Extreme Microsystems: Atomic Level Limits

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Semiconductor Research Corporation

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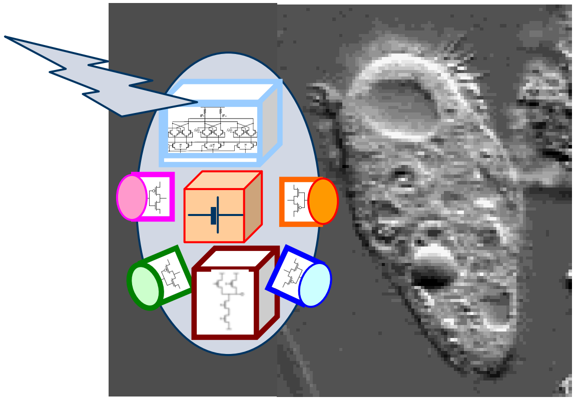
Topics

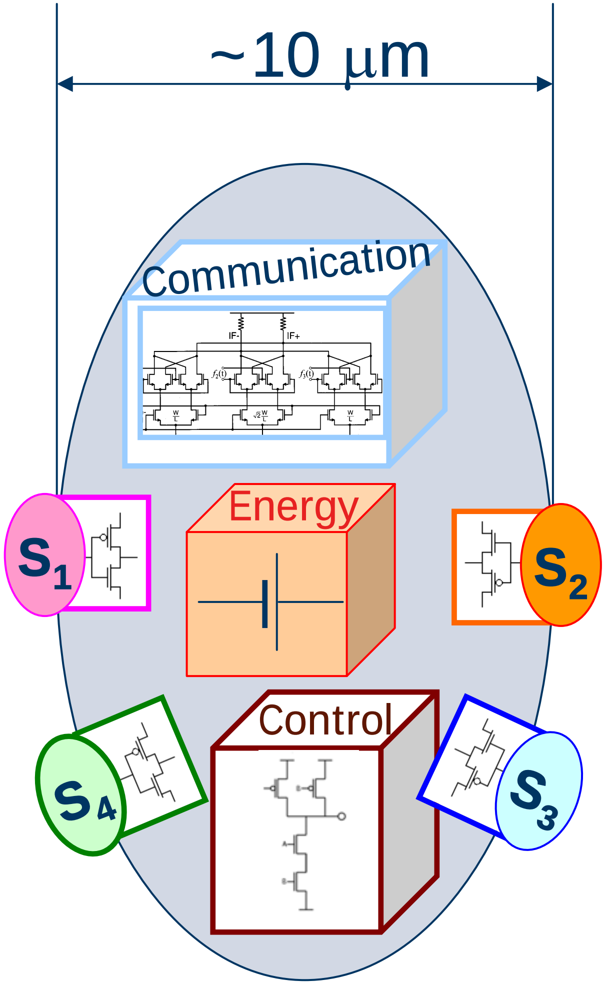
- As feature size scaling continues, integrated circuit technology might morph into integrated system technology at the atomic level
- Atomic scale considerations include
  - Energy source
  - Communication
  - Control Logic
  - Sensing

Prototypical Example of an Extreme Microsystem:

Goal: Sense the state of single living cell



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

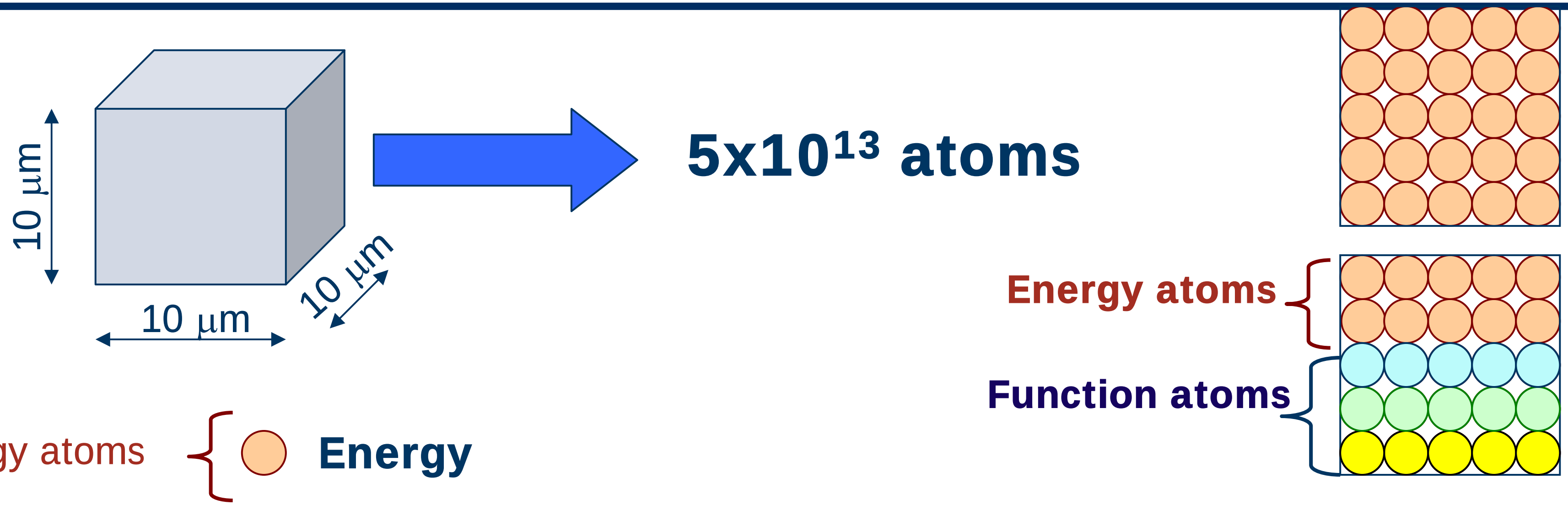
Extreme scaling needed

Thermal Limits !

Layout:

3D microcircuits

Atomistic View of System Integration



$5\text{x}10^{13}$ atoms

Energy atoms
- 🟠 **Energy**

Function atoms
- 🔵 **Communication**
- 🟢 **Logic Control**
- 🟡 **Sensing**

At this scale, we are literally designing with atoms

Energy sources

- Electrochemical cell
  - Galvanic cell
  - Fuel cell
- Radio-isotope energy sources
- Integrated Supercapacitors
- Radio-isotope energy sources
- Energy harvesting
  - Vibration
  - Electromagnetic

The Galvanic Cell

Luigi Galvani (1737-1798)

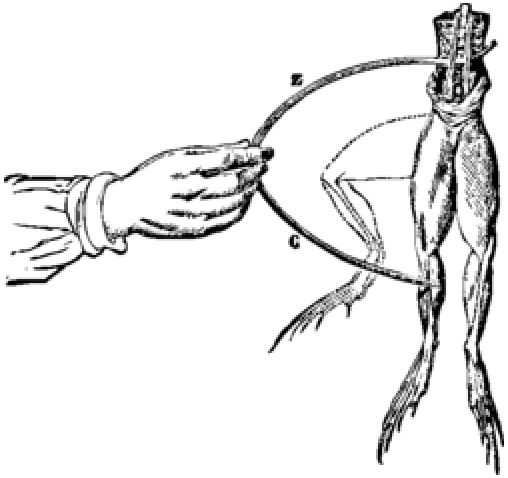
University of Bologna

Known for: *bioelectricity*

Discovered the *extreme sensitivity* of the frog's leg to week electrical stimuli that elicits muscular contraction

The first biosensor

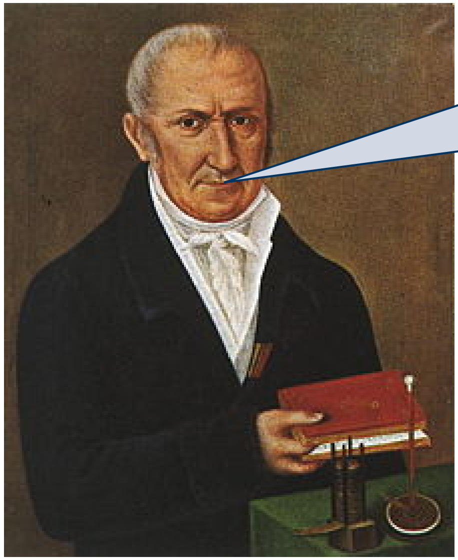
The first extremely sensitive electrometer
(even by modern standards)



The concept of *Animal Electricity*

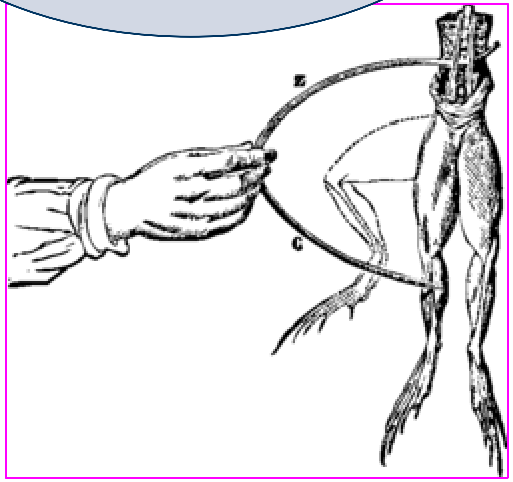
Galvani – Volta controversy

Alessandro Volta



Volta built the first battery in order to specifically disprove Galvani's theory

No animal electricity – dissimilar metals are the key



Luigi Galvani

In response, Galvani produced contractions in the absence of any metal by using nerve instead

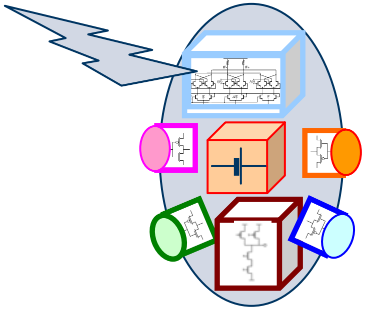
2007: Convergence

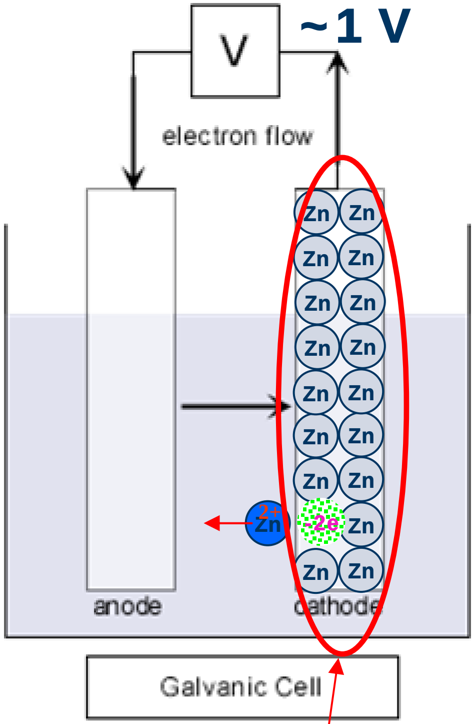
Electronics

Biolelectronics

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 electron that flow through the external connection, on the electrolyte side a metal atom must go into solution as a Me^+ ion

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

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

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

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

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

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

…

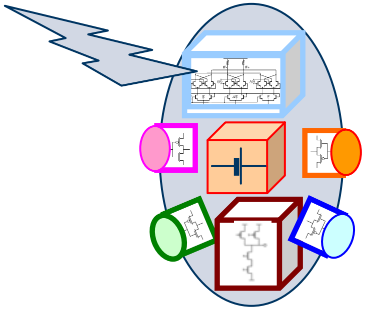
H_2

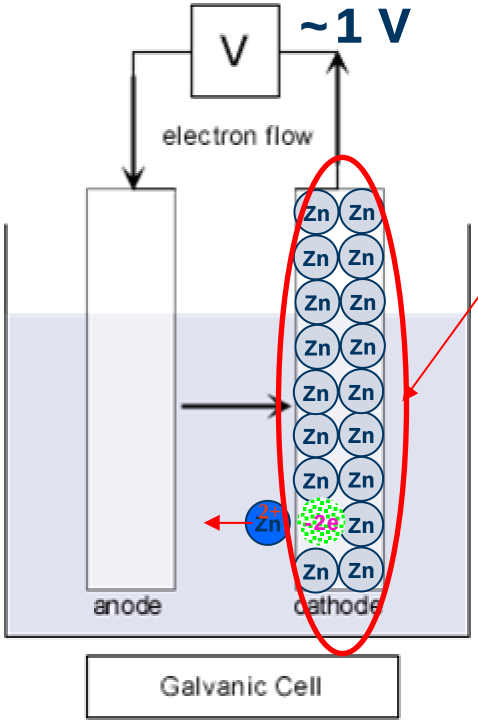
1-2 electrons

~ 0.5-3 Volts

Integrated Micro-scale Power Sources

Choice and scaling limits of micro-batteries





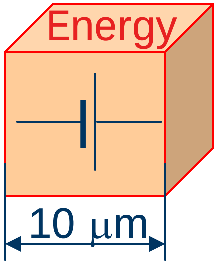
The galvanic cell consumes *atomic fuel* to produce electricity

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

$$E = I \cdot V \cdot t = (It)V = qV \sim eNV$$

Number of atoms in cathode electrode

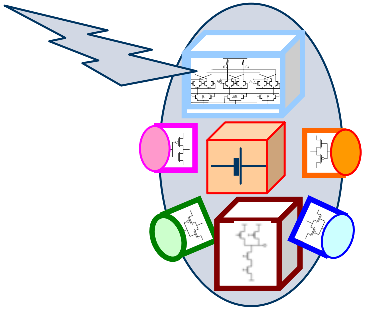
$$E_{\max} \sim eN_A \cdot 1V = 1.6\times 10^{-19} \cdot 6 \cdot 10^{23} \sim 10^5 \frac{J}{mole} \sim 10^4 \frac{J}{cm^3}$$

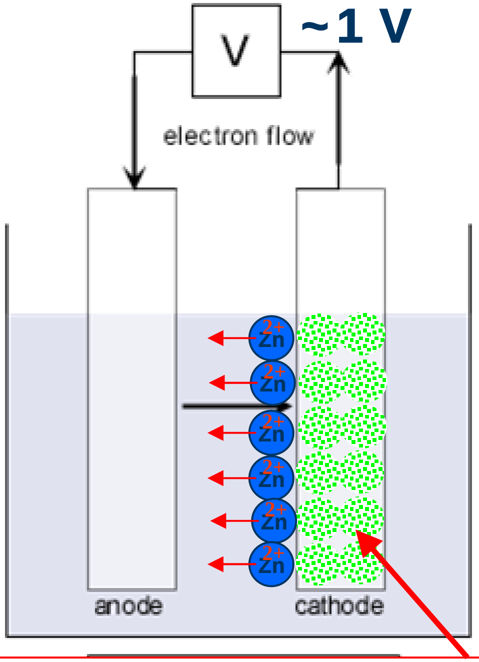


$$\boxed{E \sim (10^{-3}cm)^3 \cdot 10^4 \sim 10^{-5}\,J}$$

Integrated Micro-scale Power Sources

Choice and scaling limits of micro-batteries





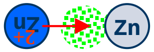
Energy → Number of atoms

The power delivery is limited by the reaction rate at the electrode-electrolyte interface, and depends on the interface area and atomic denisty

The galvanic cell is dead when the atomic fuel is exhausted

Replace the cell

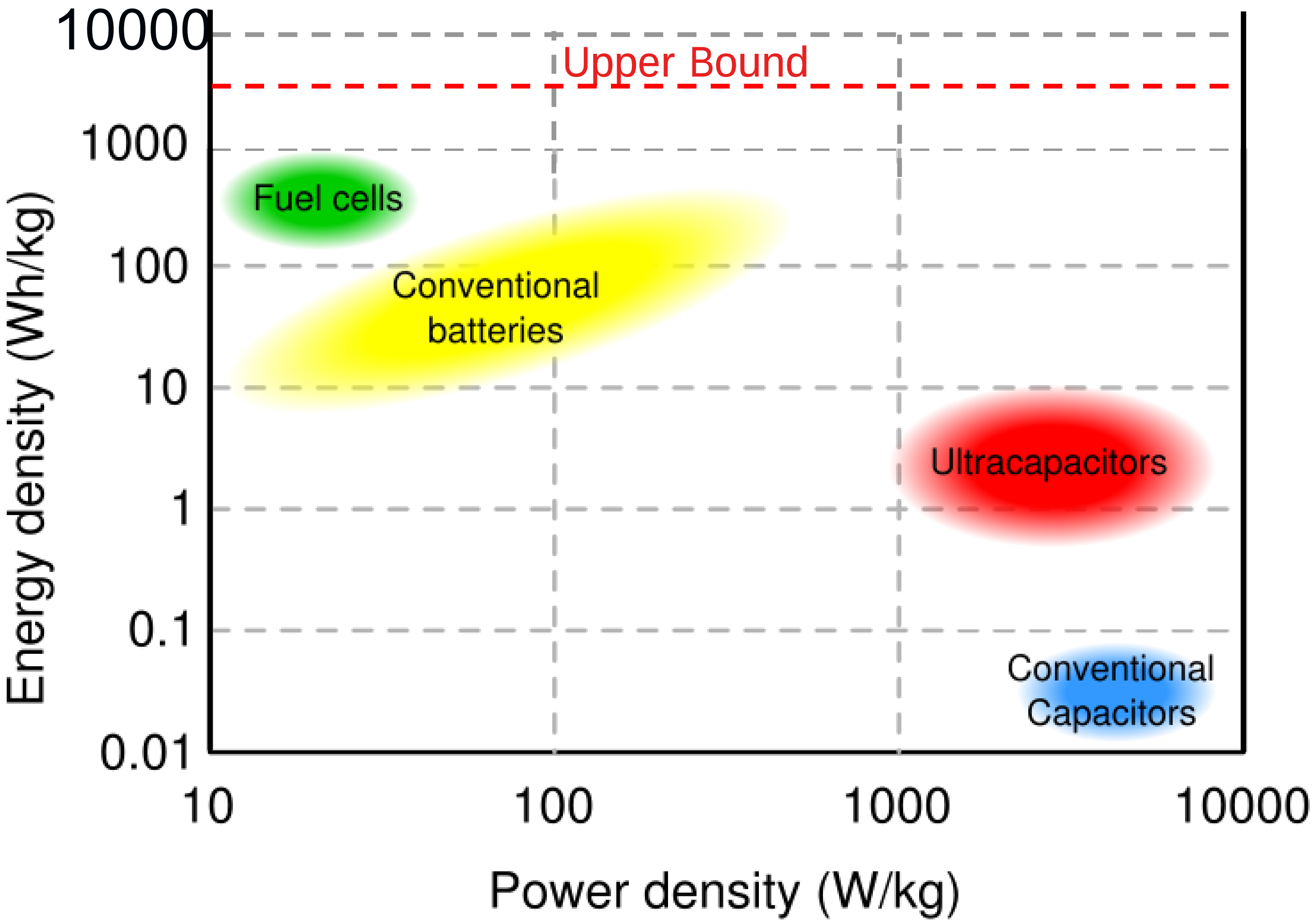
'Recharge' the cell – return atoms back to the electrodes



'Refill' the cell - replace the electrode material

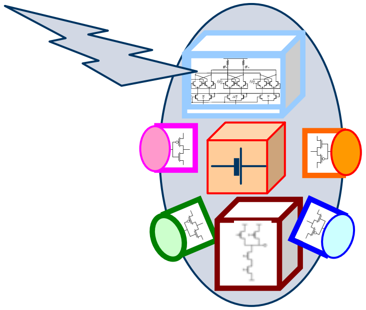
Fuel Cell

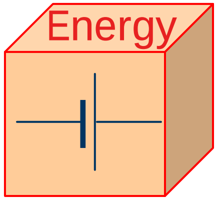
Energy vs. Power Delivery



We may need a hybrid combination

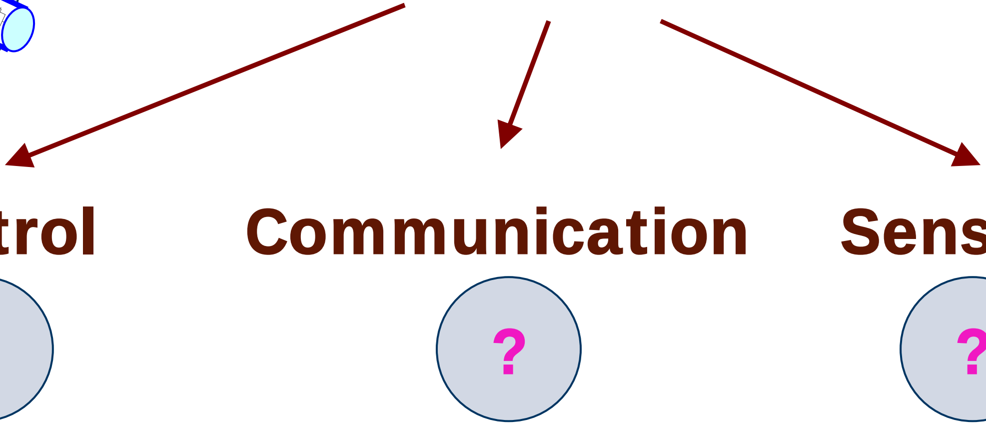
Energetics of an Autonomous Micron-Scale System Drives System Design





TOTAL

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



Control

Communication

Sensing

Communication technologies for Autonomous Micro-Scale Systems

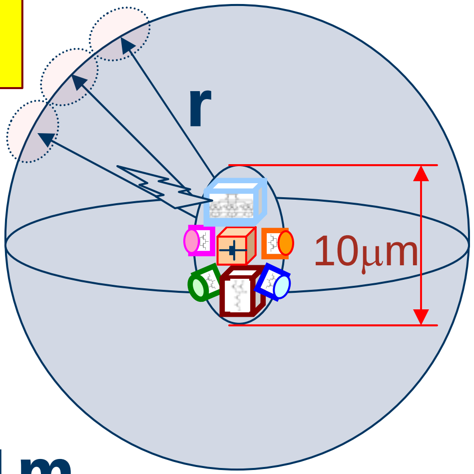
Example: Uniformly radiated wireless communication

~Friis equation

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

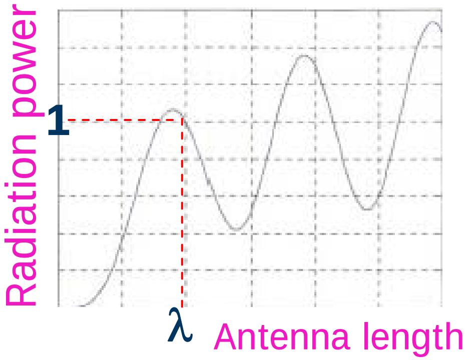
$$E_{com} = N_{photons} \cdot E_{ph}$$

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

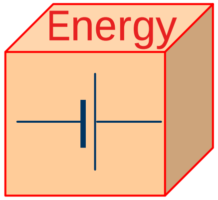


$$E_{com} \sim \frac{4\pi r^2 hc}{\lambda^3}$$

λ_{max} **~10 µm**



Example: r=1m



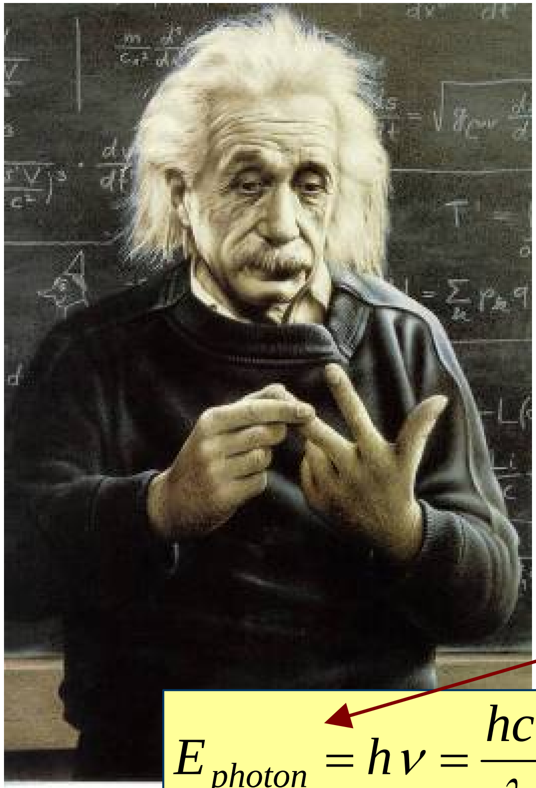
$$E \sim 10^{-5}\,J$$

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

Max number of sent bits

N_{max}=4000 bit

Wireless communications energy-size trade-off



Minimum transducer size *L*~λ (wave-length limit)

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

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

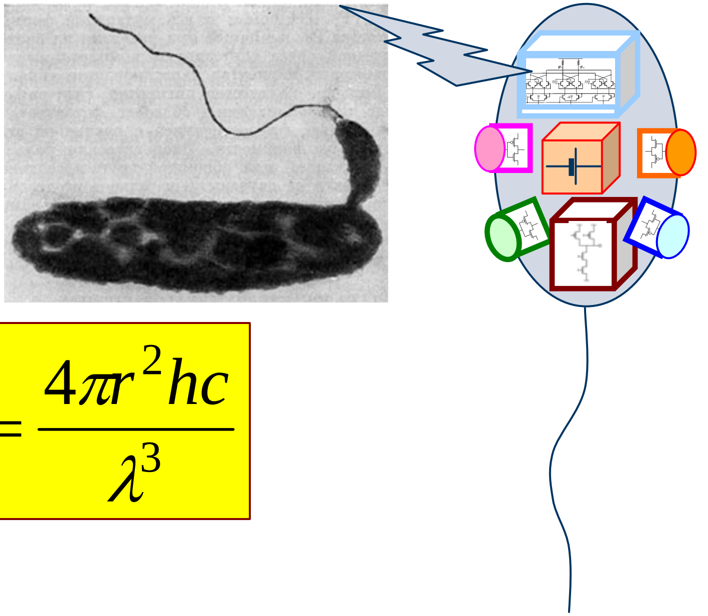
L↓ → E↑ - Einstein's relation doesn't favor scaling of radiative transducers

Communication Options

1)↑λ - External antenna

Exclude from the tight atomic budget

Eases length limits



$$E_{com} \sim \frac{4\pi r^2}{\underbrace{\lambda^2}_{N_{ph}}} \cdot \overbrace{\frac{hc}{\lambda}}^{E_{ph}} = \frac{4\pi r^2 hc}{\lambda^3}$$

CNT tail antenna?

2) Directed transmission

Orientation problem

3) Minimizing communication

should therefore maximize “cell intelligence”

Cost?

Nanoscale Devices

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

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

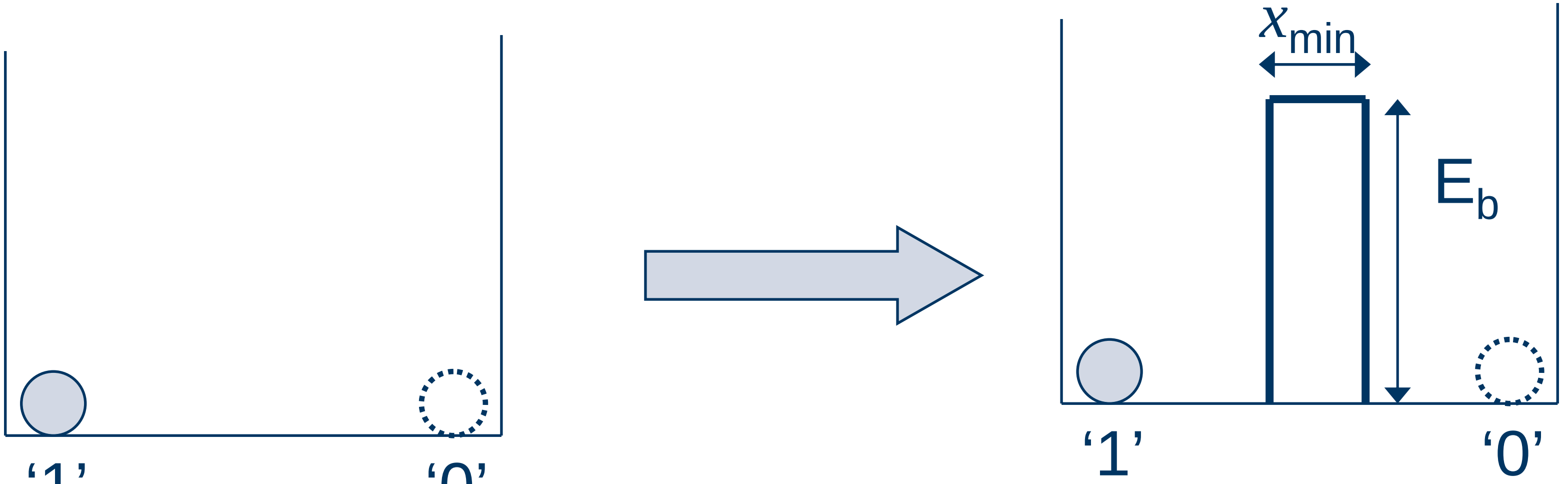
$$\Delta x \Delta p \geq \hbar$$

"Boltzman constraint" on minimum switching energy

"Heisenberg constraint" on minimum device size

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

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

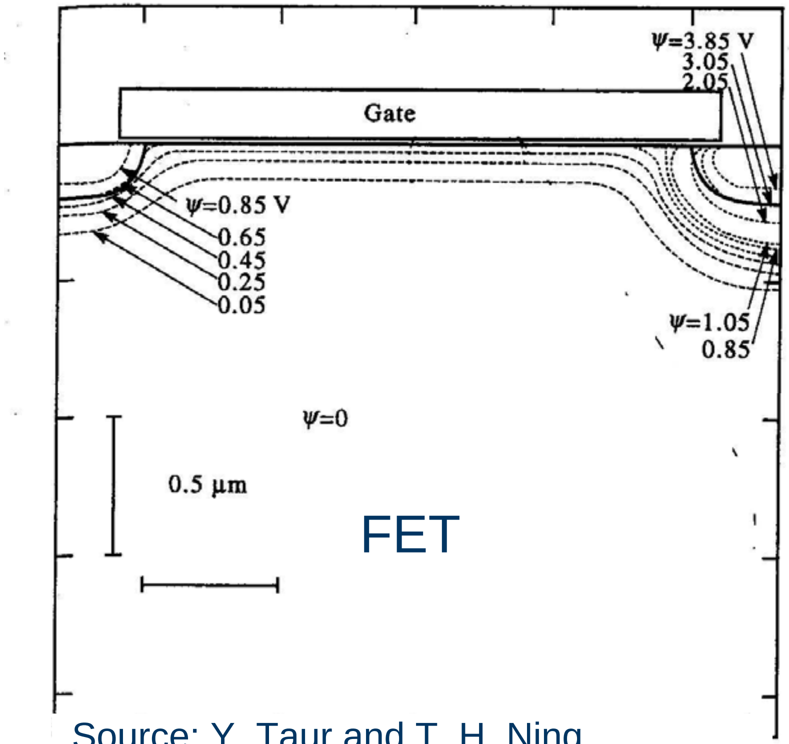


This structure cannot be used for representation/processing information

An energy barrier is needed to preserve a binary state

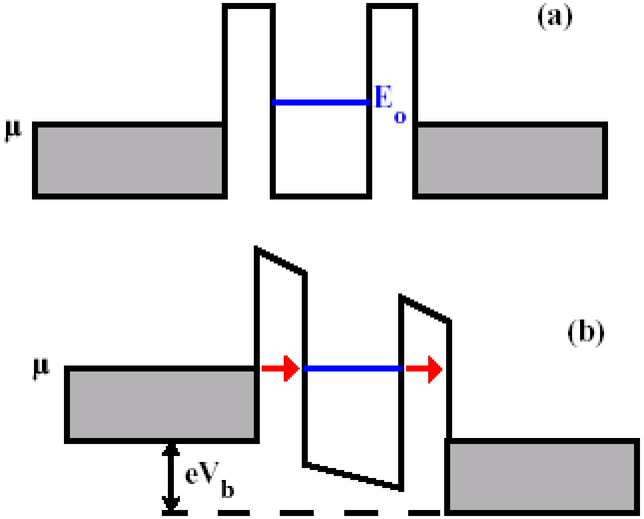
Energy Barriers in Materials

- Any electronic device contains at least one energy barrier, which controls electron flow. The barrier properties, such as height, length, and shape determine tronic devices.



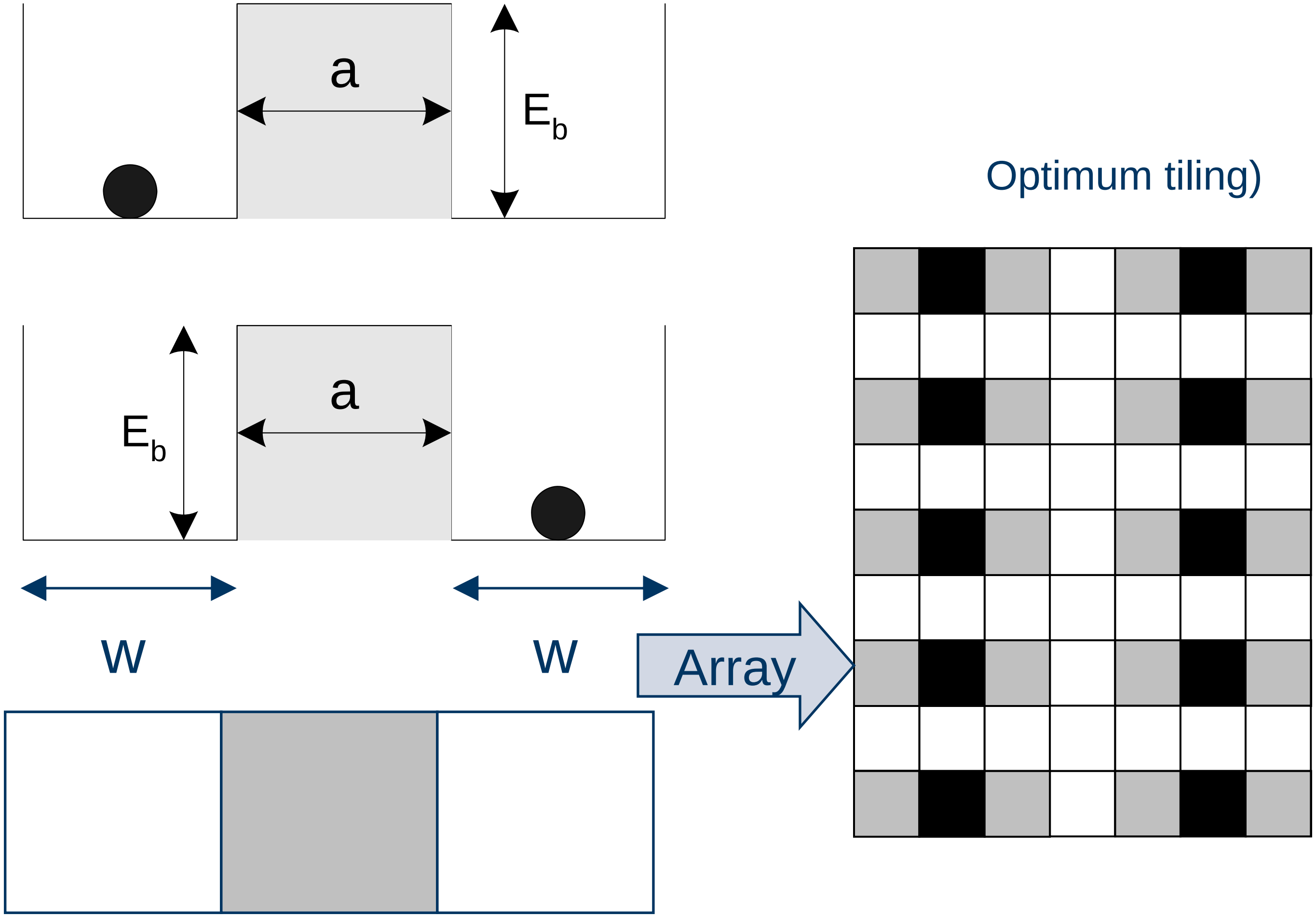
Source: Y. Taur and T. H. Ning
“Fundamentals of modern VLSI devices”
Cambridge university Press 1998

Resonant Tunnel Diode



R. Compano (Ed.)
Technology Roadmap for Nanoelectronics
(European Communities, 2001)

Two-well bit – **Universal Device Model**



Generic Floorplan
of a binary switch

Optimum tiling)

White spaces are required to provide
for isolation and interconnect

Device density

1) Upper Bound

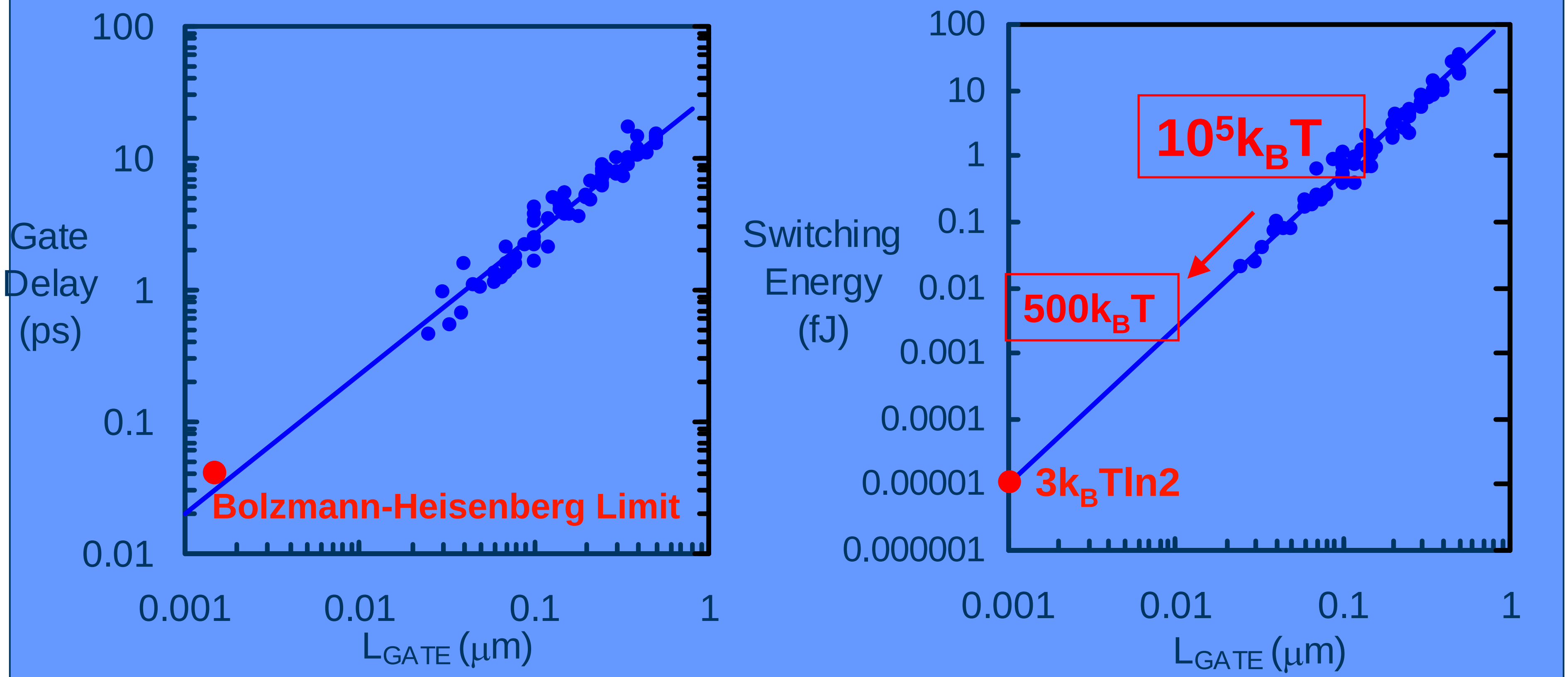
$$n_{\max} = \frac{1}{8a^2}$$

2) IC (ITRS)

$$n_{MPU} = \frac{1}{20a^2}$$

CMOS scaling on track to obtain physical limits for electron devices

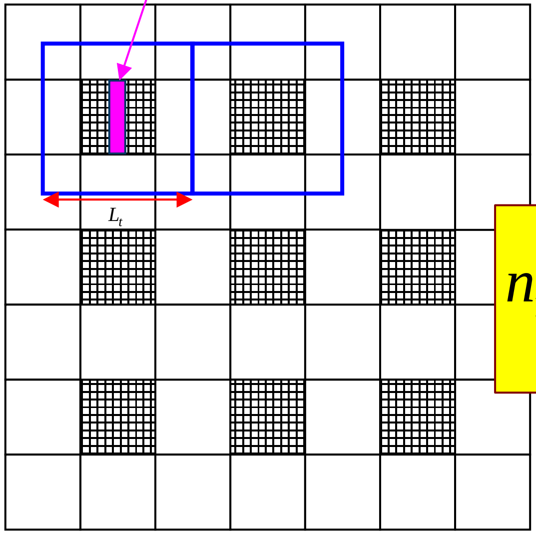
George Bourianoff / Intel



A Summary of ITRS Projections

	Energy	Size
Lower bound	$\sim k_B T$ $4\text{x}10^{-21}$ J/bit	~1 nm
Practical Limit	$\sim 500 k_B T$ $2\text{x}10^{-18}$ J/bit	~5 nm

NRI is looking for new radical solutions



$$n_{\max} \sim \frac{1}{20 L_g^{\,2}} \sim 10^{10}\, cm^{-2}$$

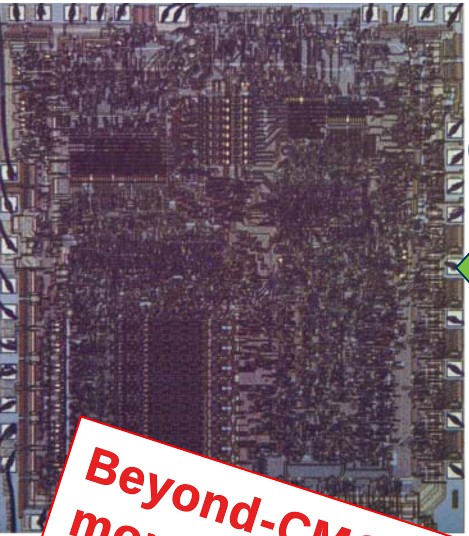
The effective dimension one transistor occupies on the MPU chip floorspace

Control Logic Unit for Autonomous Micro-Scale Systems

$$n_{\max} \sim \frac{1}{20L_g{}^2} \sim 10^{10}\,cm^{-2}$$

L_g~5nm!

$$N_{tr} = 10^{10} \cdot \left(10^{-3}\right)^2 = 10,000$$

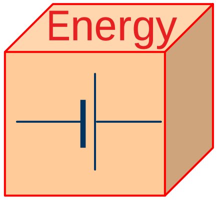


Intel 8080 (5000 trans)

Aggressive scaling is mandatory for µ-scale systems

In principle, the full MPU capabilities can be realized within 10um square if we can sustain scaling to ultimate CMOS (~5 nm gate lengths)

Beyond-CMOS devices for more functionality at less device count?



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

E_{bit}~$2x10^{-18}$ J/bit

Max number of binary transitions

~$5x10^{12}$

Complexity of Logic Unit

MAXIMUM

$$n_{\max} \sim \frac{1}{20 L_g^{\;2}} \sim 10^{10}\, cm^{-2}$$

L_g~5nm!

$$N_{tr} = 10^{10} \cdot \left(10^{-3}\right)^2 = 10{,}000$$

MINIMUM

Logic Unit must contain a minimum number of switches(e.g. transistors) if it is to do useful computation

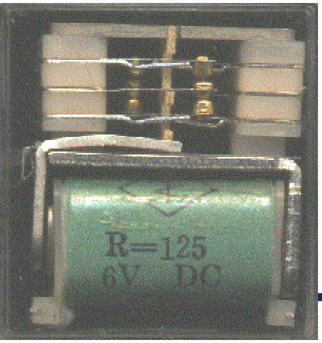
“*if one constructs the automaton (A) correctly, then any additional requirements about the automaton can be handled by sufficiently elaborated instructions. This is only true if A is sufficiently complicated, if it has reached a certain minimum of complexity”* (J. von Neumann)

If we consider a one-bit MPU as the minimum useful element, then the von Neumann threshold is ~150-200 switches

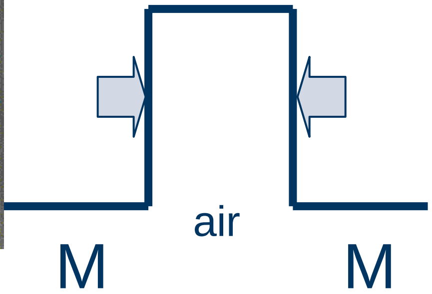
~100 ALU **~100 memory**

Unifying View on Switches and Sensors

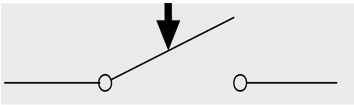
Sensors can be regarded as binary switches, whose barrier is deformed by different stimuli other than charge, e.g. *mechanical, optical, thermal, chemical*



Mechanical stimulus



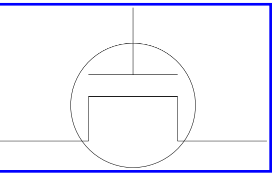
Electro-mechanical switch≈Pressure sensor

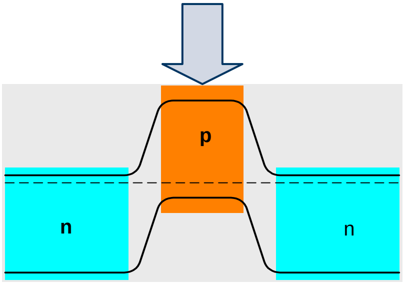


Min size ~ 5 nm

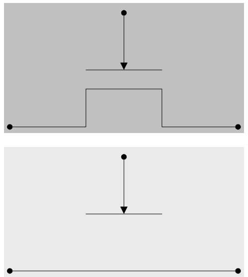
E_{bit}~10^{-18} *J/bit*

Electrical Stimulus





Transistor=Electronic Switch ≈Charge Sensor



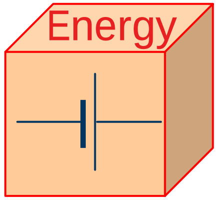
In principle, the sensor can be powered by the energy of the external stimulus

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

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
  - **Example:** Micro-palpation
    - High-resolution tactile imaging has many potential applications
    - Typical spatial resolution of tactile sensors> 1mm
    - We need resolution < 1μm with high sensitivity

Energetics of an Autonomous Micron-Scale System



TOTAL

Per Bit

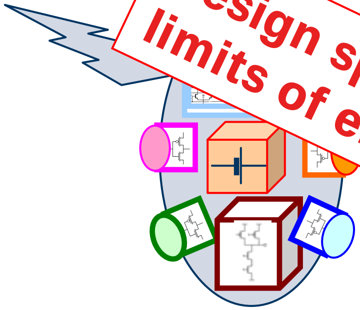
$E \sim (10^{-3} c$ [illegible] 10 [illegible] $\sim 10^{-5} J$

$E_{bit} \sim 500 k_B T$

2×10^{-18} *J/bit*

Alternative energy sources?

Design space is bounded by the limits of electrochemical sources



$$N = \frac{E_{total}}{E_{bit}} \sim$$

10^{12} equivalent binary transitions

Control Logic

~10^4 transistors

~5×10^{12} binary transitions

~10^{-18} J/bit

Communication

~4000 transmitted bits

~10^{-9} J/bit

Communication is costly

Sensing

Min size ~ 5 nm

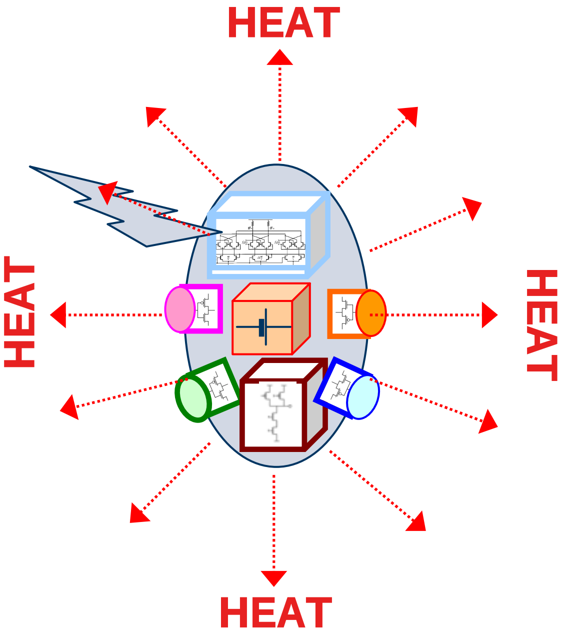
~10^{-18} J/bit

Size-Energy-Sensitivity tradeoffs?

Energetics of an Autonomous Micron-Scale System: Thermal Aspects

Heat will be produced as result of cell operation

Heat production rate is another design constraint



$$\dot{q} = \frac{P}{A} = \frac{E}{t \cdot A}$$

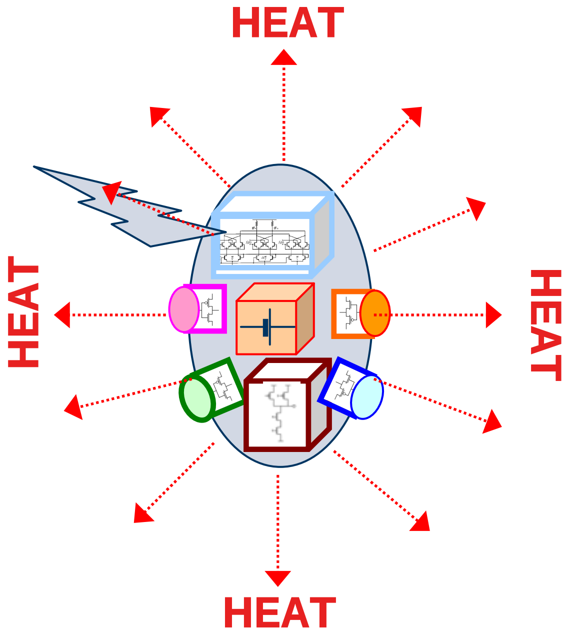
Surface Area
6x10µm x 10µm

Control Logic
~10^{-18} J/bit

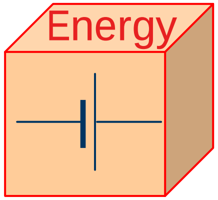
Communication
~10^{-9} J/bit

Sensing
~10^{-18} J/bit

Energetics of AMS: *THERMAL LIMITS*



How fast can we use stored energy?



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

$$\dot{q} = \frac{P}{A} = \frac{E}{t \cdot A}$$

P=3 nW

q=0.5 mW/cm^2

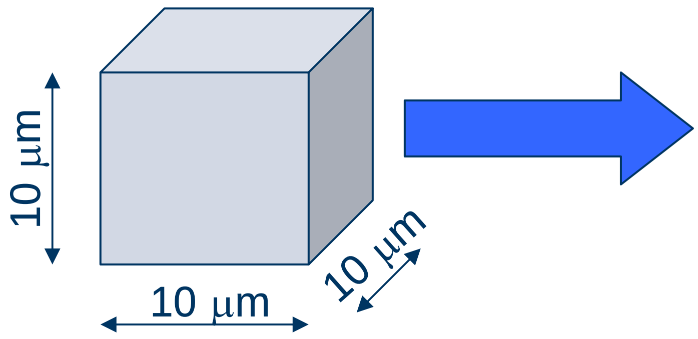
Surface Area

6x10μm x 10μm

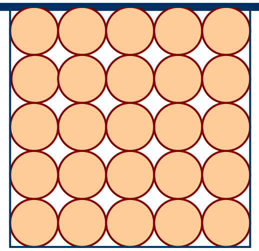
Suppose we want the microcell to function at least 1 h

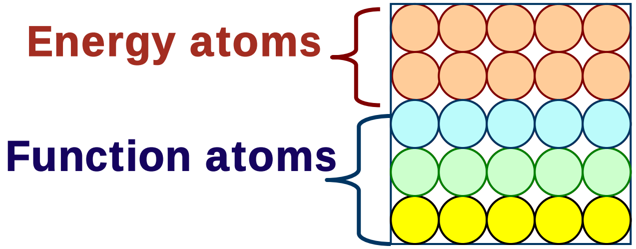
The projected heat production should be easily tolerated

Atomistic View of System Integration



5x10^{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	**Functional atoms/device**	**Energy atoms/bit**
Communication	>5x10^{9}	10^{9}
Logic	5x10^{9}	10
Sensing	5x10^{7}	<10

Summary: Extreme Microsystems

- Extremely-scaled CMOS technology should support computation and control for the ten micron cube
  - Beyond CMOS devices may offer more functionality at lower device count
- 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 electrochemical sources
  - Alternative energy sources should be investigated
- Communication energy/volume expenditures is most costly activity – should therefore maximize "system intelligence"
- Potential for arrays of nano-scale sensors needs further exploration