrier system
- **'Sensor'** which reads the state
  - e.g. FET/binary switch
- **'Selector'** which allows a memory cell in an array to be addressed





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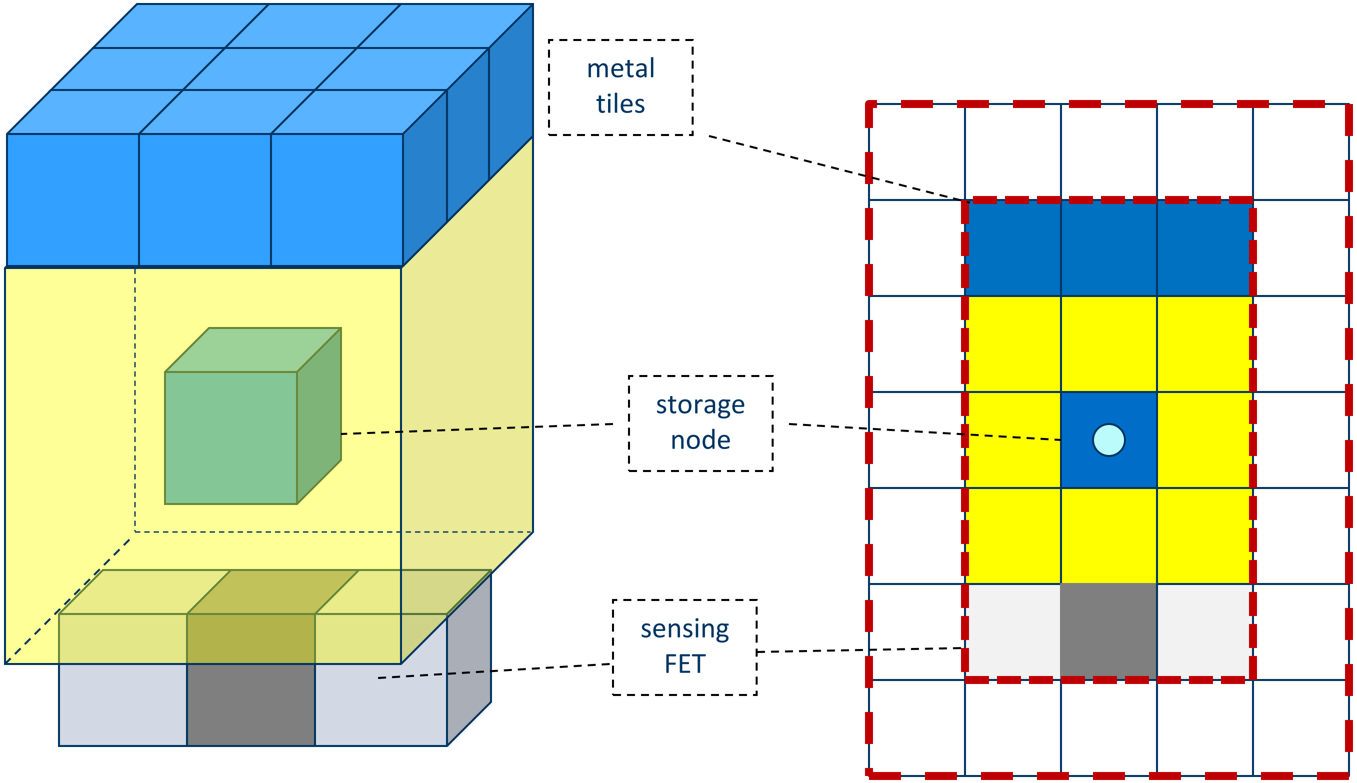
All three components impact scaling limits for memory devices

Minimal Electronic Memory: Volume bounds



E_{bit}~1.3 eV~2×10^{-19} J ~ 50kT

$N_{max}=5\times10^{13}$ bits

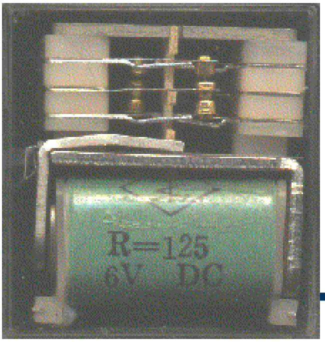
$$n_{3D}\sim\frac{1}{(5a\times5a\times7a)}=\frac{1}{175\,a^3}\sim10^{16}\,\frac{bit}{cm^3}$$

Integrated Nano-sensors

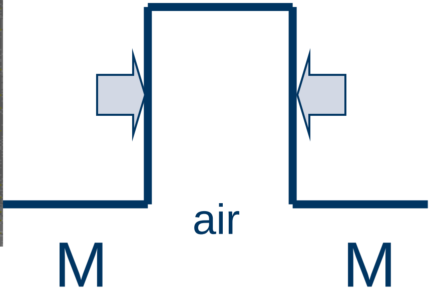
- Sensors are Critical Components for microsystems
- What are scaling limits of the sensors?
  - **Size-Sensitivity tradeoffs for different Stimuli?**
- Single sensor may be not enough
  - Decision making data management often require **pattern** sensing and analysis
    - Arrays of Micro- and Nanosensors
    - Multiple Stimuli
    - High-resolution mapping
- Semiconductor Nanowires have a potential for sensor application
  - e.g. large specific surface area

Unifying View on Switches and Sensors

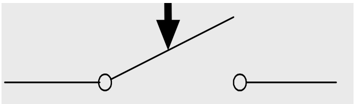
Sensors can be regarded as binary switches, whose barrier is deformed by different stimuli other than charge, e.g. *mechanical, optical, thermal, chemical*



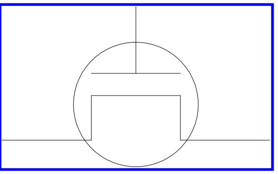
Mechanical stimulus

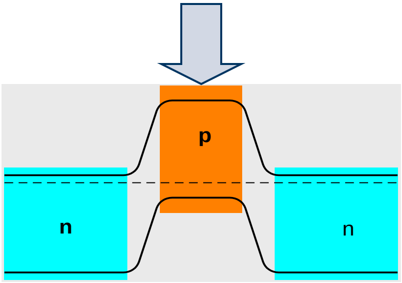


Electro-mechanical switch≈Pressure sensor

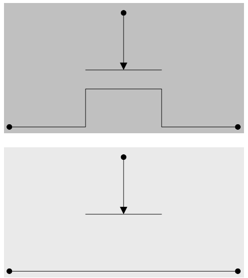


Electrical Stimulus





Transistor=Electronic Switch ≈Charge Sens



Min size ~ 5 nm

E_{bit}~10^{-18} *J/bit*

E_{bit}~$2.5x10^{-18}$ J

$N_{max}=4x10^{12}$ bits

In principle, the sensor can be powered by the energy of the external stimulus

All information devices, both switches and sensors, contain at least one energy barrier, which controls information carriers. The barrier properties, such as height, length, and shape determine the device characteristics

4. COMMUNICATION IN THE SMALL

Scaling of EM transducer (Maxwell)

Energy of communication in a micron-size system (Einstein)

Communication technologies for Autonomous Micro-Scale Systems

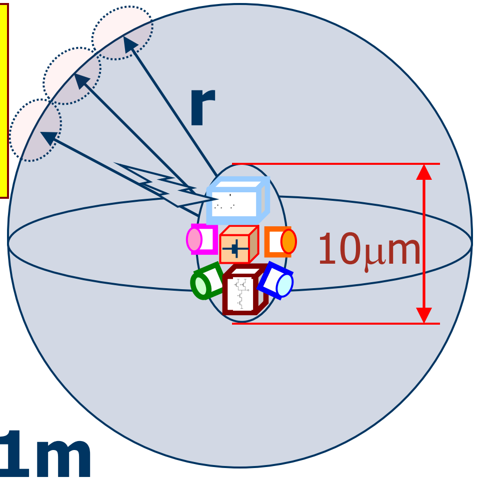
Example: Uniformly radiated wireless communication

$$E_{com} = N_{photons} \cdot E_{ph}$$

$$E_{ph} = h\nu = \frac{hc}{\lambda}$$

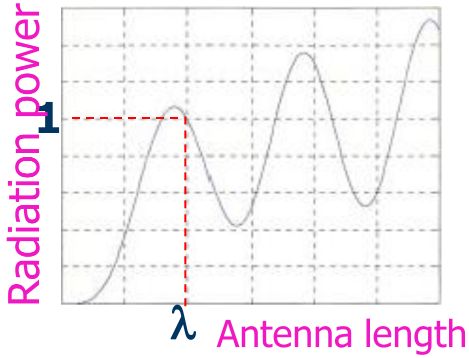
$$N_{photons} \sim \frac{4\pi r^2}{\lambda^2}$$

~ Friis equation

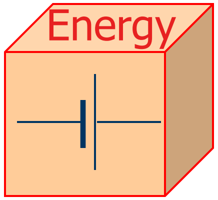


$$E_{com} \sim \frac{4\pi r^2 hc}{\lambda^3}$$

λ_{max}~10 μm



Example: r=1m



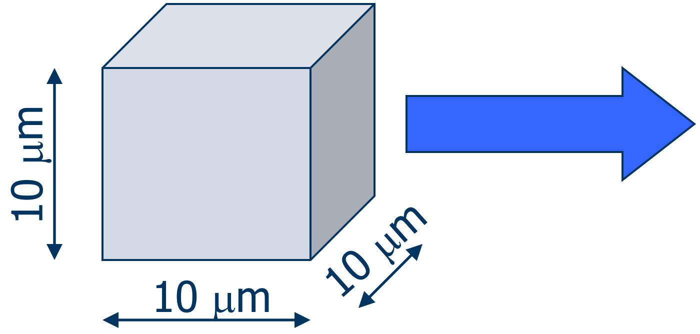
$$E \sim 10^{-5} J$$

$$E_{com} = 4\pi \left(\frac{1}{10^{-5}}\right)^2 \cdot \frac{6.62 \cdot 10^{-34} \cdot 3 \cdot 10^8}{10^{-5}} = 2.5 \cdot 10^{-9} \frac{J}{bit}$$

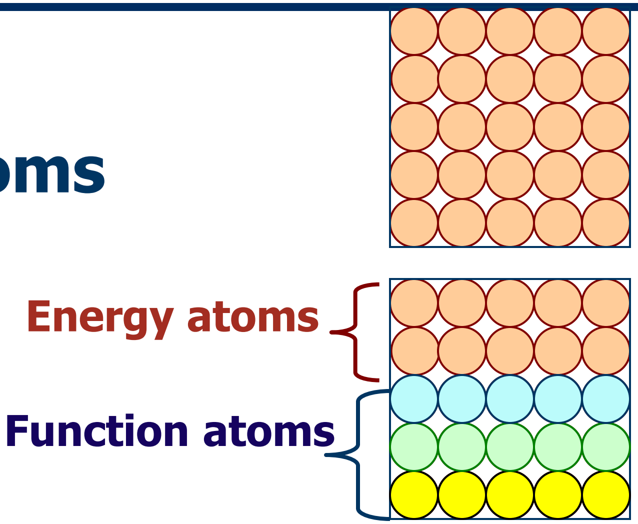
Max number of sent bits

N_{max}=4000 bit

Atomistic View of System Integration



5×10^{13} atoms



Energy atoms
- 🟠 **Energy** *~ 1 at/eV*

Function atoms
- 🔵 **Communication** *~ 10^{-9} J/bit~10^{10} eV/bit*
- 🟢 **Logic Control** *~5e9 at/transistor (integrated), ~10^{-18} J/bit~10eV/bit*
- 🟡 **Sensing** *~5e7 at/sensor (stand-alone)*

Function	Energy atoms/bit
Communication	10^9
Logic	10
Memory	1
Sensing	<10

Summary: Extreme Microsystems

- Extremely-scaled CMOS technology should support computation and control for the ten micron cube
  - Beyond CMOS devices
  - 3D integration
- Technology issues aside, it appears that a careful atomic-level trade-off could yield a functional system.
- Micron-scale energy sources are key to extreme microsystems
  - Design space is bounded by the limits of energy sources
- Communication energy/volume expenditures is most costly activity – should therefore maximize "system intelligence"
  - Data compression algorithms
  - Greater system autonomy
- Potential for arrays of nano-scale sensors needs further exploration

Thank you!