Exploring the Boundaries of Ultra-Low Power Design - Microscopic Wireless

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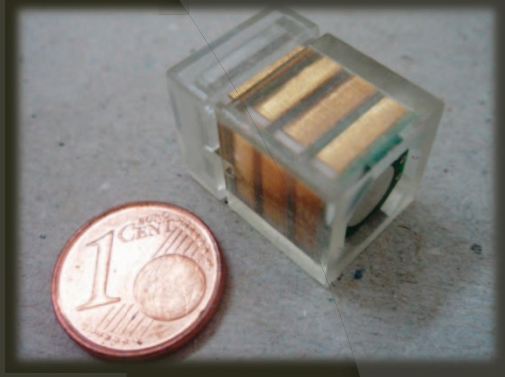
The Sensory Swarm

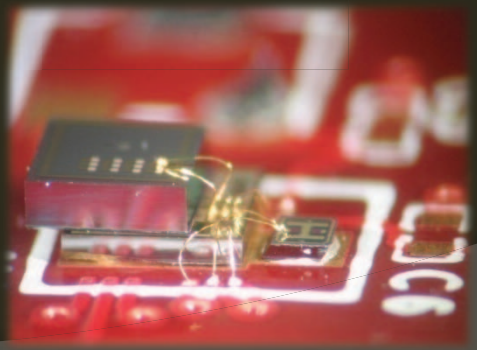
"Adding senses to the Internet"

Trillions of connected devices

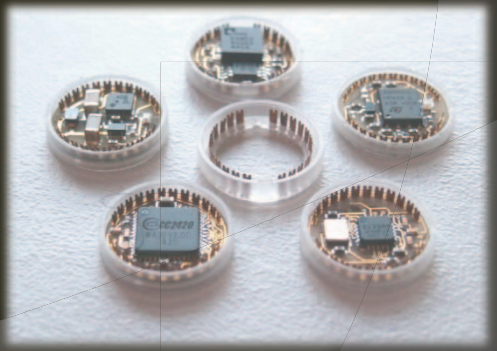


UCB PicoCube

The driver for Ultra-Low Energy design over past years



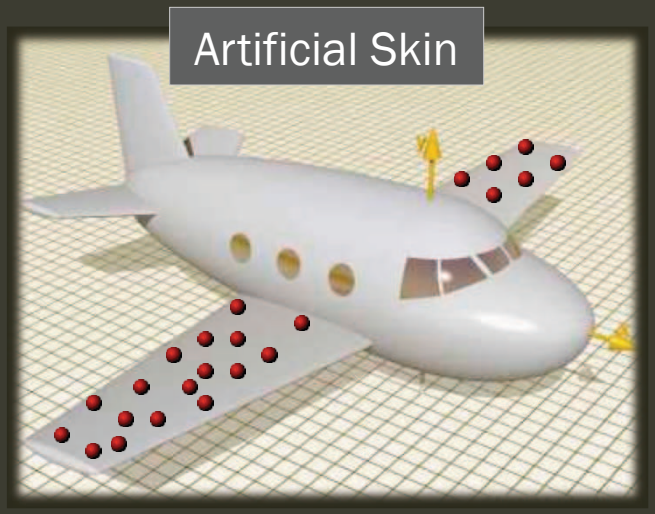
UCB mm^3 radio

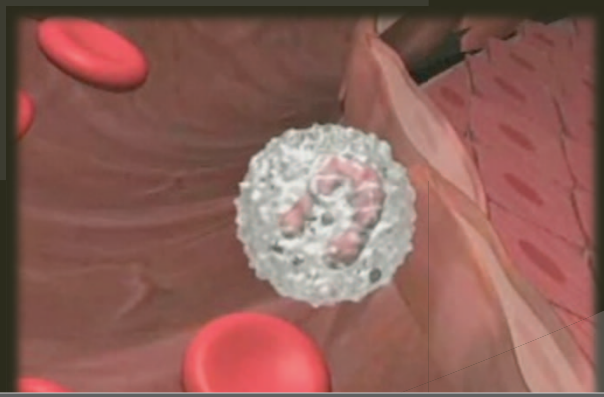


Philips Sand module

Yet … True Immersion Still Out of Reach

Microscopic Wireless: < mm^3, < 1 μW





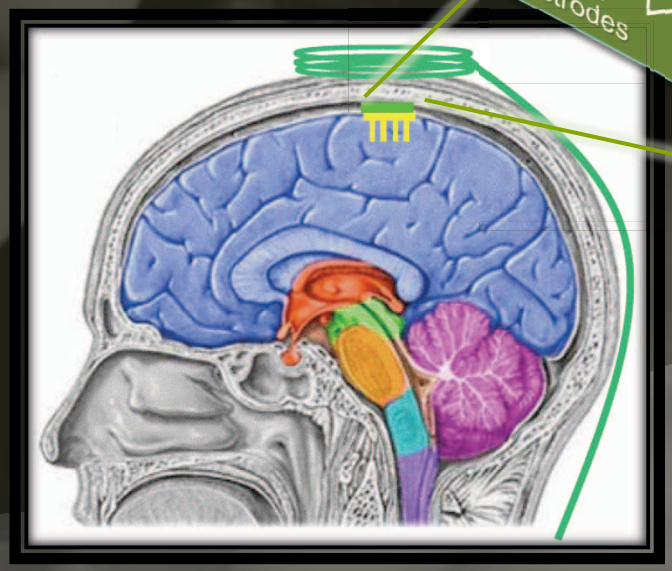
Another leap in size, cost and energy reduction

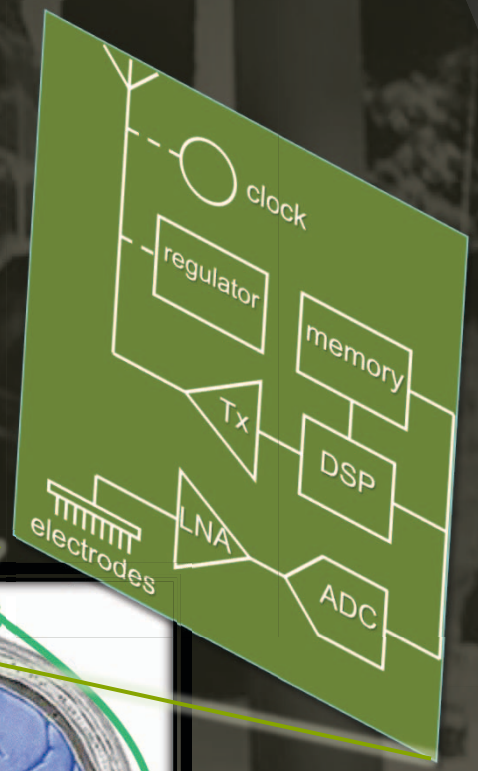
Example: Microscopic Wireless to Power Brain-Machine Interfaces (BMI)

The Age of Neuroscience

BMI – The Instrumentation of Neuroscience

- Learning about operation of the brain
- Enabling advanced prosthetics
- Enabling innovative human-machine interfaces



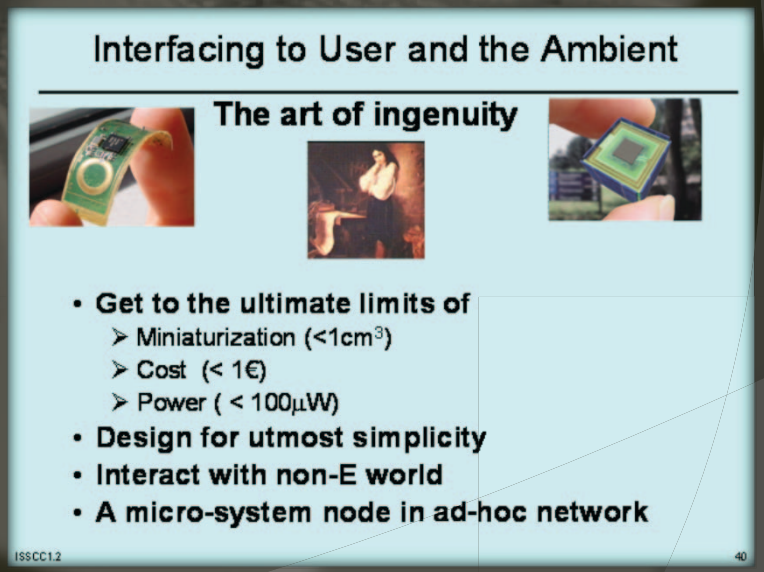


mm^3 nodes
remotely powered
uWs to 1 mW
power budget

Why Is This SO Interesting?

Microscopic wireless technologies to have profound impact on information processing and communication for decades to come.

- Traditional scaling rules to have minor impact
- Scaling is in the number of components, not in the transistor sizes
- A path to “More Than Moore” or “Beyond Moore”



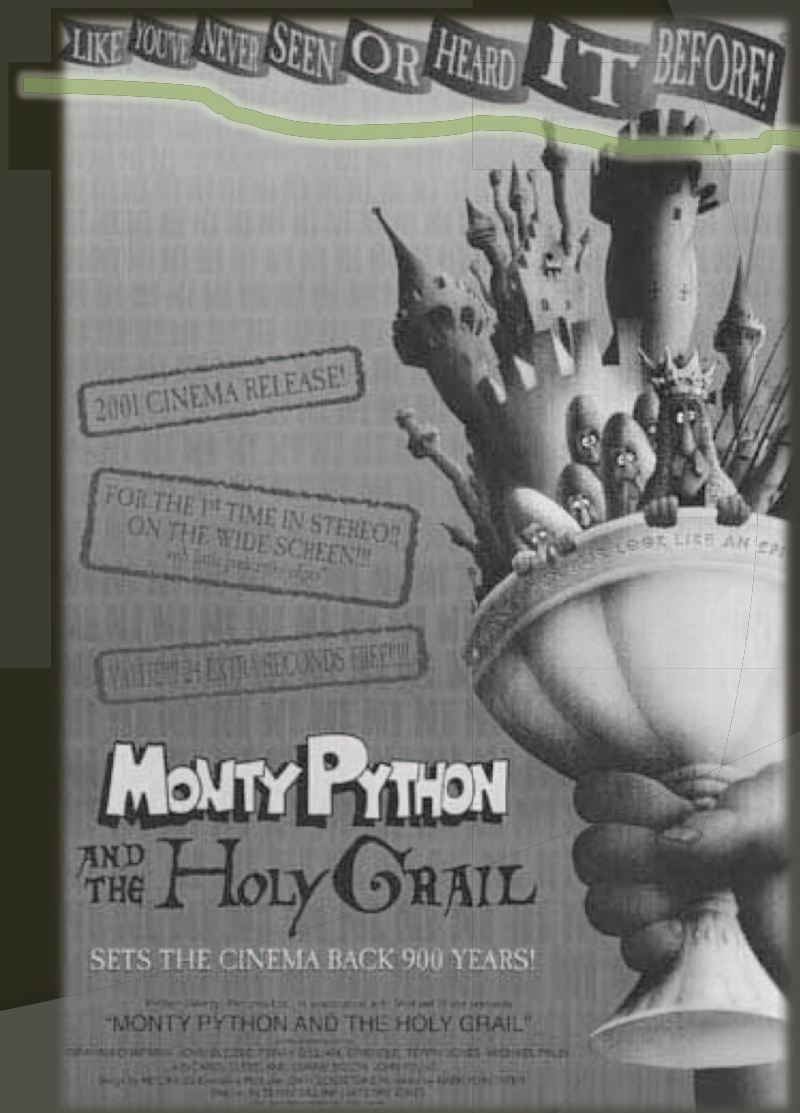
[H. De Man, Keynote Address, ISSCC 2005]

The Holy Grail: Reducing the Energy/Operation

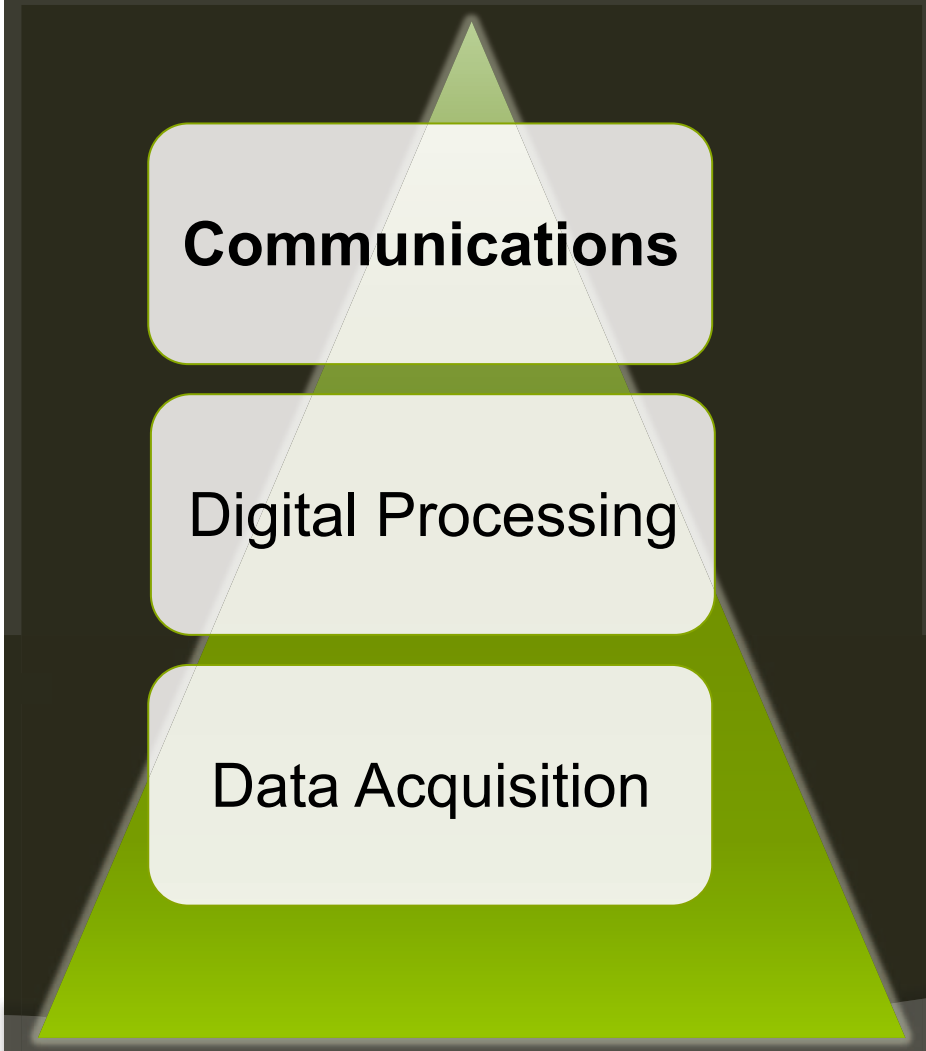
Communication

Digital Processing

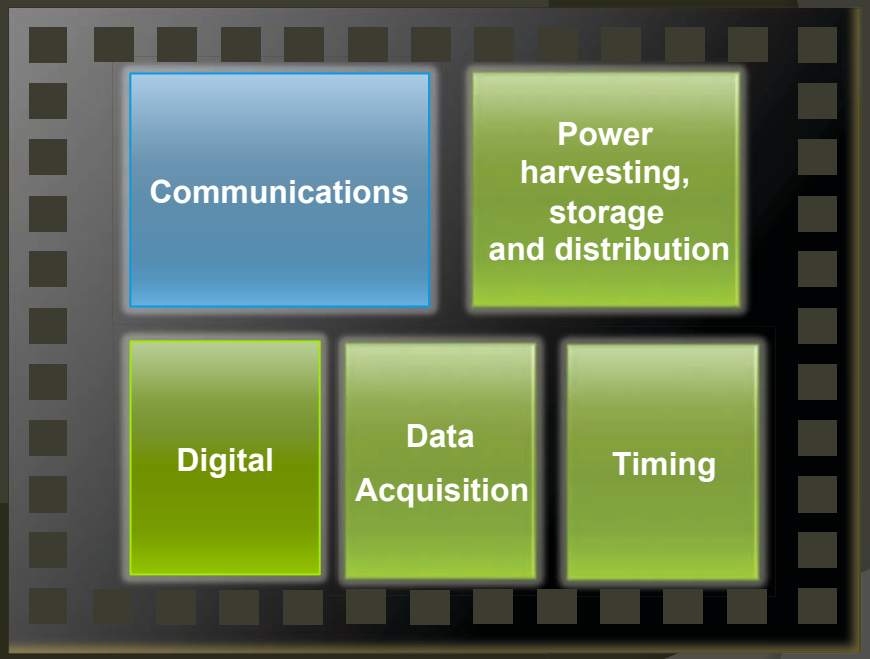
Data Acquisition



The Holy Grail: Reducing the Energy/Operation



Wireless communication dominant factor

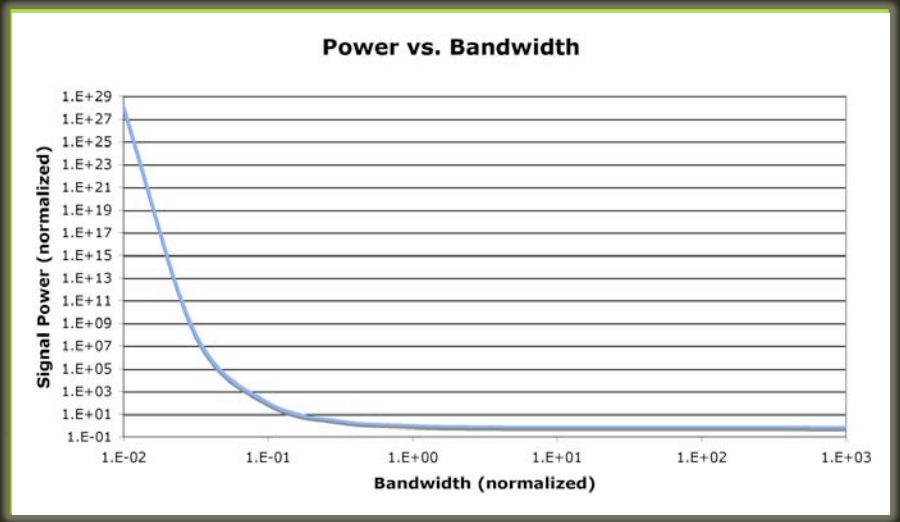


Primary Challenge:
Improving TX Efficiency & Combatting Overhead

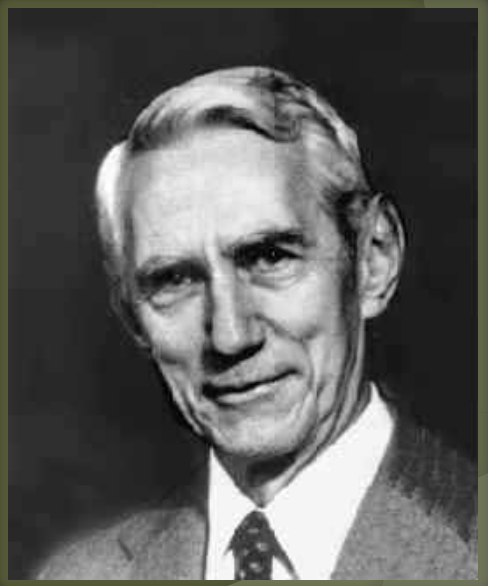
Short Distance Wireless Communication

The Achievable Bounds are well Known

Ideal link: Modulation achieves Shannon capacity,
noiseless zero power RX, ideal TX (100% efficiency).



Minimum energy/bit (infinite bandwidth) =
kTln2 x Link Budget



Claude Shannon

Works well for long distance links, somewhat irrelevant for short distances

Short Distance Wireless Communication

The Reality – State of the Art

☐ = (ideal energy/bit) / (actual energy/bit)

Example1: [Chee06 TX, Pletcher 08 RX] Low sensitivity ULP receiver

= (Link margin * kT ln 2) / ((P_{Tx} + P_{Rx}) / R)

= (72db * 2.9e-21) / (1.05mW/100e3)

= -53.6 dB

Example2: [Chee06 TX, Otis 05 RX] High sensitivity Low-rate receiver

= (Link margin * kT ln 2) / ((P_{Tx} + P_{Rx}) / R)

= (100db * 2.9e-21) / (1.55mW/5e3)

= -40.3 dB (10 m link)

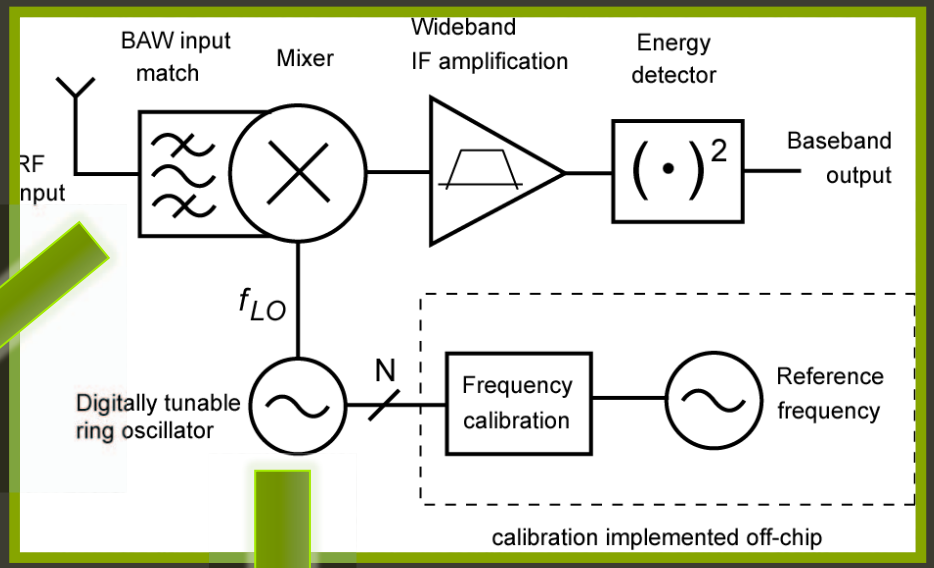
Transmitter inefficiency and receiver overhead dominate

Observe: This assumes perfect synchronization between TX and RX
This is far from the case in typical sensor applications

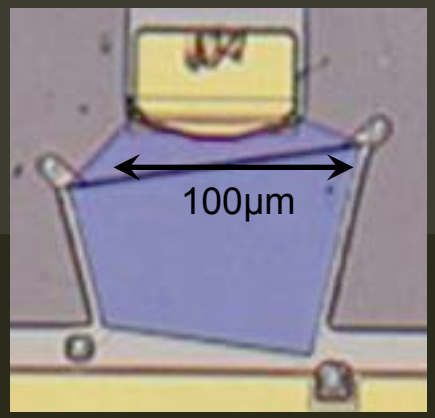
[After analysis by B. Cook, PhD, UCB]

Creativity: Combining passive components with technology scaling

Example:
50 μW 100 kbit/sec receiver

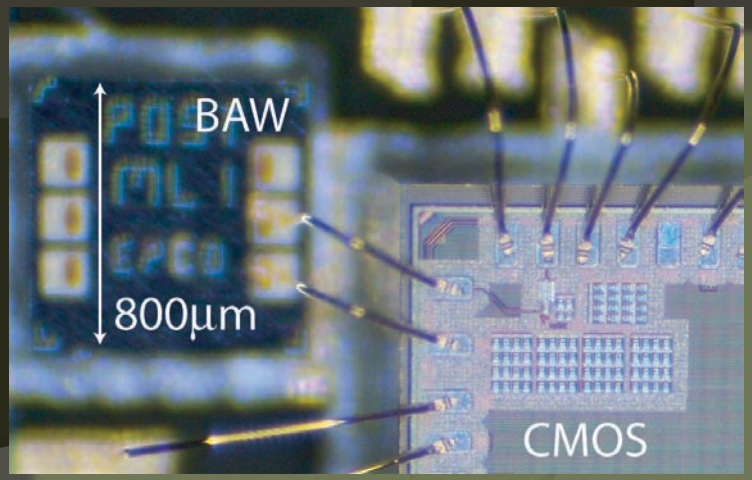


0.5V VDD
-72 dBm sensitivity



Enables usage of inaccurate ring oscillator as mixer (scales with technology)

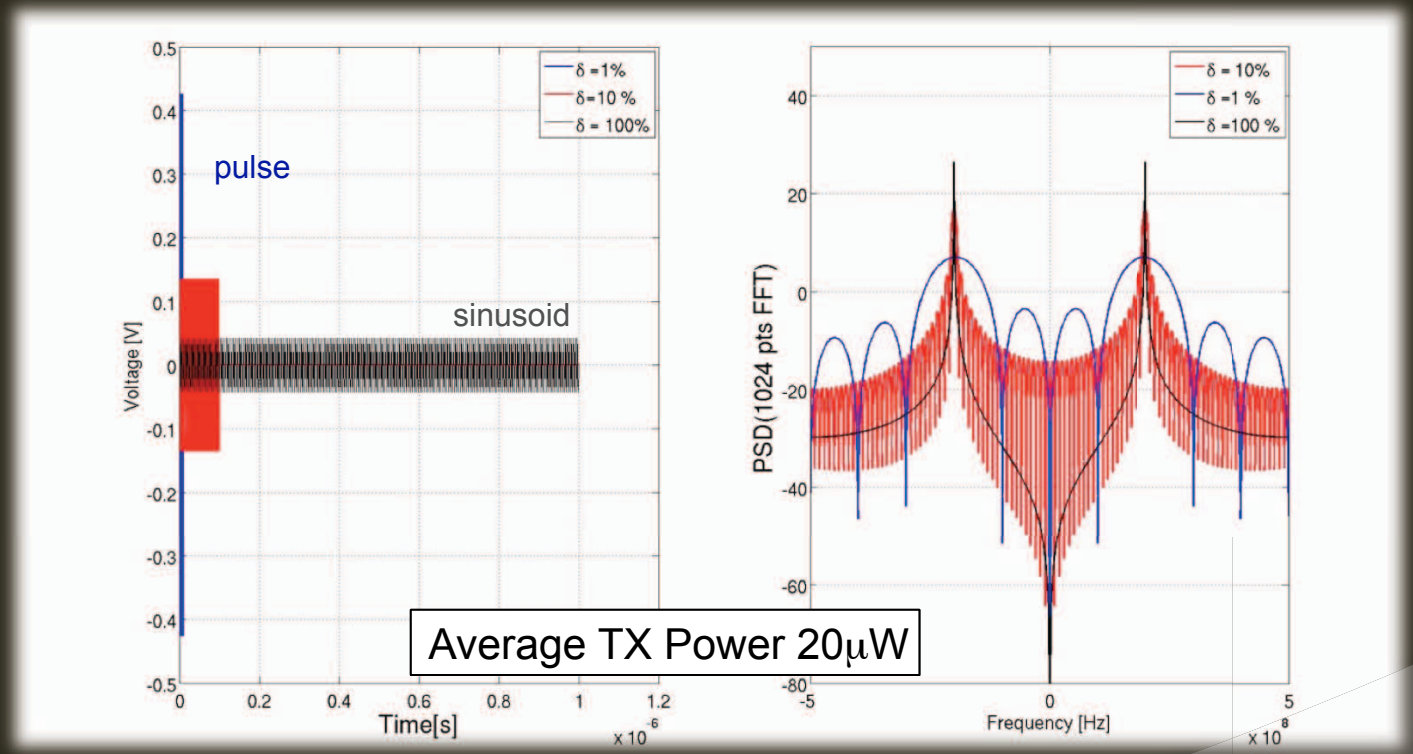
BAW resonator (FBAR) provides frequency selectivity



[N. Pletcher, ISSCC'08]

The Opportunity

- Sensing applications are largely asymmetrical
  - Tx is what matters!

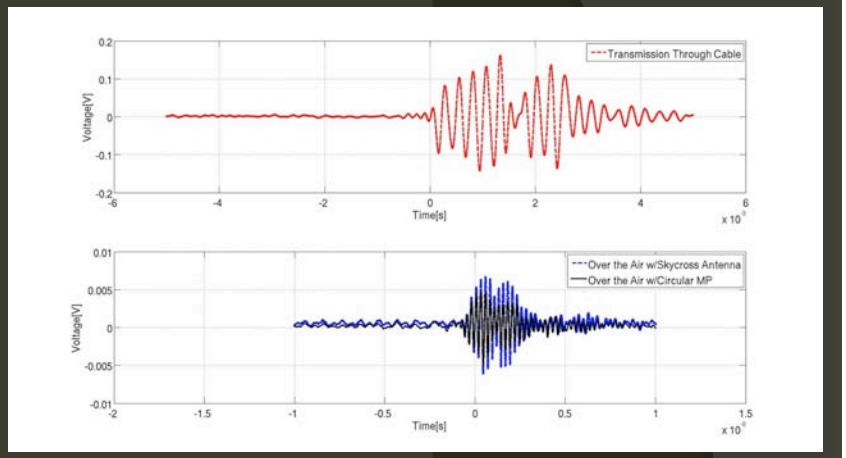


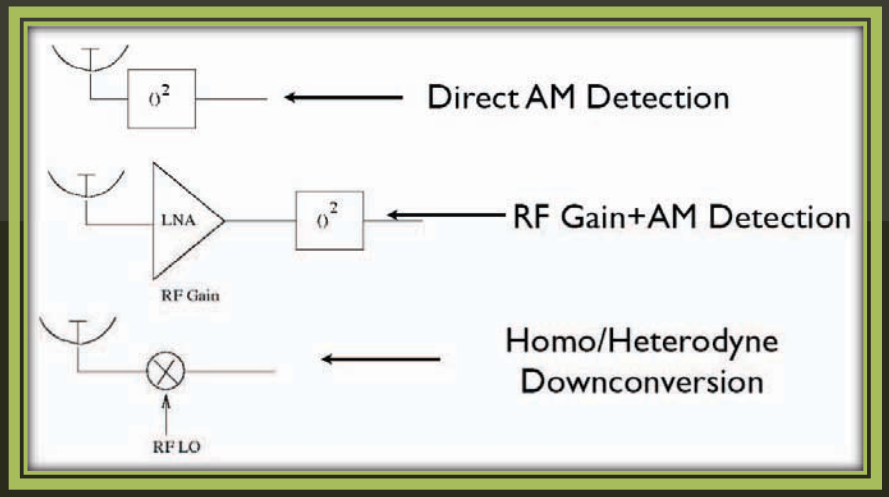
The Lure of Pulse-Based Communications:
Higher TX efficiency + Duty Cycling

[Courtesy: S. Gambini, UCB]

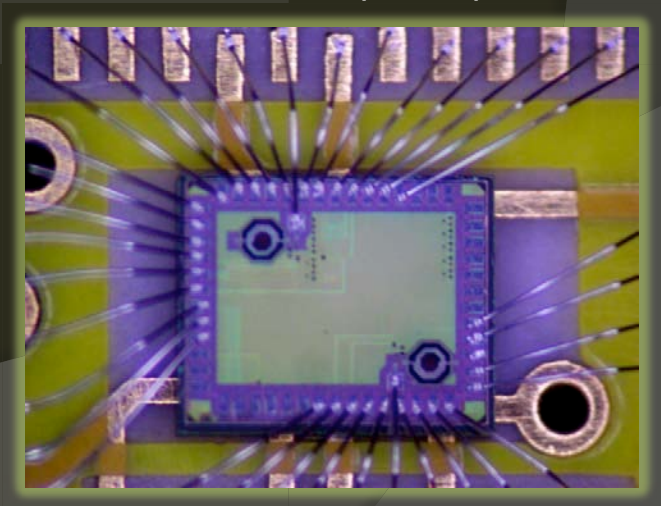
Pulse-Based Communication

- Highly efficient transmitter – reduced overhead
- Energy efficiency set by timing accuracy - improved by technology scaling
- Make receiver chain as simple as possible – augment using digital tuning





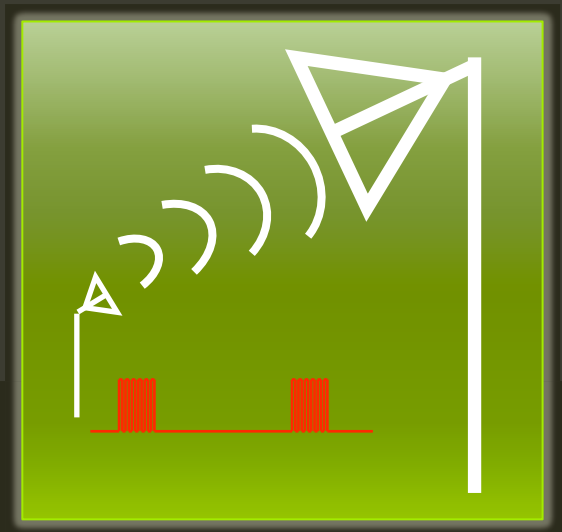
1 Mbit/sec
1-5 cm distance
6 GHz carrier
25pJ/100pJ TX/RX



Revisiting the Opportunity

- Most sensing applications are asymmetrical
  - Tx is what matters!

Pulse-Based TX



Scales with technology
Ideal duty cycling
Needs power source

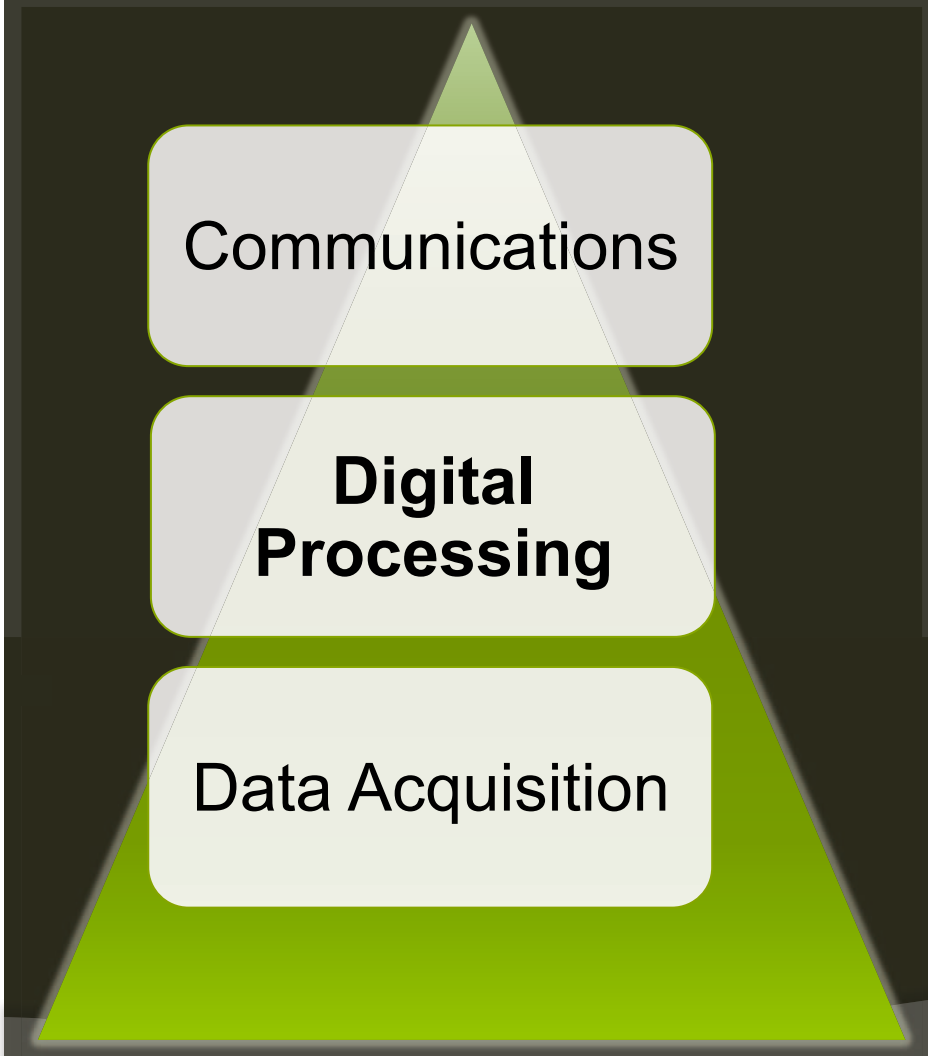
Reflective (RFID)

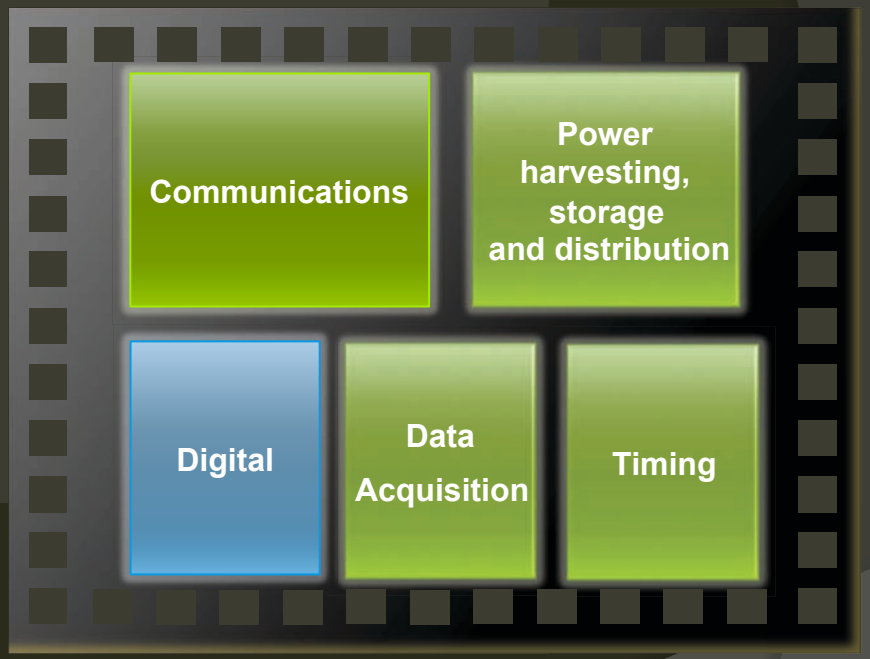
Zero-power
Very low sensitivity
Low data rates

Reflective Impulse

Best of both worlds

The Holy Grail: Reducing the Energy/Operation





Primary Challenge:
Improving TX Efficiency & Combatting Overhead

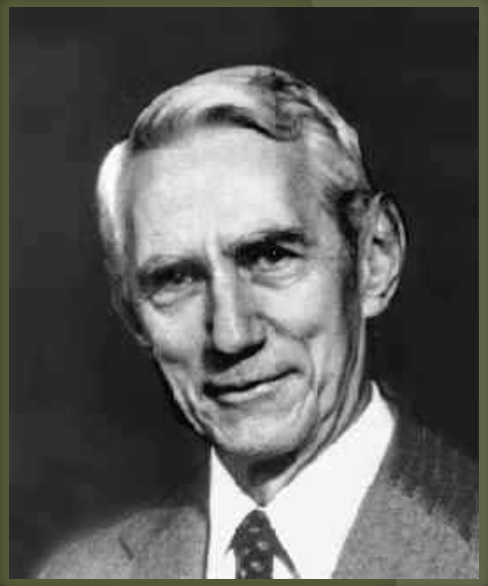
Energy Limits in Digital

John Von Neumann

Shannon-Von Neumann-Landauer Bound:

Minimum energy/ operation = kTln(2)

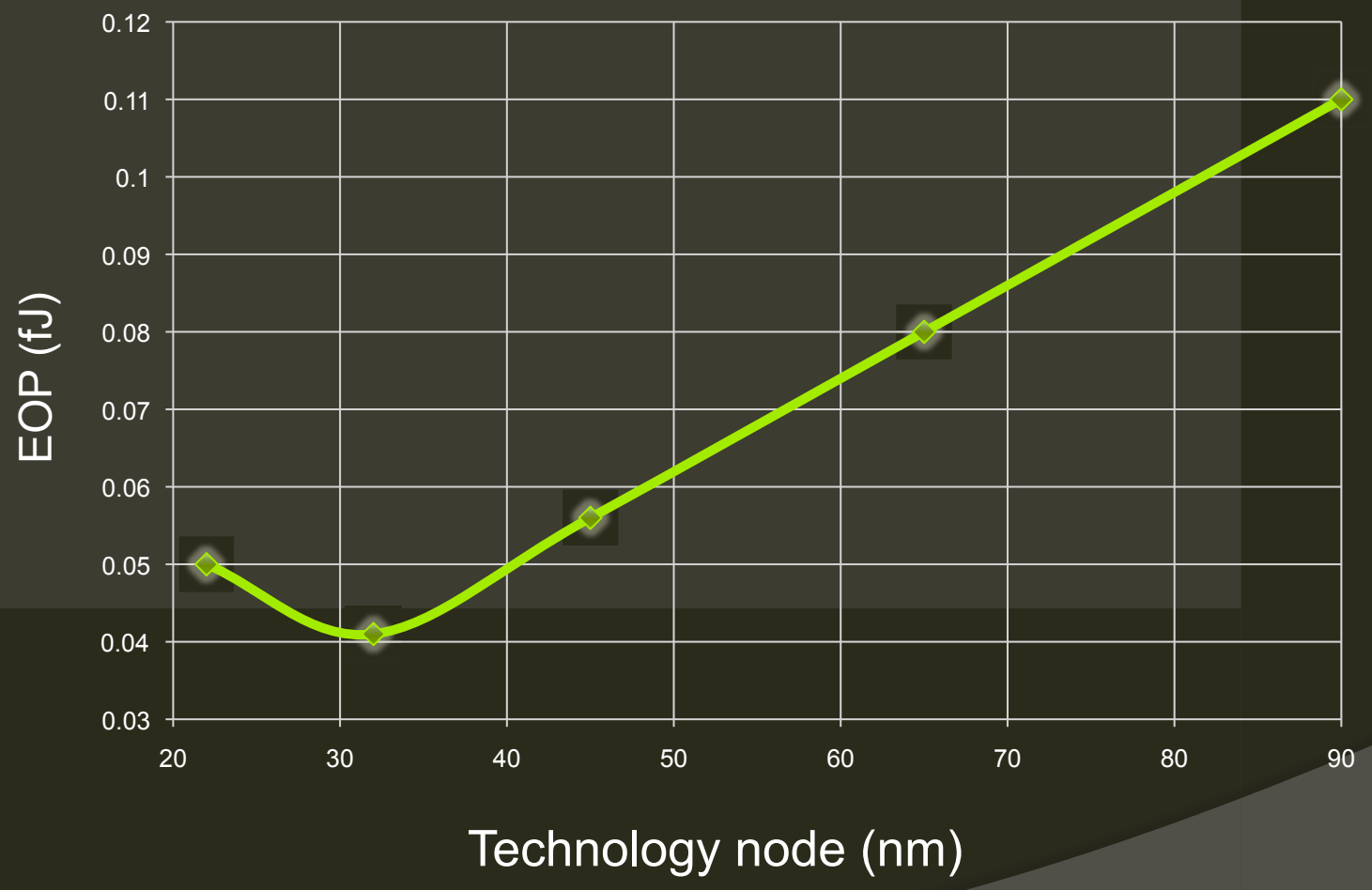
= **4.10^{-21}J/bit** at room temperature



Claude Shannon

More than 4 orders of magnitude below current practice (65 nm at 1V)

Technology Scaling Not the Solution

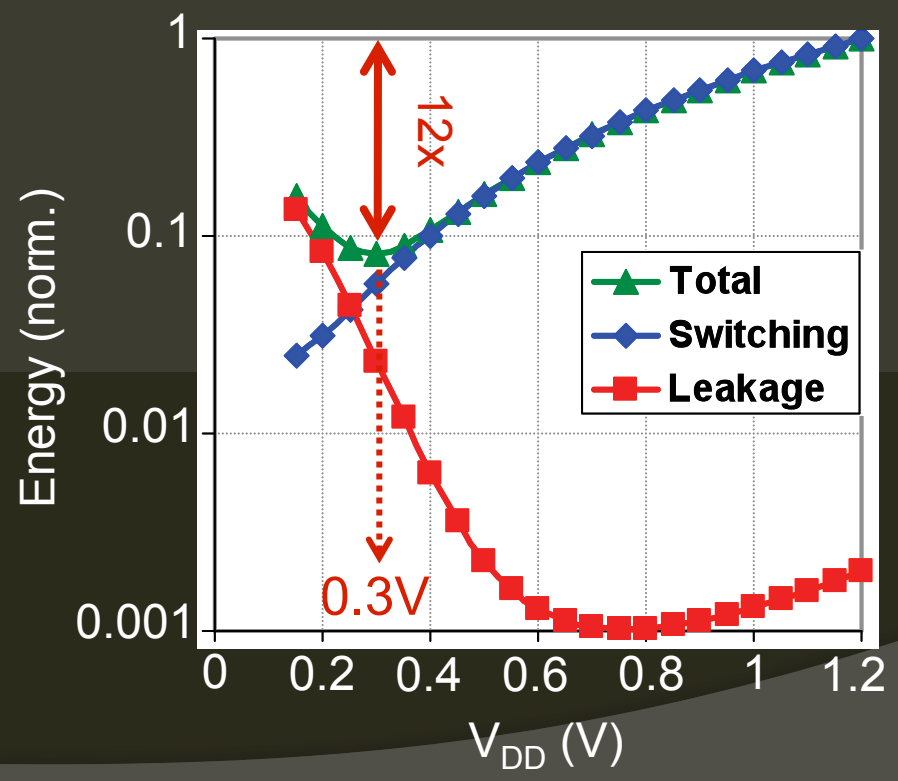


[Based on actual and predictive models]

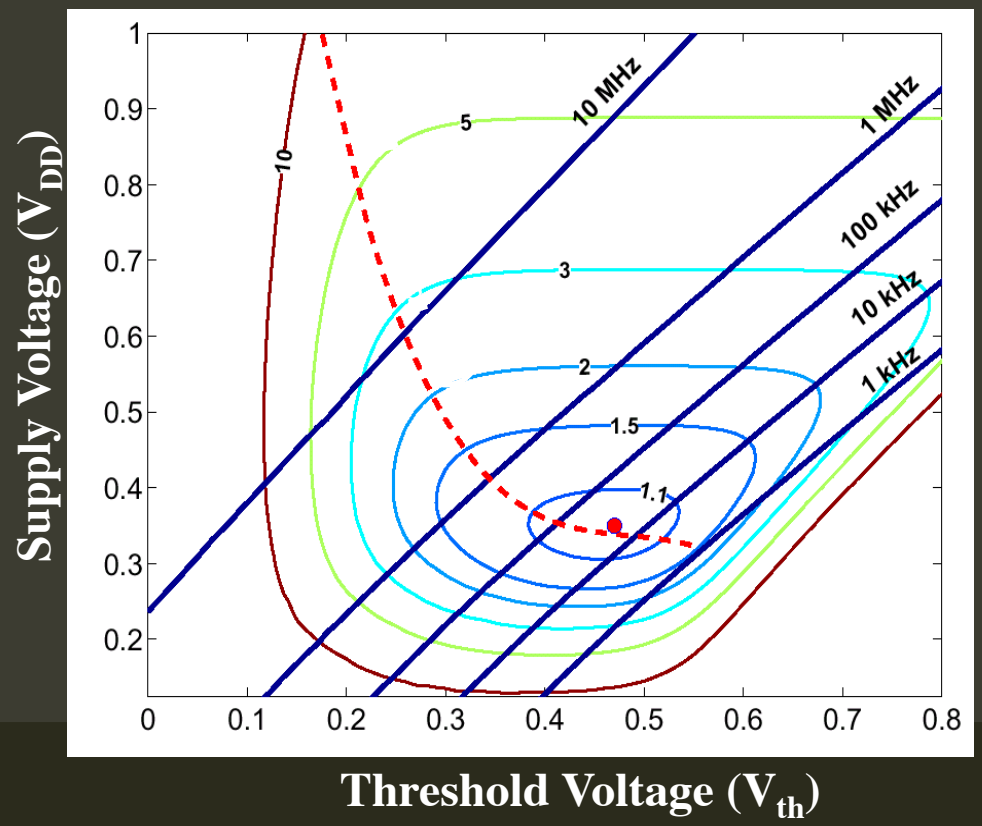
Lowering Supply Voltage Only Option

(recoup performance through parallelism)

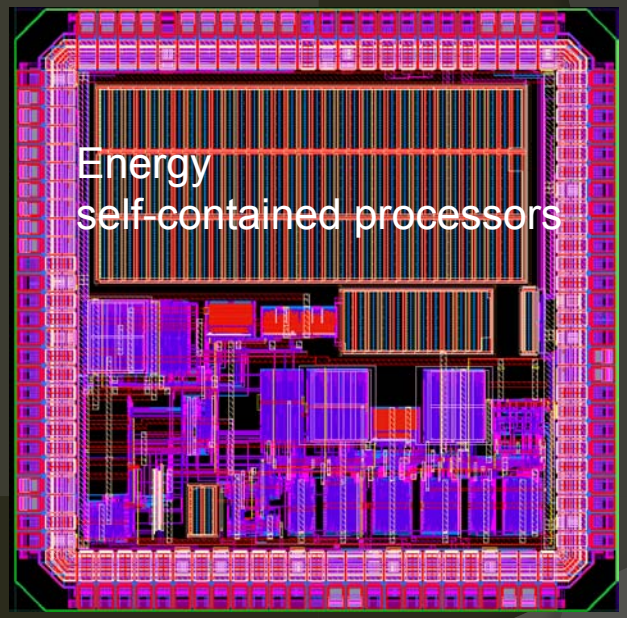
BUT: CMOS Has Minimum Energy Point Set by Leakage



Sub-Threshold Operation Leads to Minimum Energy/Operation



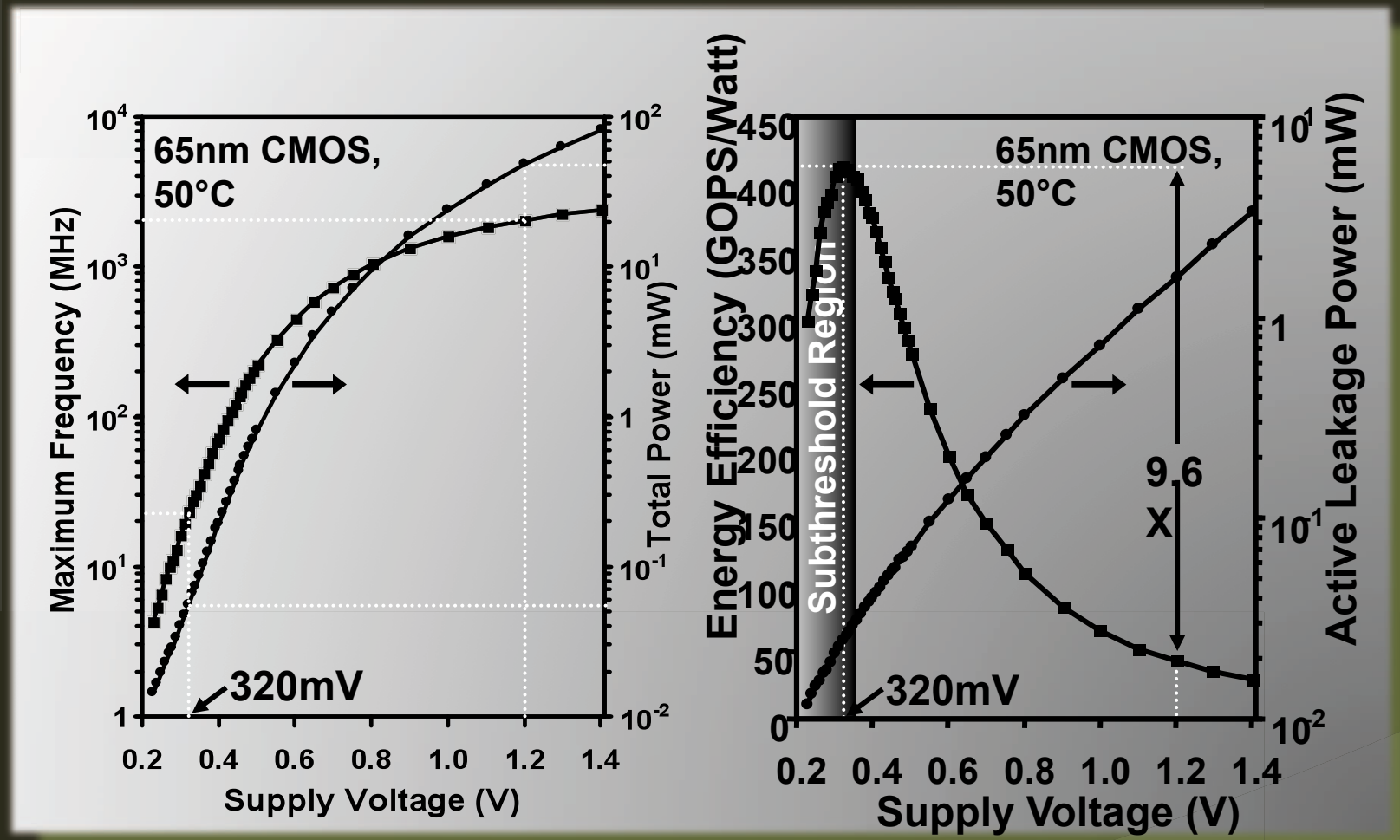
Energy-Aware FFT Processor
[Chang, Chandrakasan, 2004]



Subliminal μprocessor for retinal implants
3 pJ/inst @ 350 mV
[Blaauw, VLSI'07]

But at a huge cost in performance and variability

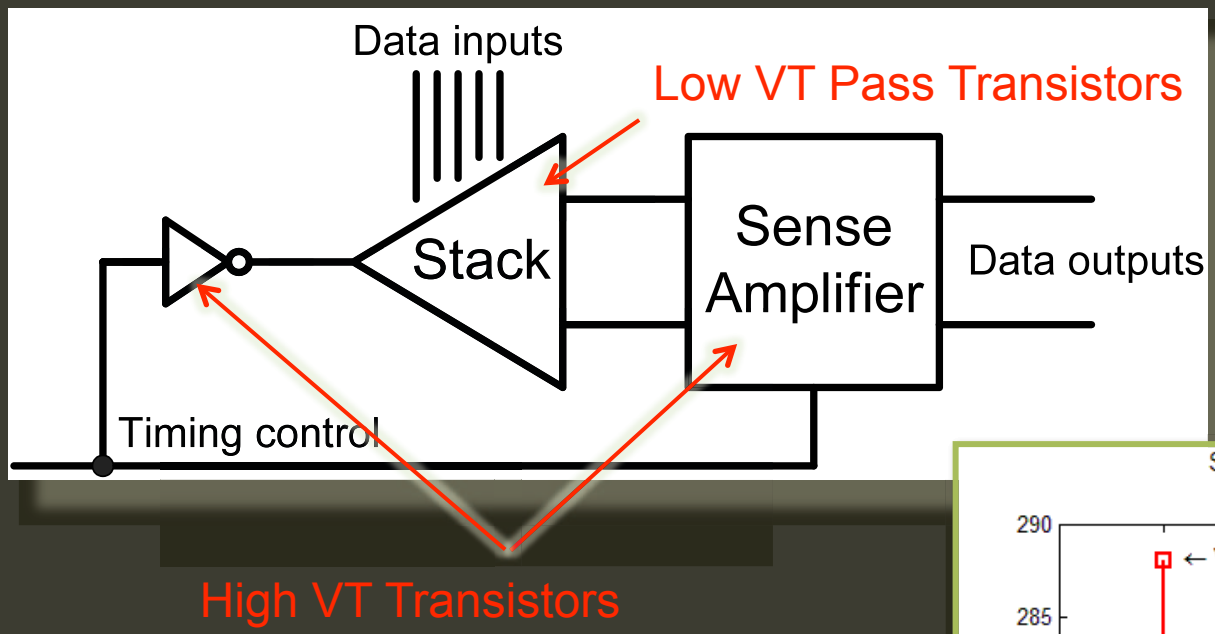
Back off a Little: Design in the VTH + ΔV Space



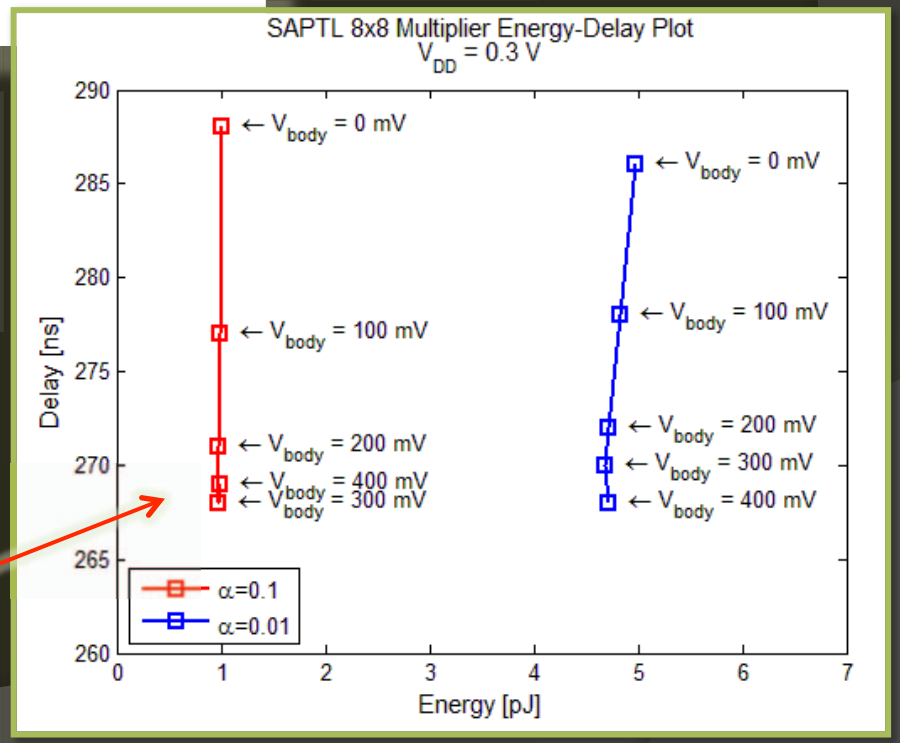
[H. Kaul et al, ISSCC08]

Challenges: Modeling, Variability

Leakage-Insensitive Logic?



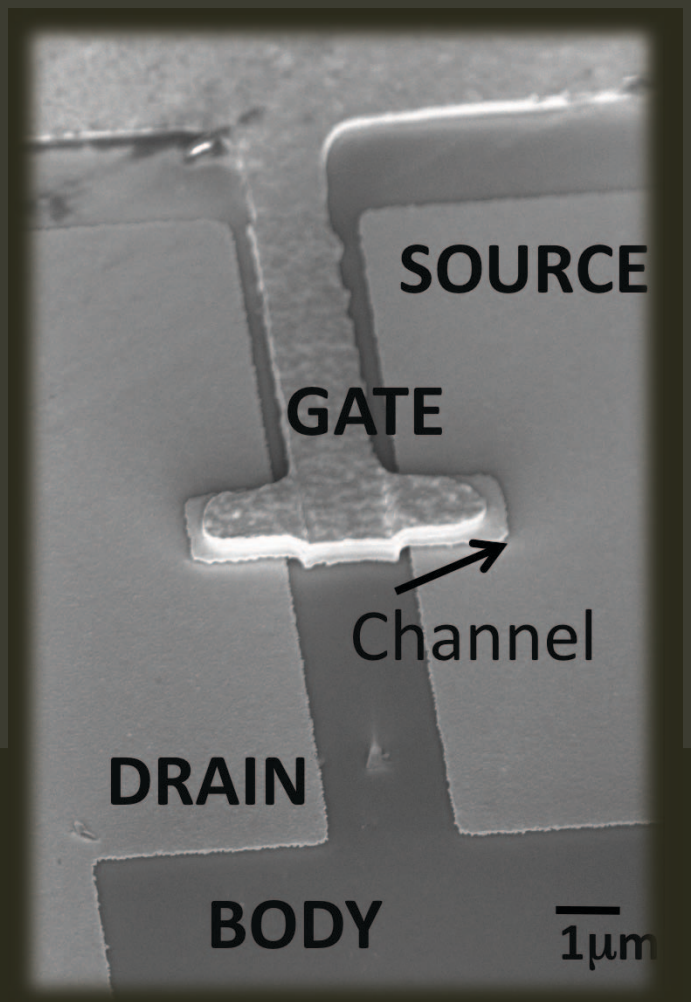
SAPTL
[Alarcon, 07]



Logic: Moderate Inversion
Driver and SA: Subthreshold

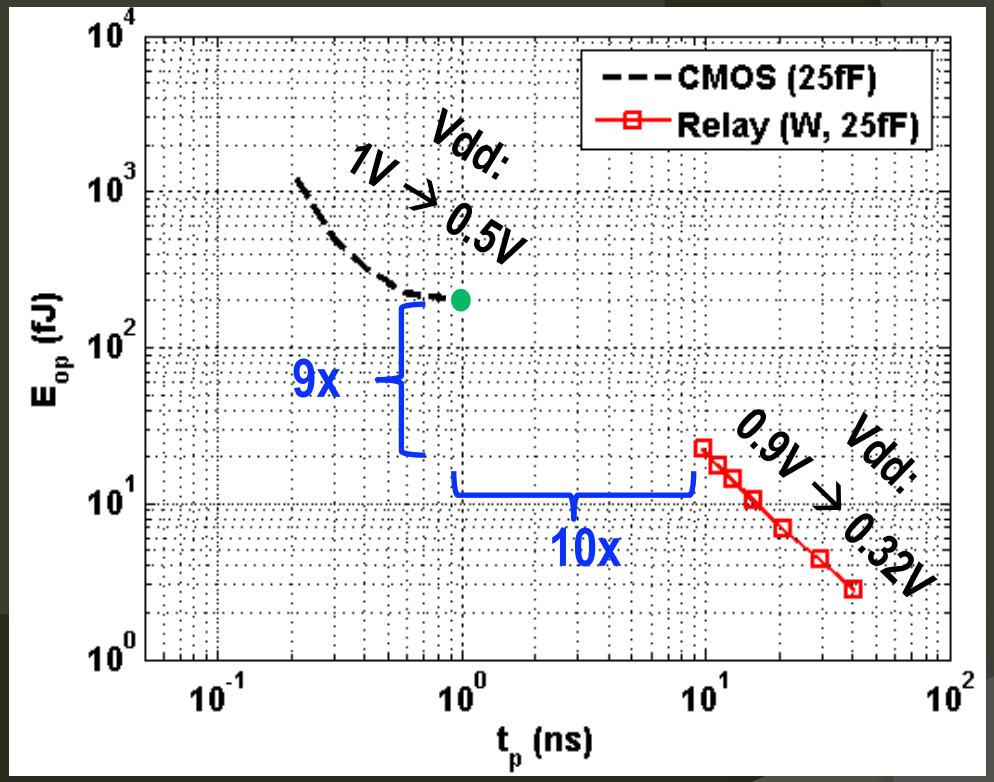
Minimal impact on leakage when reducing VTH

How About Mechanical Computing?



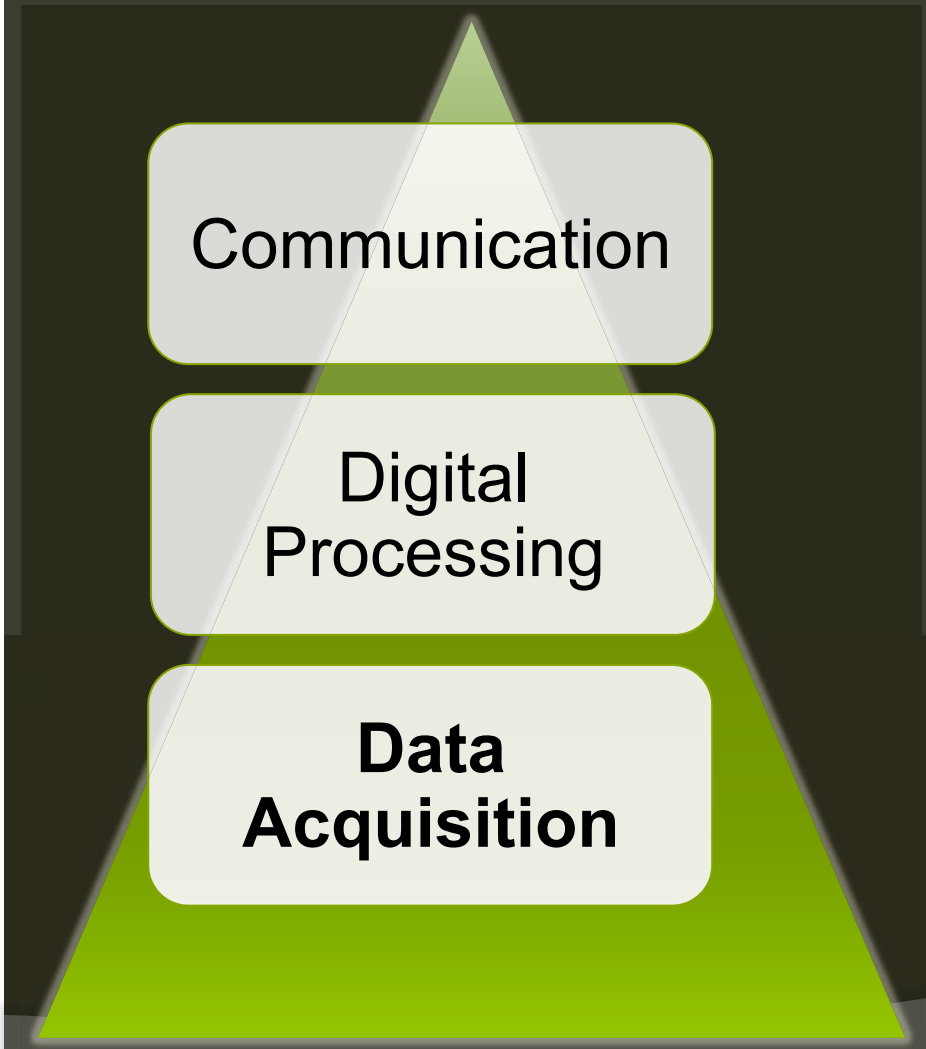
NEMS Relay

Energy/op vs. Delay/op across V_{dd}

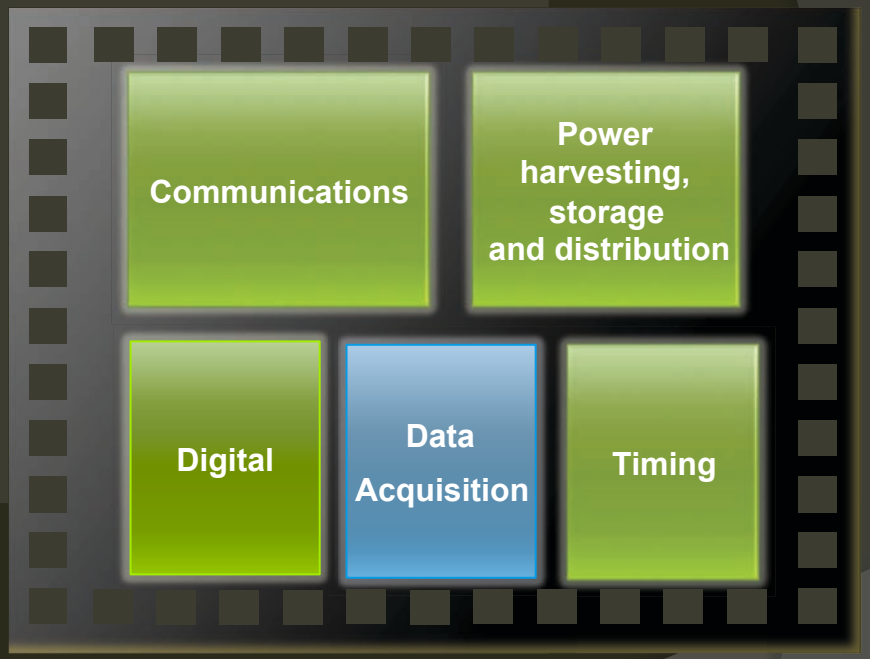


[Courtesy: TJ King, E. Alon, UCB]

The Holy Grail: Reducing the Energy/Operation



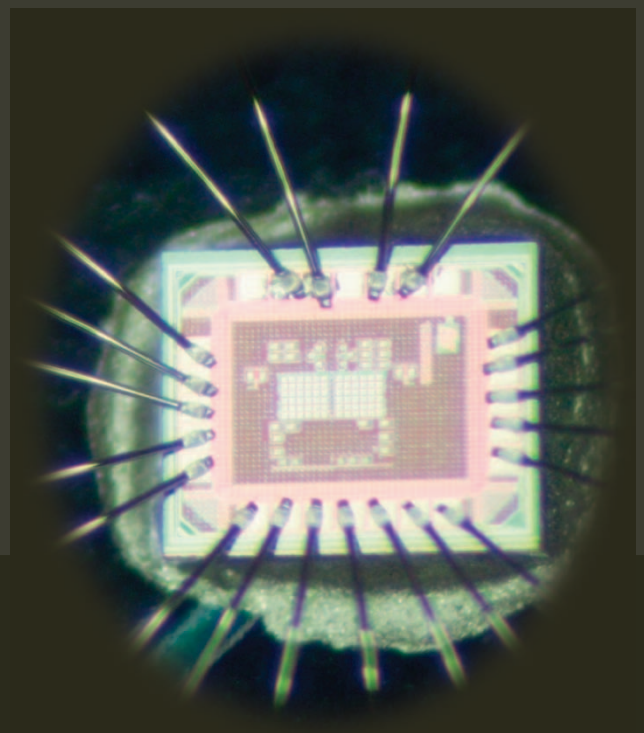
Microscopic Systems need more than digital



Challenge:
Even harder to scale voltage

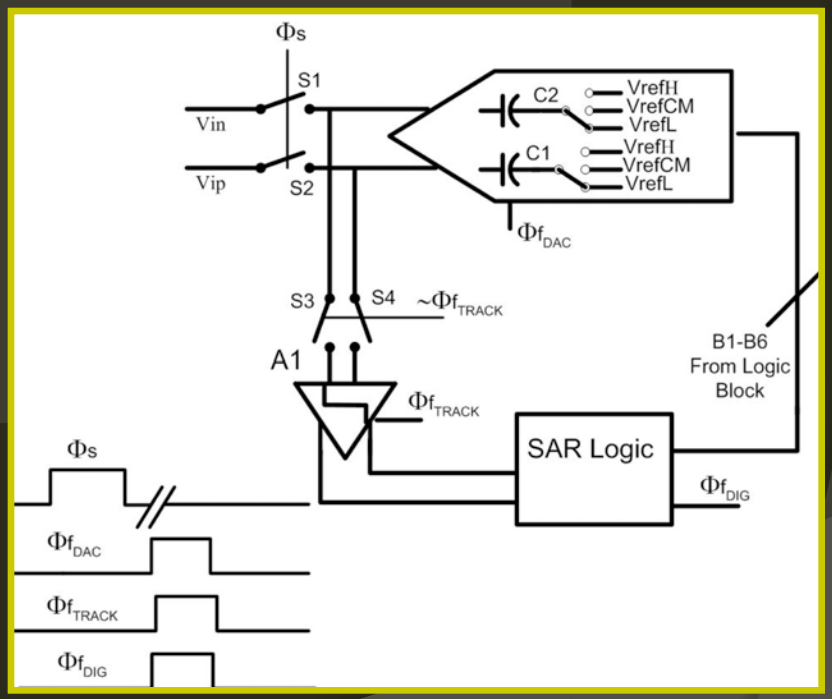
The Limits of Low-Voltage Signal Conversion

Voltage reduction limited by noise (high accuracy) or matching considerations (low accuracy)



14 μW 0.5 V 1.5 MS/s 6 bit SAR
120 fJ / Conversion Step

[S. Gambini, '07]

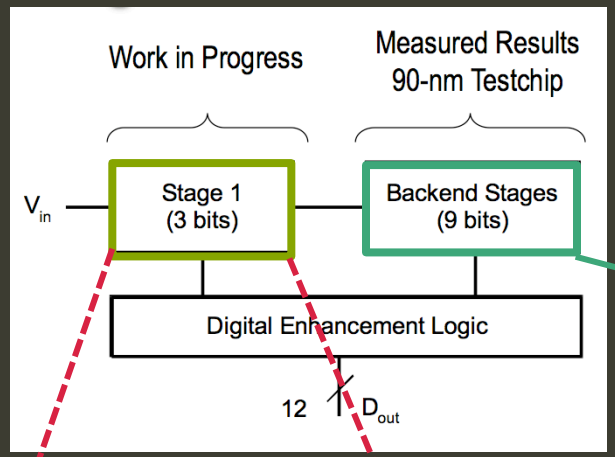


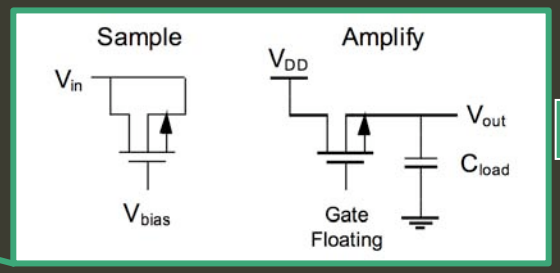
Innovative architectures explore minimization of "active analog"

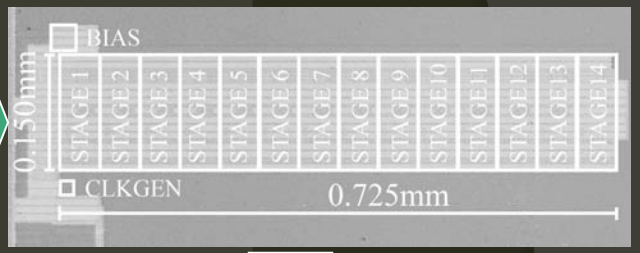
Mostly Digital ADC's

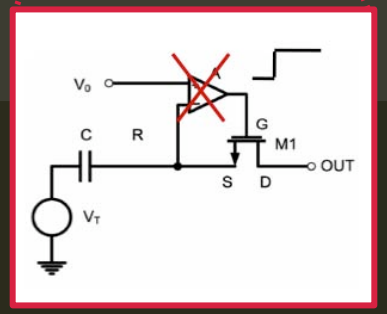
Example: Pipelined converter

On track to 20 fJ/conversion step

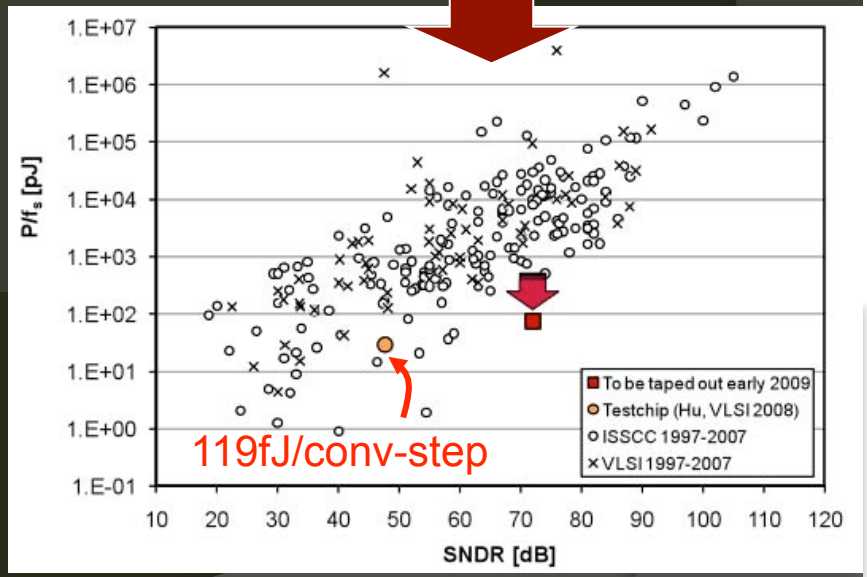








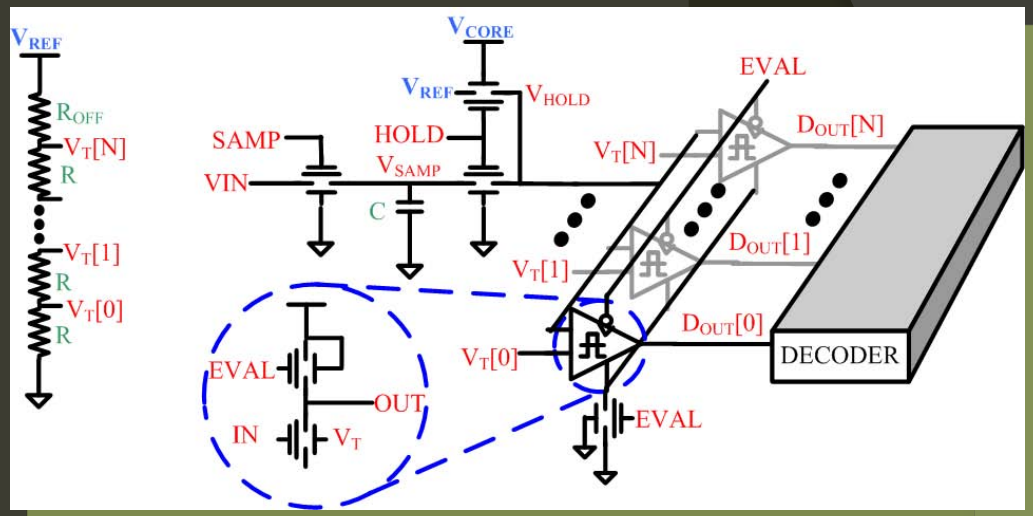
Charged-based bucket brigade pipeline *without* usual gain-boost amp, *with* new digital correction

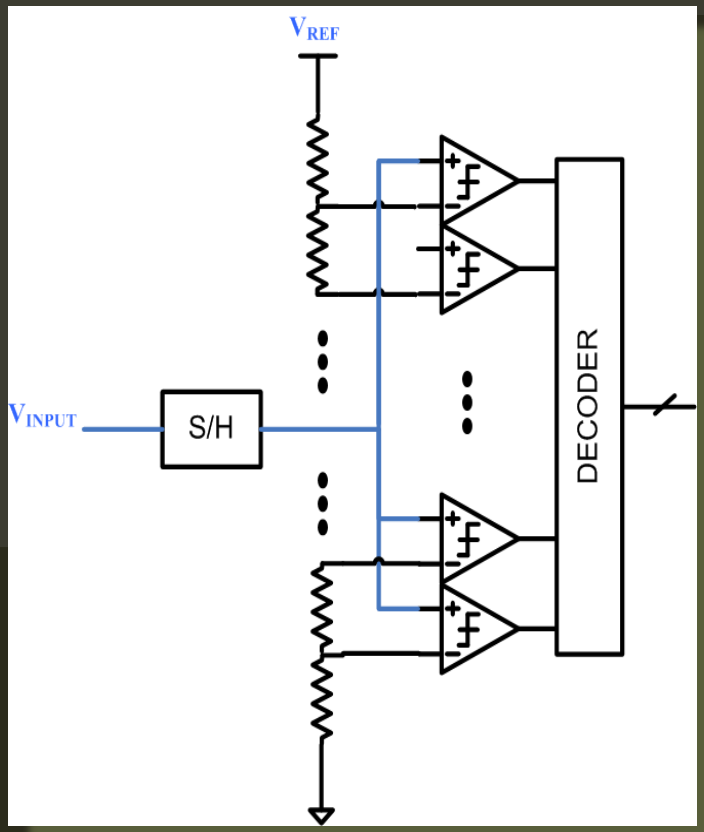


[Courtesy: B. Murmann, Stanford]

Avoiding Transistors Altogether?

Revisiting the NEMS Relay





Flash Analog-Digital Converter

V_{core} = 0.3V

C = 500fF

R = 4kΩ

V_{REF} = 1V

f_{samp} = 10 MS/s

6-bit res: 5.5fJ/conv

[Courtesy: E. Alon '09]

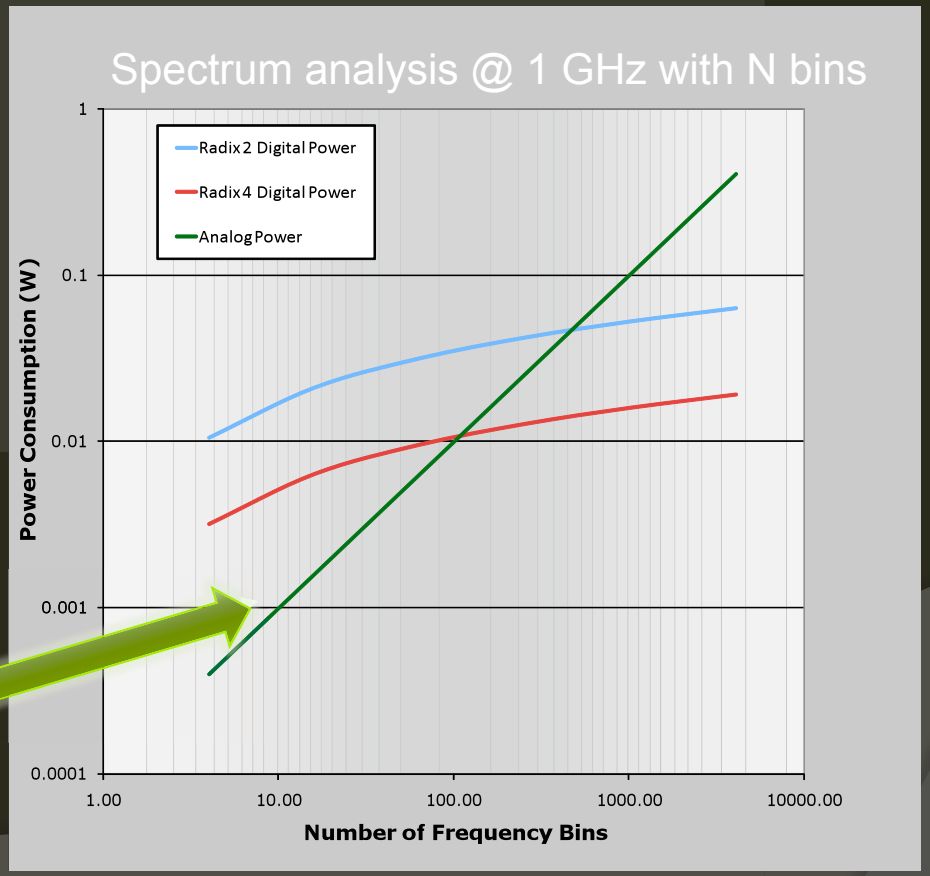
How about a NEMS Spectrum Analyzer?

60 MHz
Q = 48,000

1.2 GHz
Q = 14,600

1.5 GHz
Q = 11,555

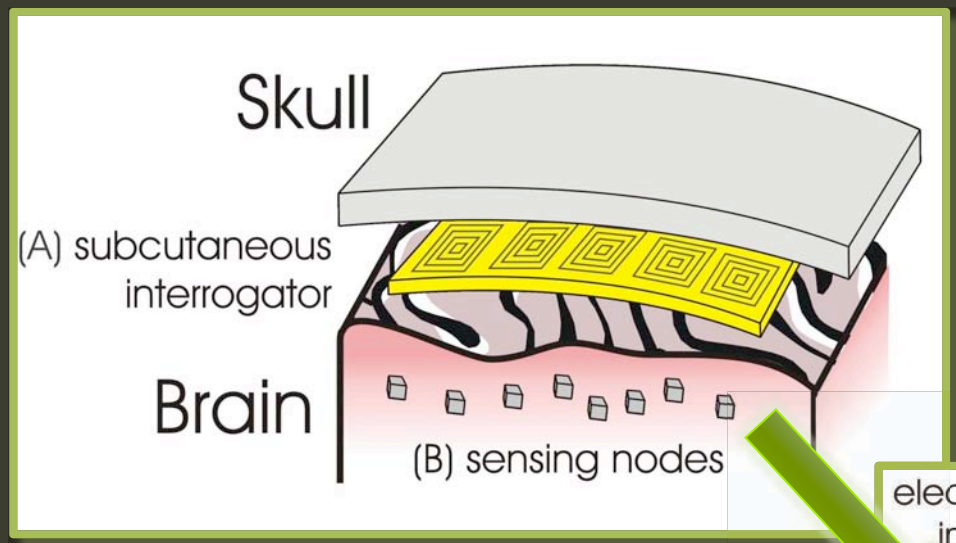
1mm^2 = roughly 2000 resonators
Assume 100 μW / analog channel



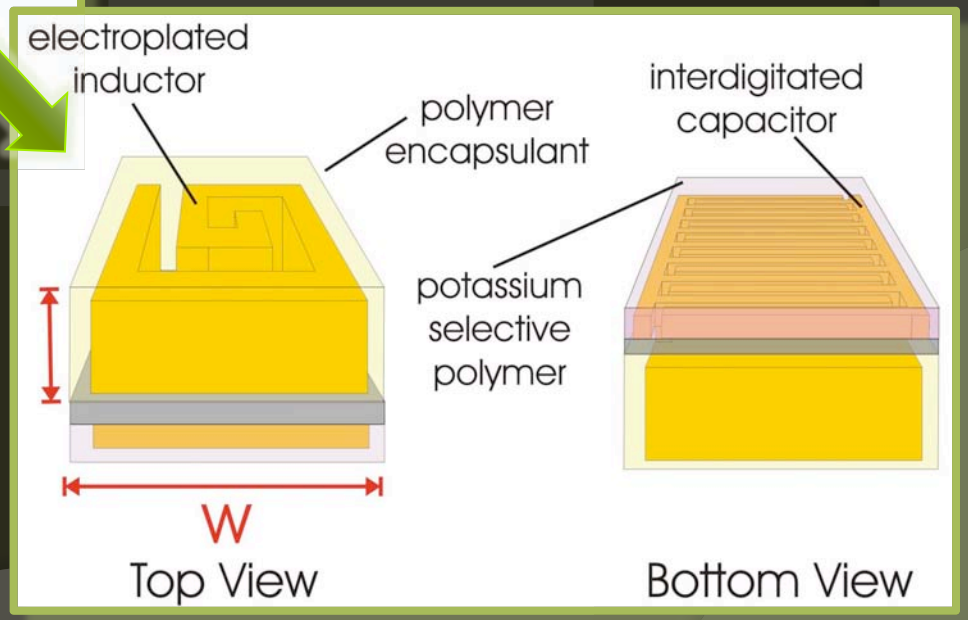
Mechanical-Analog wins for low resolutions

[Courtesy: J. Richmond]

An Extreme Perspective – Combining Passive Sensing and Communication



Immersed neural activity sensor:
Potassium-modulated resonator



Powered and interrogated by array of
Ultra low-power wireless transceivers

[Courtesy: M. Maharbiz, UCB]

Some Reflections …

- For information-technology revolution to go forward, further scaling of energy per operation essential
- Plenty of room for innovative architectures and computational paradigms
- But … Potential of CMOS ultimately limited
- Exploration of innovative materials, active and passive devices, and architectures exploiting them is a must

Microscopic wireless as ground-breaker and game-changer