ULTRA-LOW-POWER BIO-INSPIRED AND BIOMEDICAL SYSTEMS

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FOE Talk

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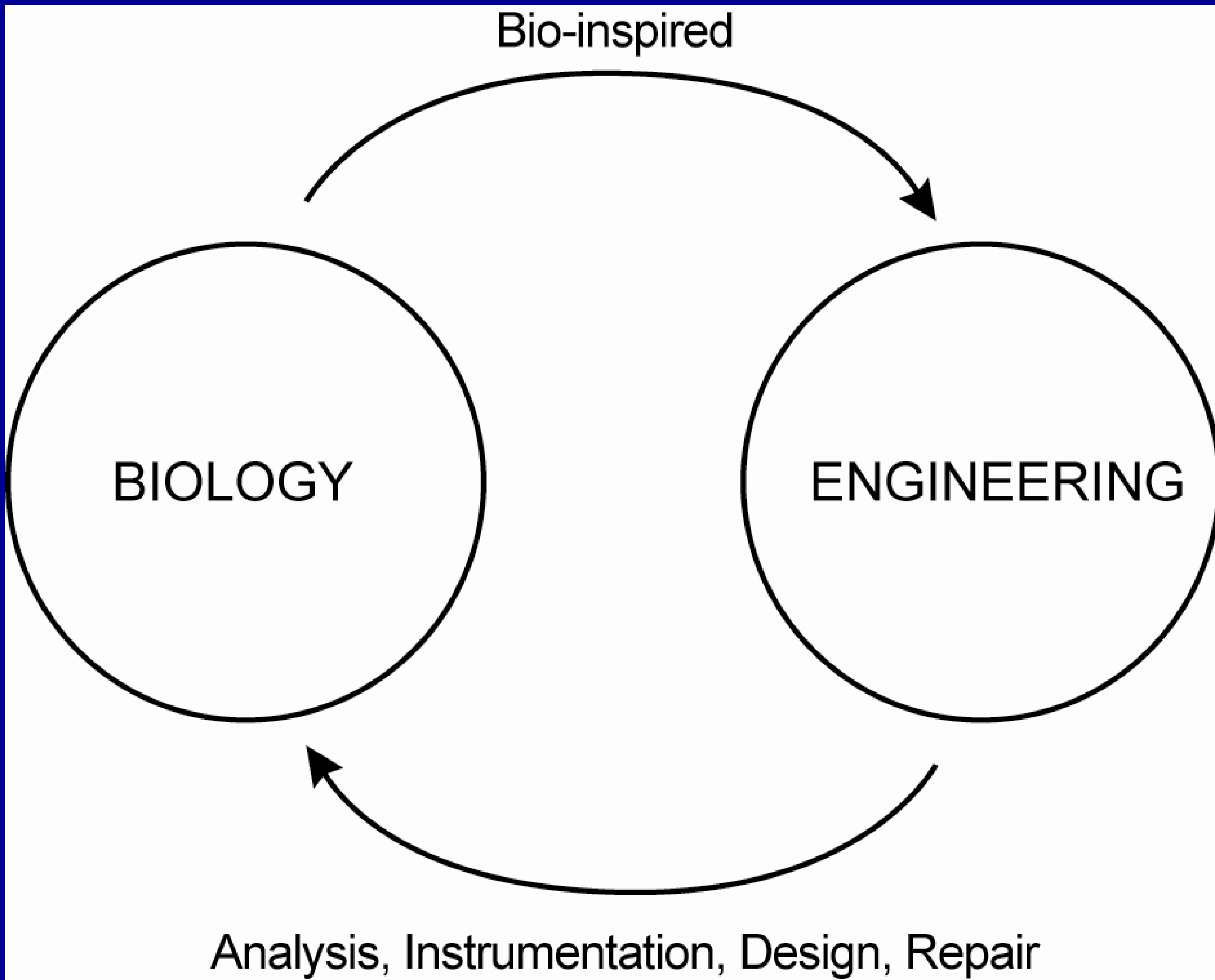
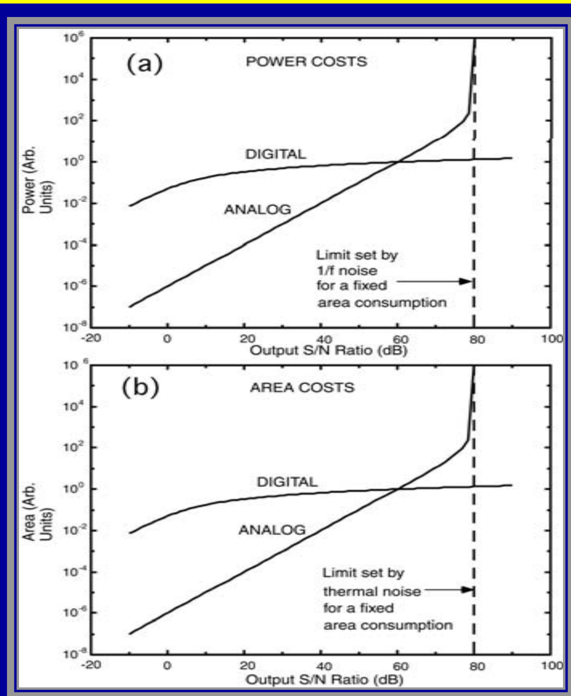

Bio-inspired
BIOLOGY
ENGINEERING
Analysis, Instrumentation, Design, Repair

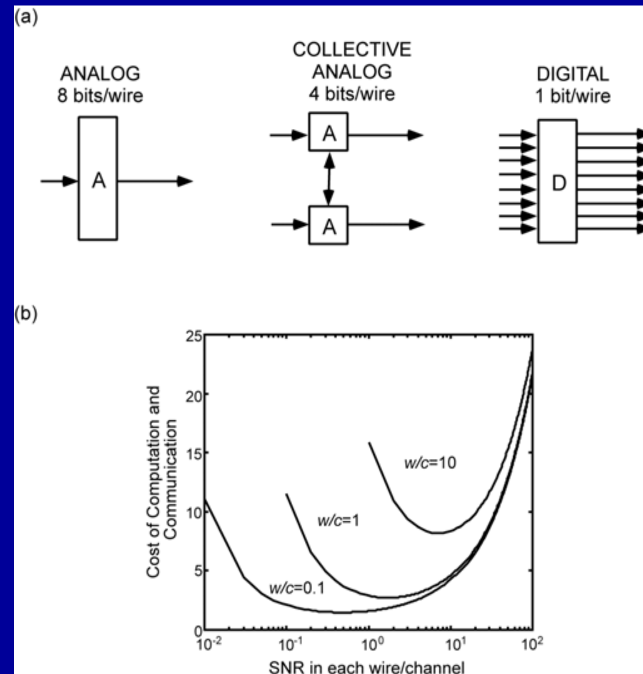
ANALOG COMPUTATION VS. DIGITAL COMPUTATION

Analog	*Digital*
• Compute on a **continuous** set e.g. R [0,1]	• Compute on a **discrete** set e.g. {0,1}
• Primitives of computation arise from the **physics** of the computing devices: **Physical relations** of NFETs, PFETs, capacitors, resistors, floating-gate devices, KVL, KCL, etc. The **amount of computation squeezed out of a single transistor is high.**	• Primitives of computation arise from the **mathematics** of Boolean logic: **Logical relations** like AND, OR, NOT, NAND, XOR, et. The transistor is used as a switch, and the **amount of computation squeezed out of a single transistor is low.**
• One wire represents **many** bits of information	• One wire represents **one** bit of information
• Computation is **offset-prone** since it is sensitive to the parameters of the physical devices.	• Computation is **not offset-prone** since it is insensitive to the parameters of the physical devices.
• Noise due to **thermal fluctuations** in physical devices.	• Noise due to **roundoff error** and **temporal aliasing.**
• Signal **not restored** at each stage of the computation.	• Signal **restored** at each stage of the computation
• In a cascade of analog stages, noise starts to **accumulate** and build up.	• Roundoff-error does **not accumulate** significantly for many computations.
• **Not easily programmable.**	• **Easily programmable.**
• **Graceful soft degradation**	• **Catastrophic hard failure**

THREE BIG INSIGHTS ABOUT ANALOG VERSUS DIGITAL

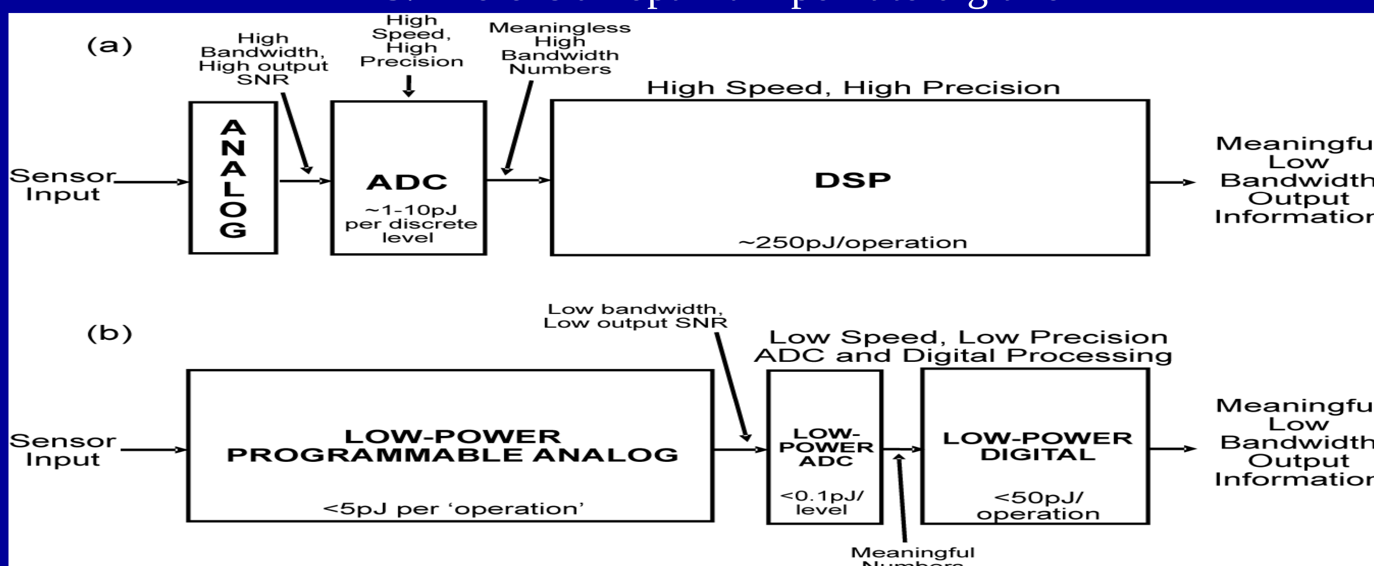
1. Analog is more efficient than digital at low precision and vice versa.



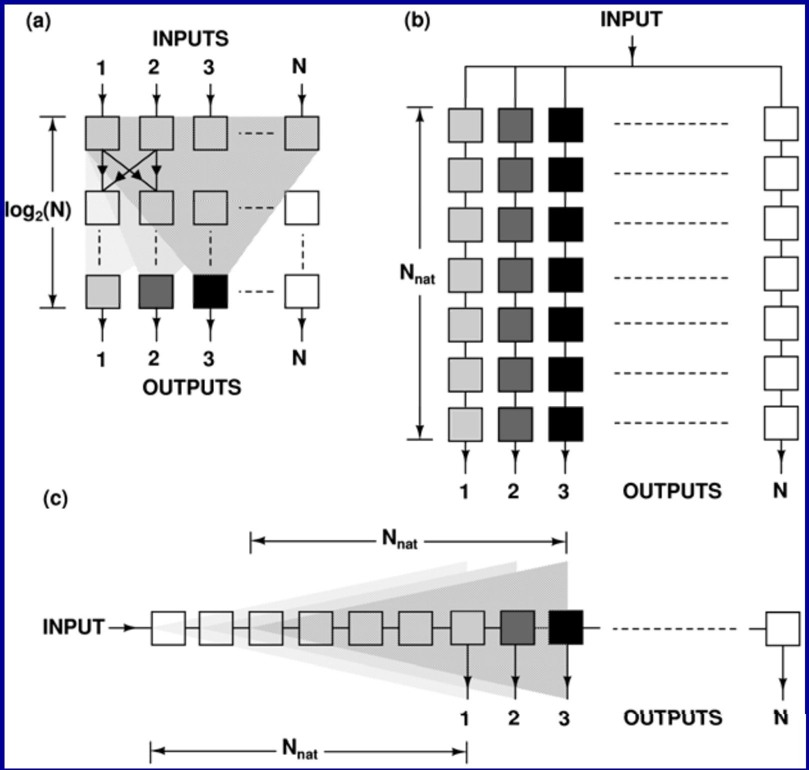


2. Collective analog or mixed-signal computation as in biology is more energy efficient than purely analog or purely digital computation.

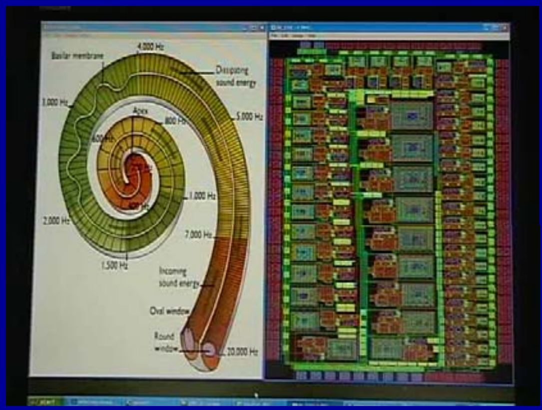
3. There is an optimum point to digitize

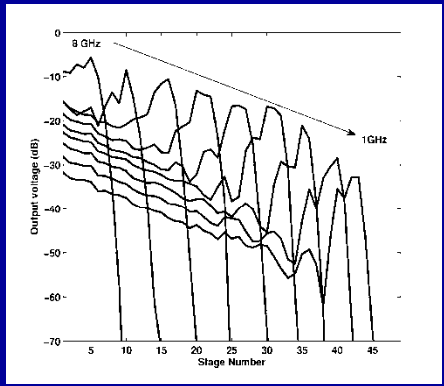


SPECTRUM ANALYZERS: MAN VERSUS NATURE



THE 'RF COCHLEA'

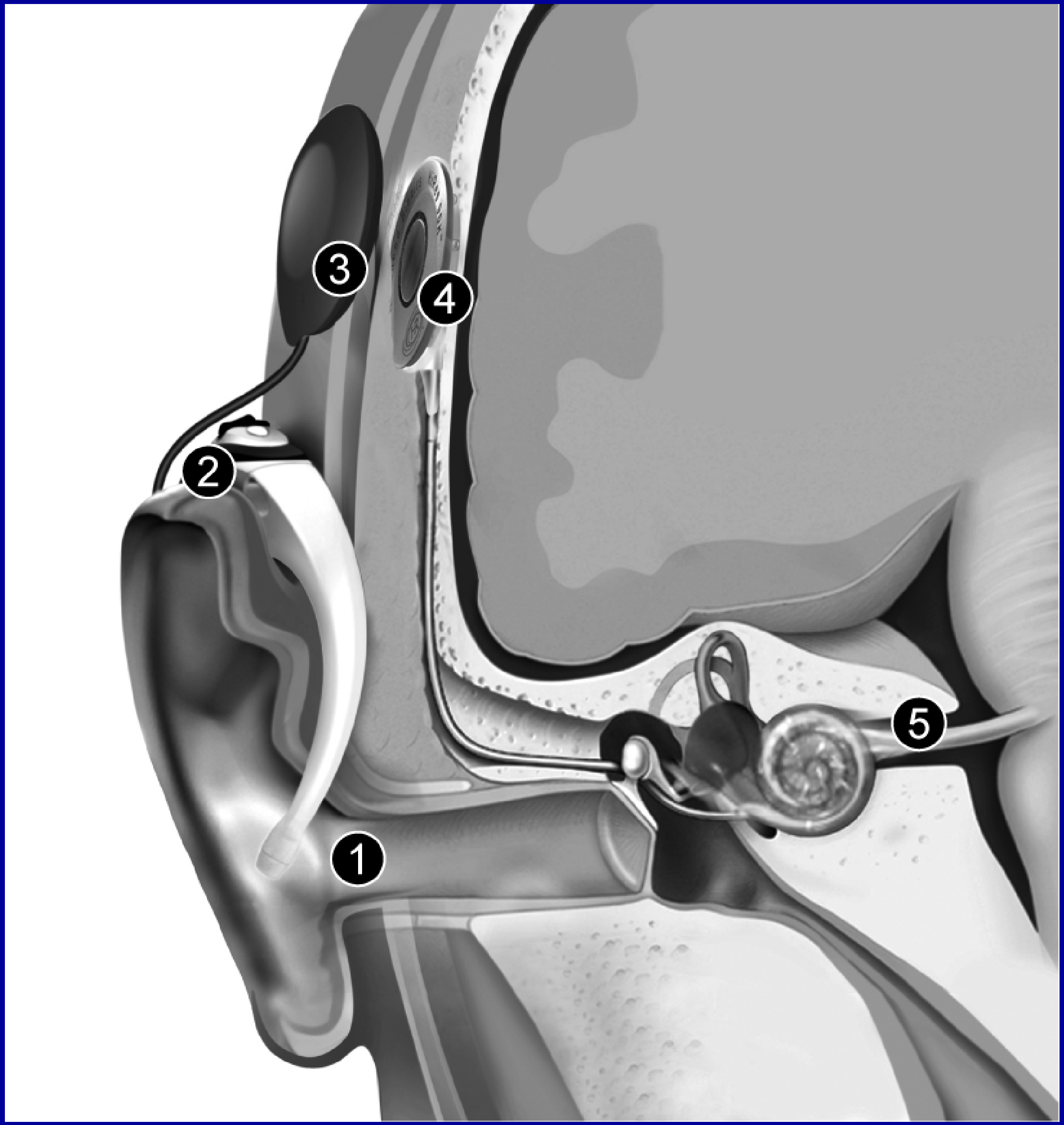




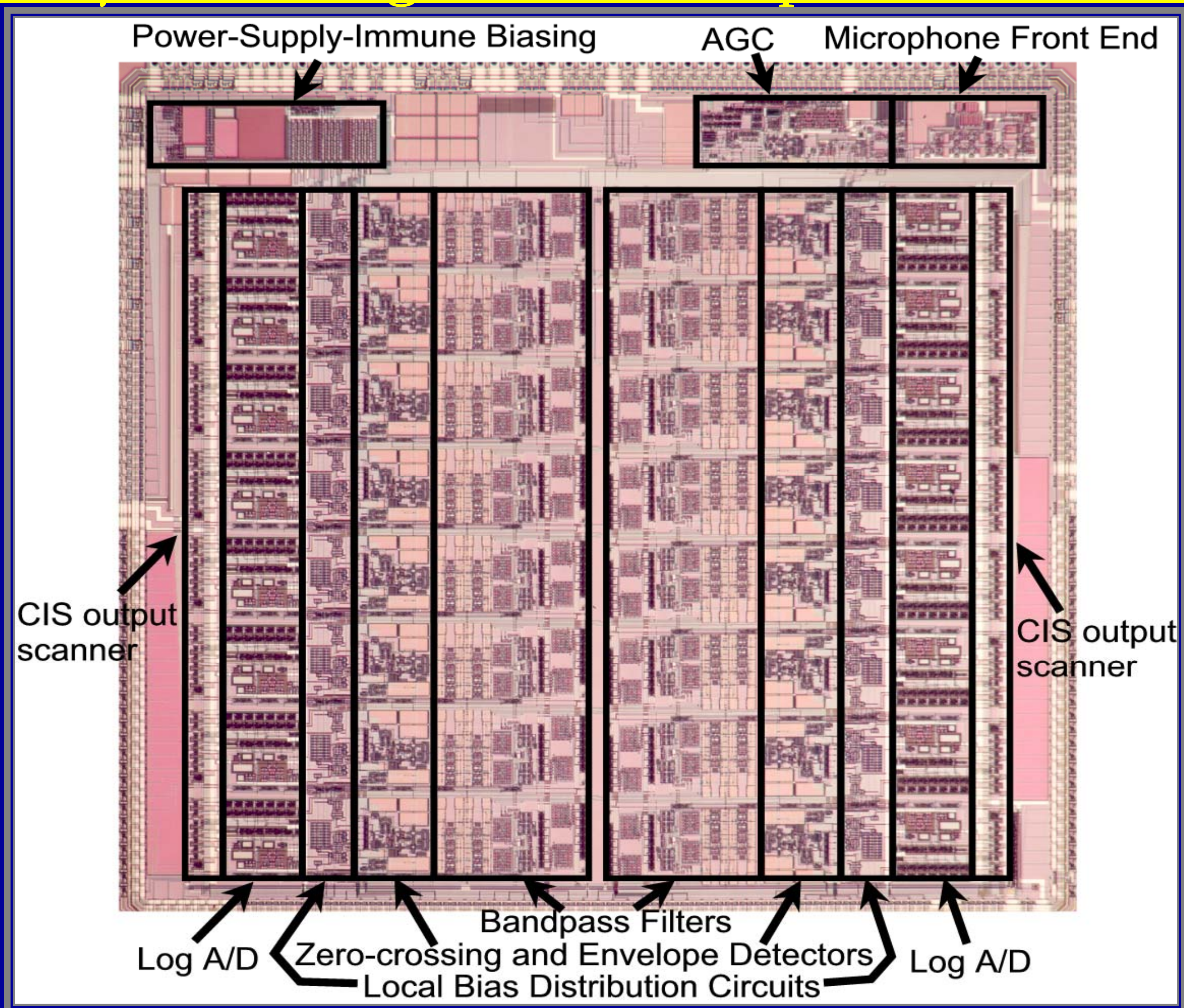
20x lower hardware cost than an analog filter bank
100x lower power than direct digitization.

Topology	Acquisition time	Hardware complexity	Parallelism
Analog filter bank * #	O(*N*)	O(N^2)	*N*
FFT *	O(*N* log(*N*))	O(*N* log(*N*))	*N*
Cochlea #	O(*N*)	O(*N*)	*N*

Cochlear Implant for the Profoundly Deaf

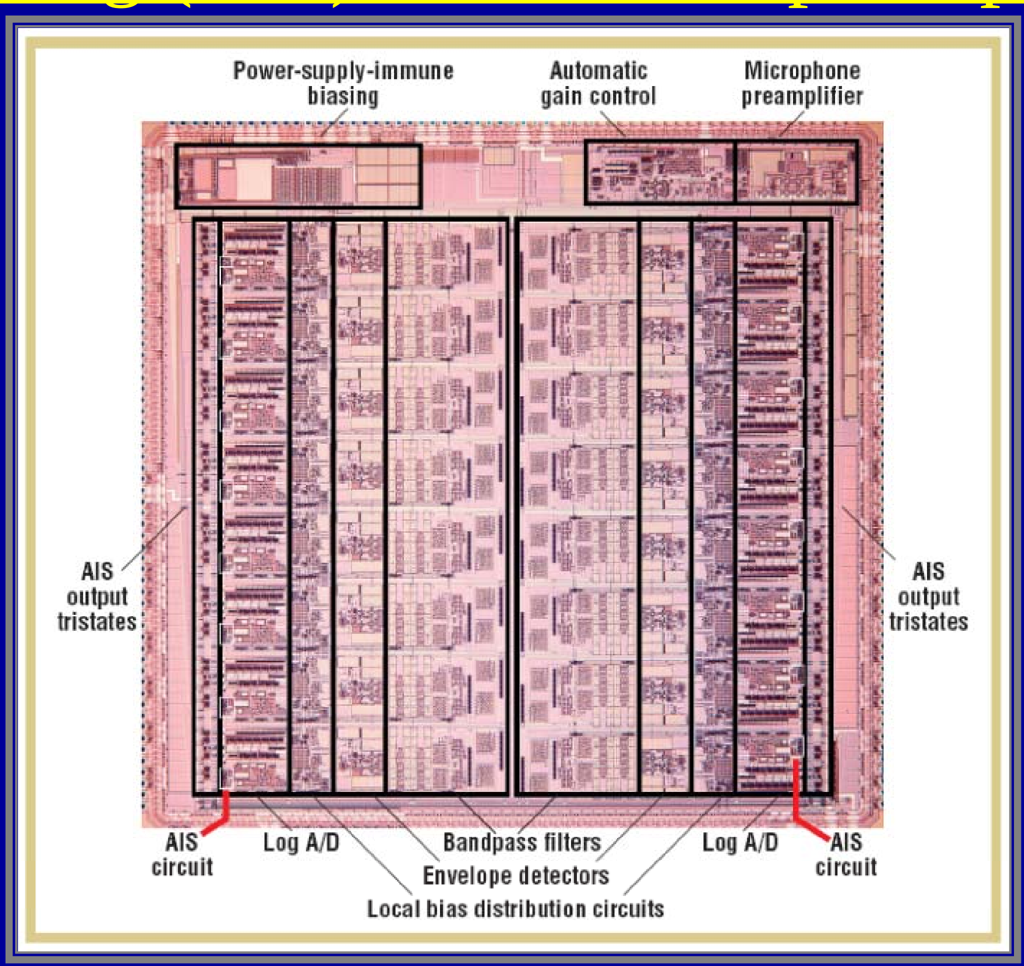


251μW Analog Cochlear-Implant Processor



1. 20x lower power than current A-D and DSP designs. 2. Will enable 30yr battery operation on a single 100mAh battery with 1000 wireless recharges and 750µW to spare for stimulation power. 3. Solution at or near energy-efficient optimal even at the end of Moore's law 4. First test with cochlear-implant subject was successful and she understood speech with it. 5. Robust to power-supply noise, temperature variations, thermal noise, and transistor mismatch. 6. The chip has 373 programmable bits that can change 86 patient parameters.

357μW Bio-inspired Asynchronous Interleaved Sampling (AIS) cochlear-implant processor



Allows phase and consequently music information to be encoded for deaf patients with very low stimulation power: It can automatically sample high-intensity channels finely and low-intensity channels coarsely thus preserving low average power across all channels.

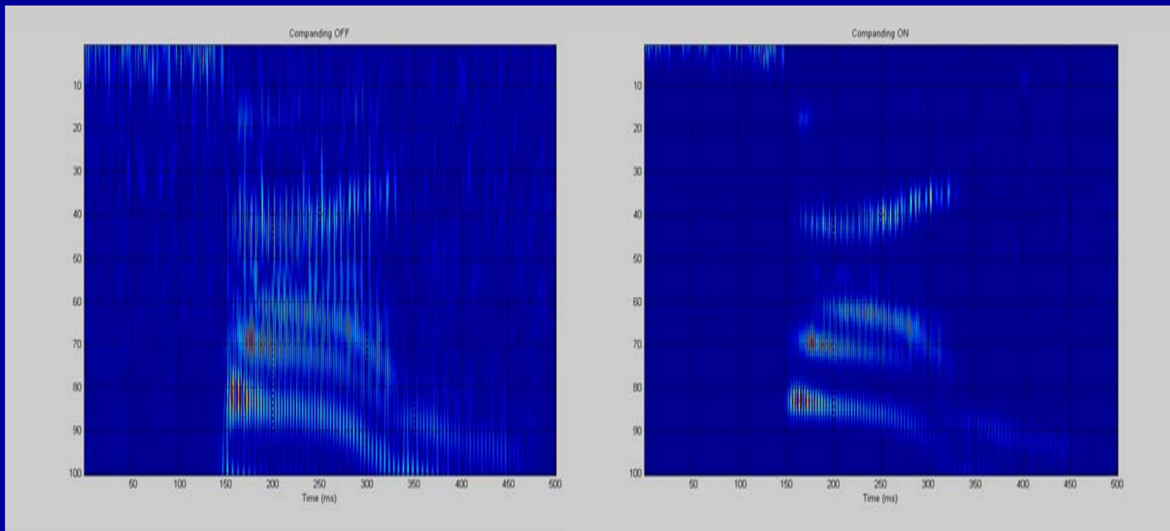
Original

Envelope Only (Traditional cochlear implants)

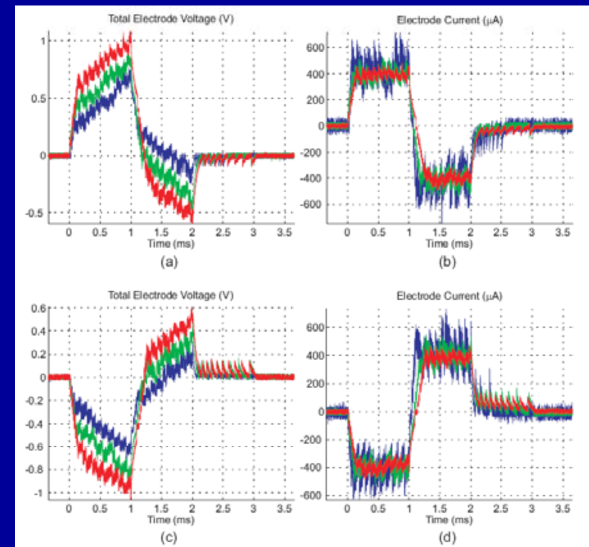
AIS (Envelope + Phase)

COCHLEAR-IMPLANT BUILDING BLOCKS (http://www.rle.mit.edu/avbs/)

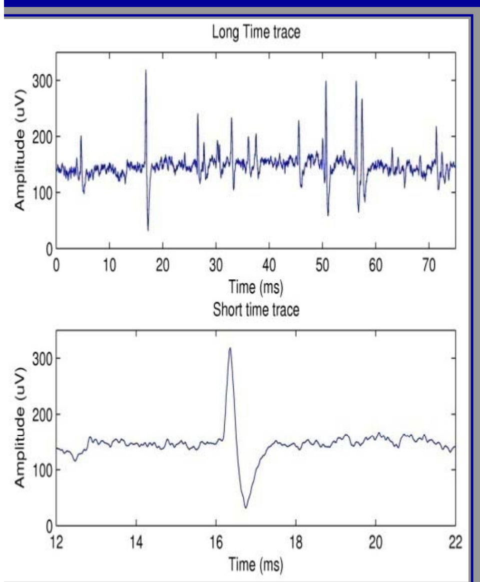
Cochlea-Inspired ‘Companding’ Algorithm for Noise Reduction



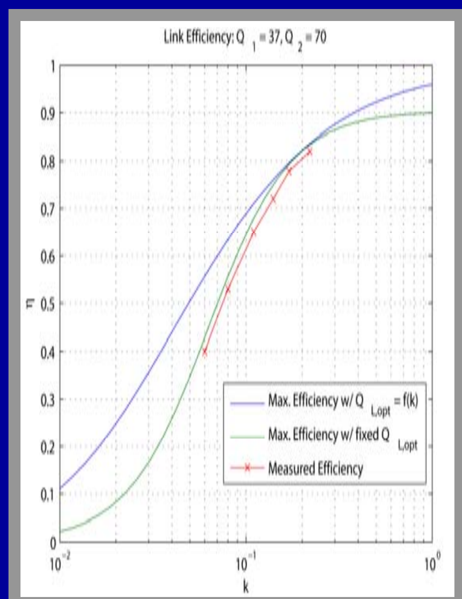
Ultra-energy-efficient ‘adiabatic’ energy-recycling neural stimulator



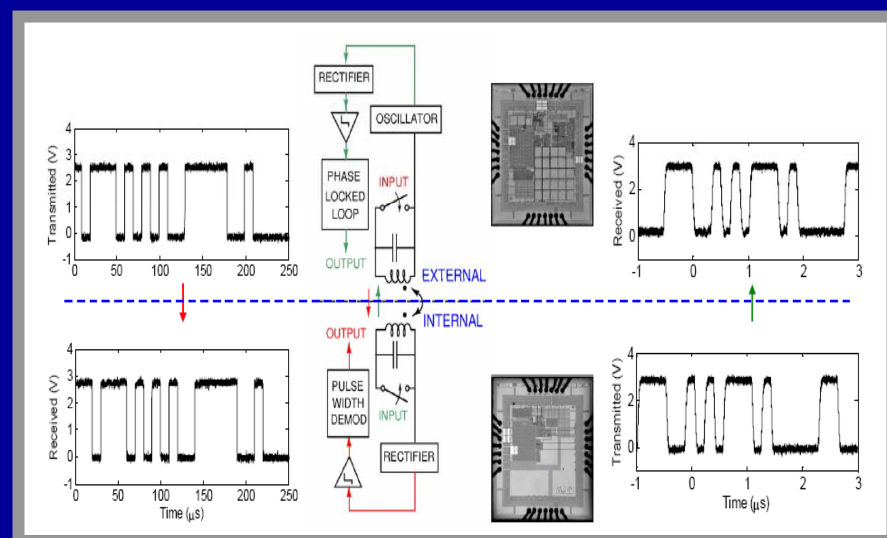
Micropower Neural Amplifier



Wireless Recharging

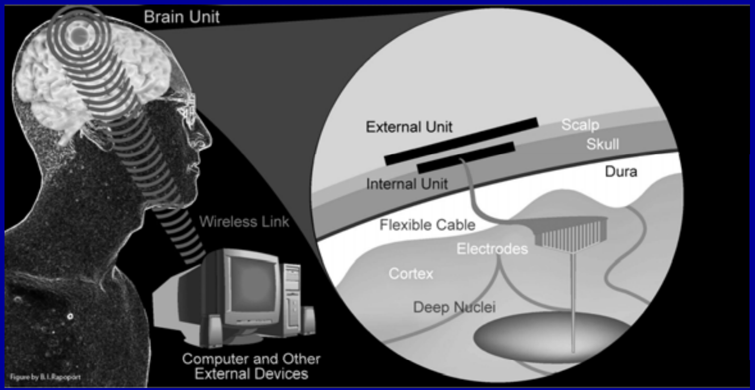


1 nJ/bit Impedance-Modulation Wireless Telemetry System

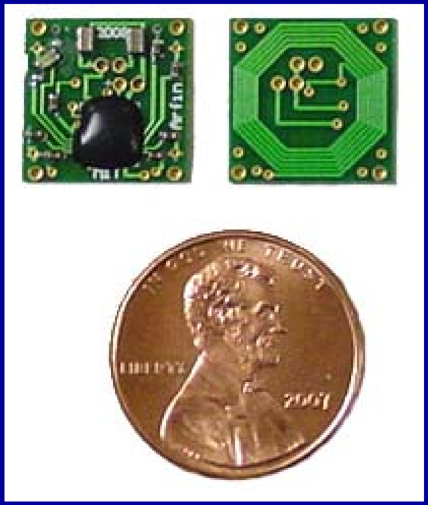


In-vivo testing of Systems

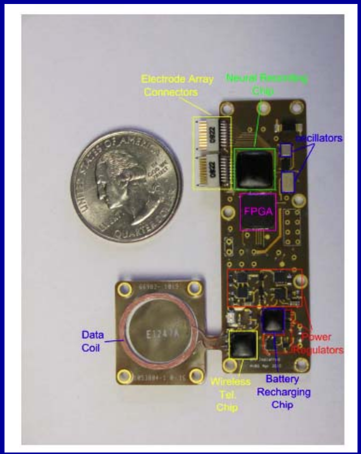
Brain Implant for the Blind or Paralyzed



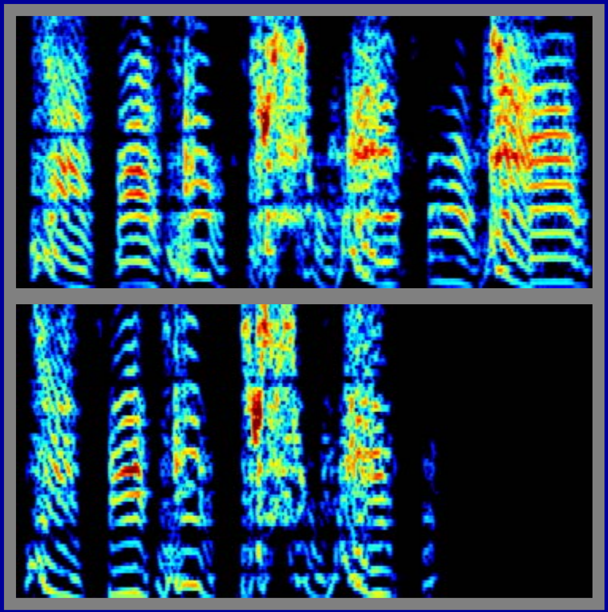
Wireless Neural Stimulation



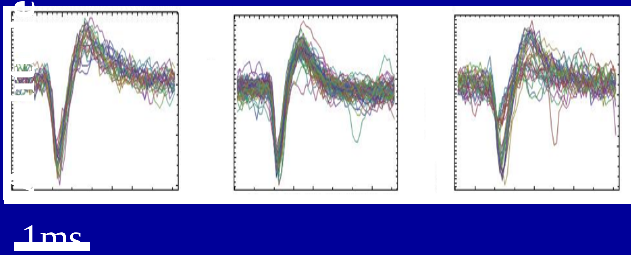
Wireless Neural Recording



Bird Song Data



Monkey Action Potential Data



SPECIFICATIONS OF A HUMAN CELL

- 10 μm overall size
- 10^7 biochemical operations per second
- 1 pW power consumption
- 30,000 node gene-protein molecular network with nanoscale devices.
- 20kT per molecular operation
(vs. 10^5 kT in advanced electronics)
- 0.36 nm between base pairs in DNA. Average protein is 5 nm.
- Functions: sensing, communication, actuation, feedback regulation, molecular synthesis, molecular transport, detoxification, defense, self assembly of organism from a single embryonic cell.

The cell is a marvel of nanotechnology

Biology computes efficiently and precisely
with noisy and unreliable components on noisy real-world signals.

Biology exploits collective analog or hybrid computation to achieve this feat

Cells are 'Mixed-Signal Nanotechnology Supercomputers'

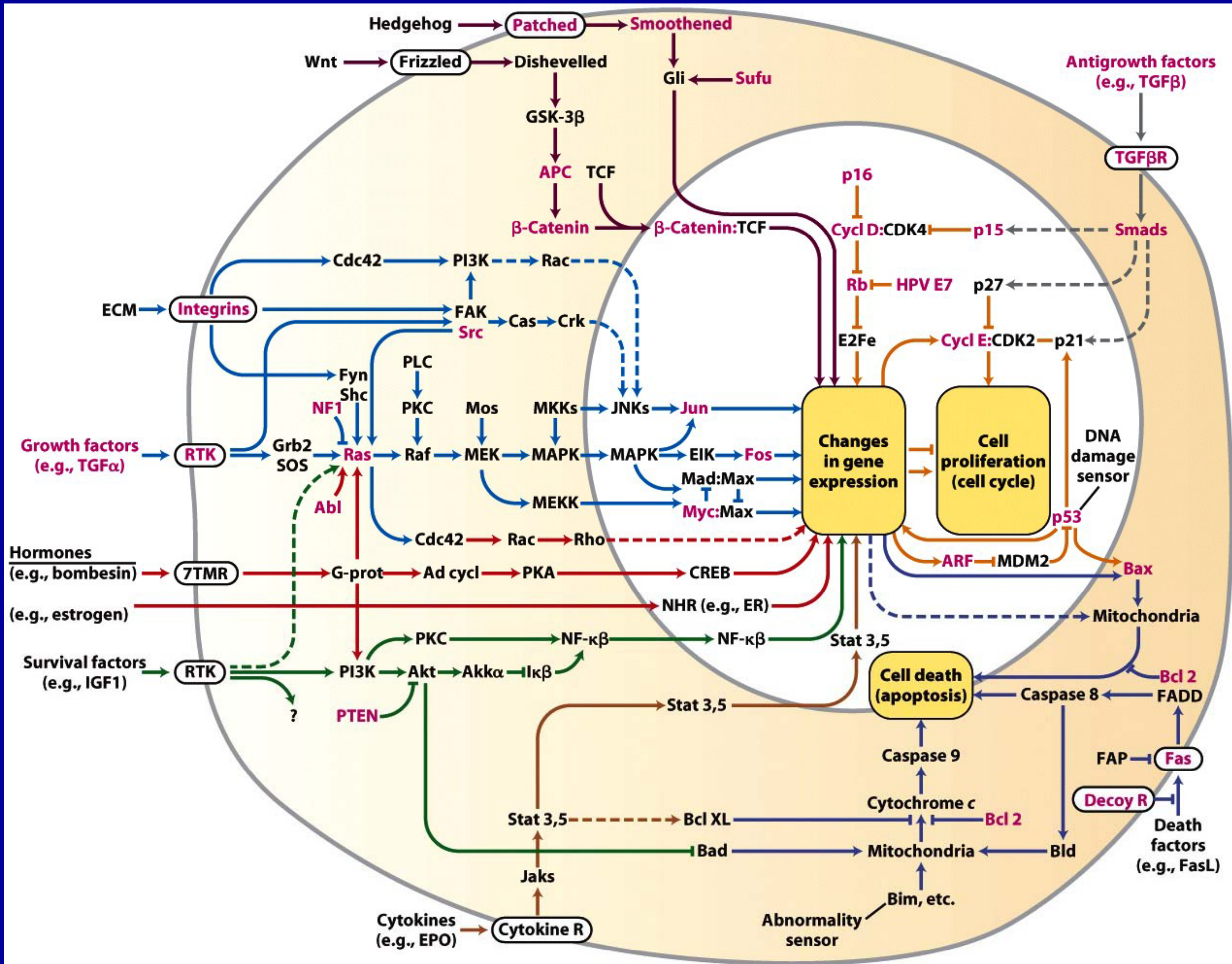
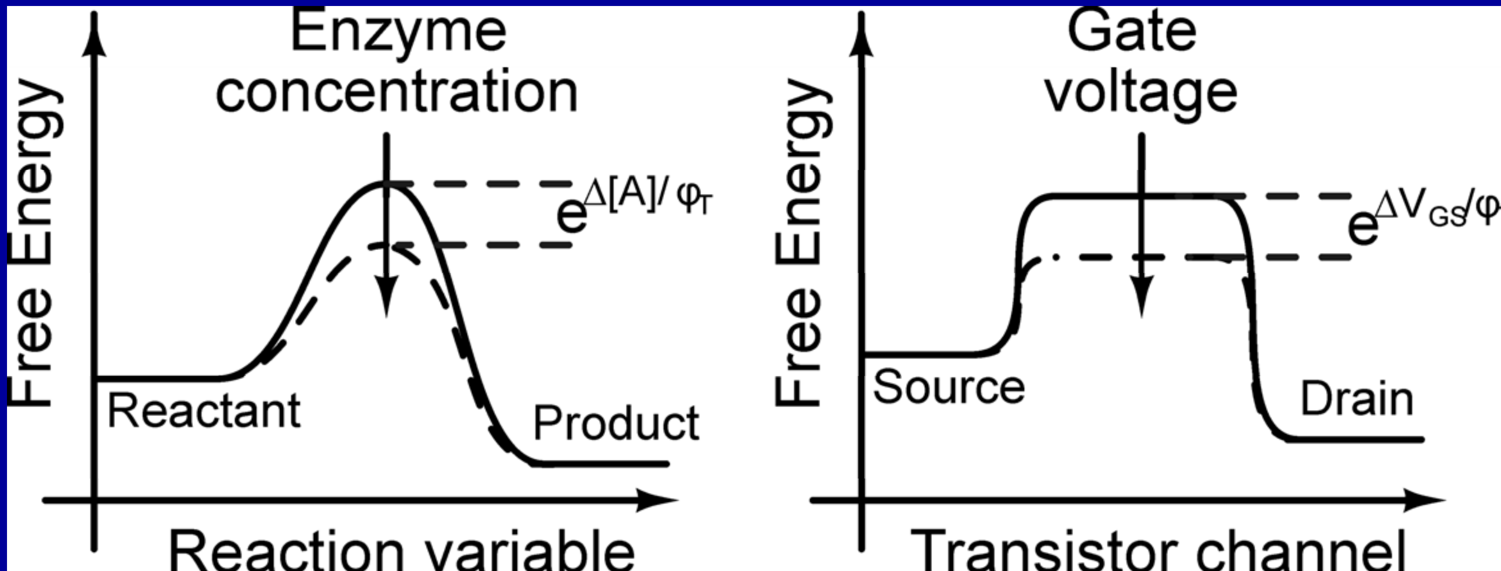


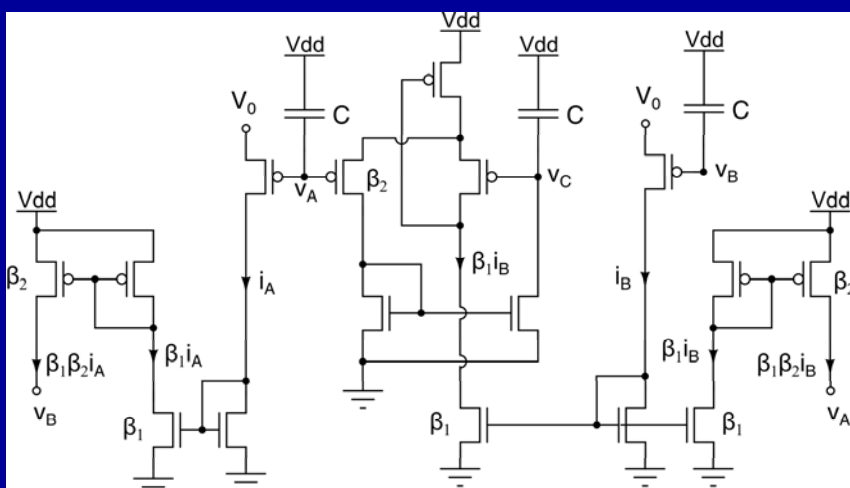
Figure 25-15
Molecular Cell Biology, Sixth Edition

Feedback Loops are critical in providing robustness to signal and device noise and in adapting to signal statistics.

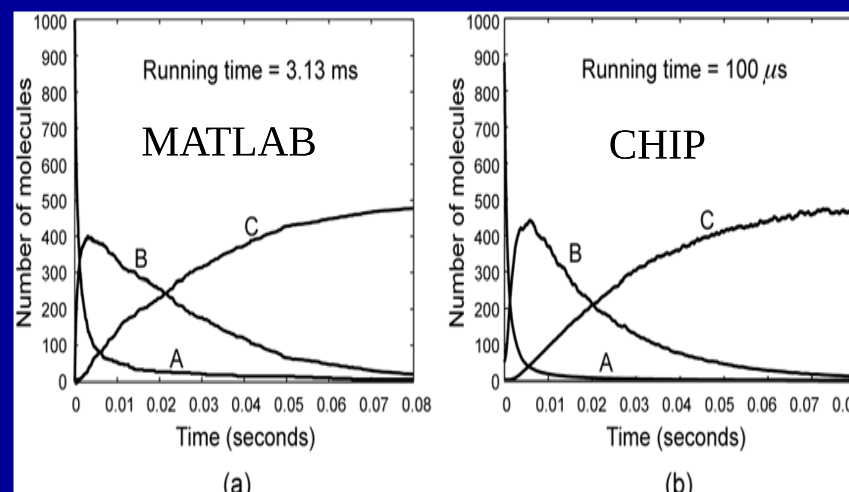
DEEP CONNECTIONS BETWEEN CHEMISTRY AND SUBTRHESHOLD ELECTRONICS



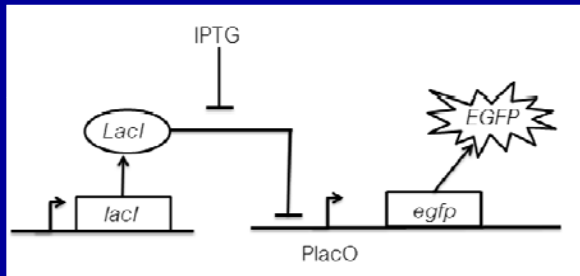
Programmable Chemical Reaction Circuit

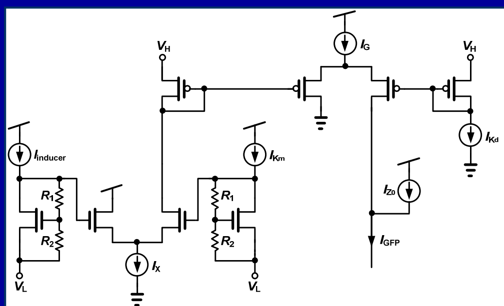


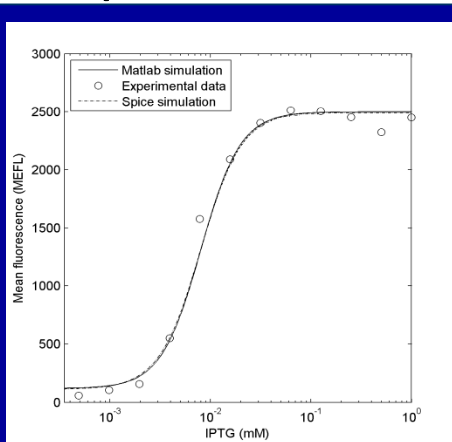
Electronic simulation of coupled chemical reactions

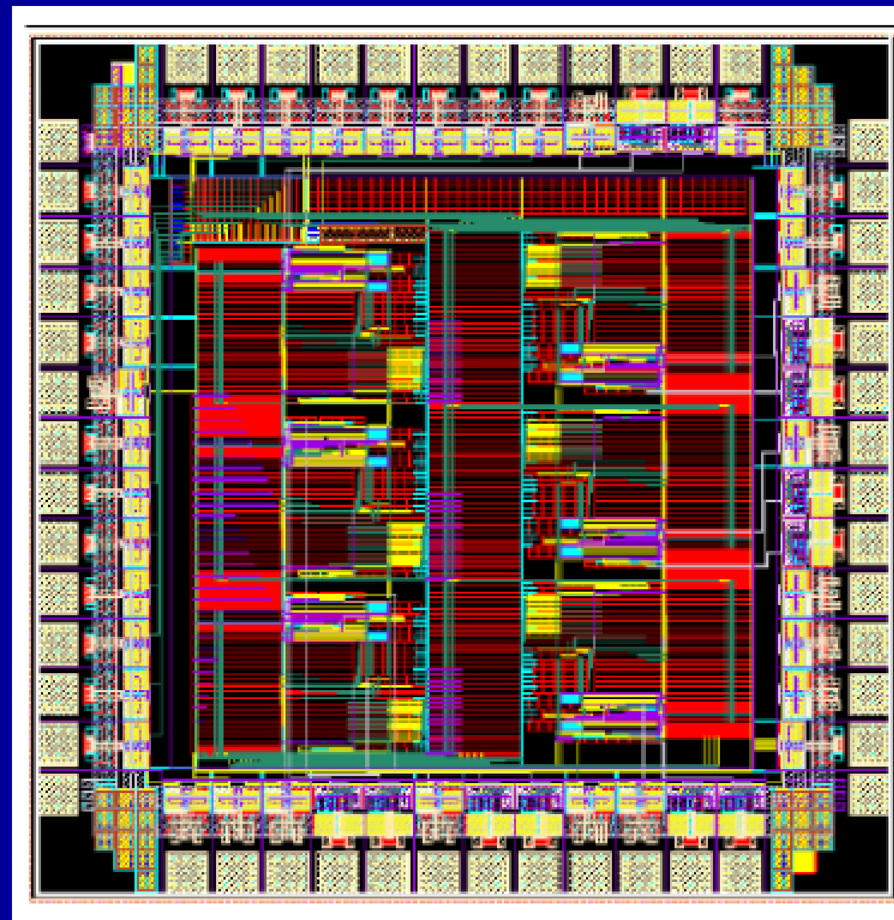


‘Cytomorphic Systems: From Cells to Electronics and Electronics to Cells:



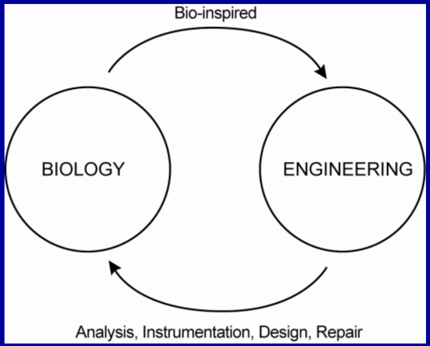


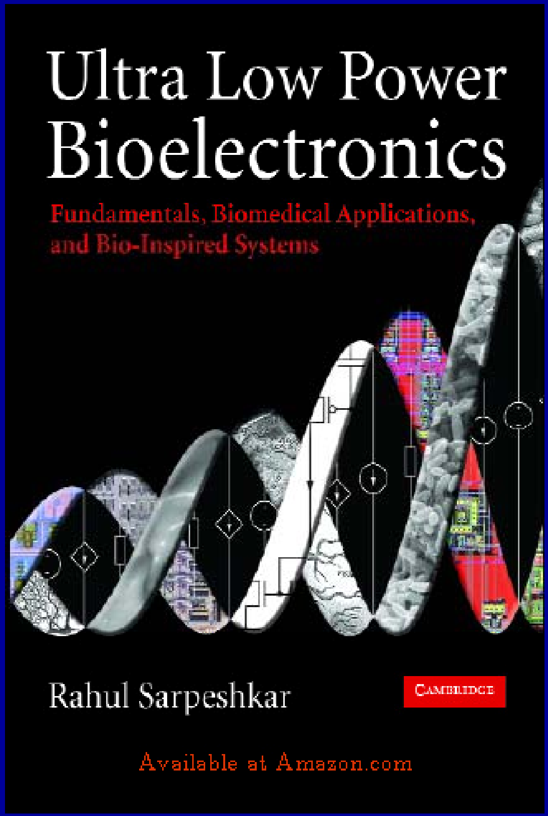




Gene network

Potential Applications: 1. Ultra-fast **digitally programmable** stochastic simulation of large-scale extra-cellular and intracellular networks (cells, organs, systems, the body) by ‘analog supercomputers’. 2. Circuit design for synthetic biology, e.g., for the design of genetic circuits in non-medical and medical applications. 3. Circuits-and-feedback robustness analysis of network sensitivity to gene mutations in several diseases like cancer and diabetes.





SUMMARY

1. **Three insights** from an analog-vs-digital analysis: 1) Analog is more efficient than digital at low local precision and vice versa; 2) Collective analog or hybrid computation as in biology is more energy efficient than either analog or digital computation; 3) There is an optimum point to digitize.
2. An **RF Cochlea,** a cochlea-inspired highly parallel architecture for ultra-fast RF spectrum analysis via collective analog computation outperforms both FFT and analog filter bank architectures.
3. Ultra-low-power electronics and bio-inspired signal processing for **cochlear implants for the deaf and brain implants for the blind and paralyzed** were discussed.
4. I discussed how a new field that I term ***cytomorphic electronics,*** i.e., electronics inspired by cell biology could be enabled by a powerful mapping between the equations of chemistry and the equations of subthreshold electronics. This mapping enables analog circuit design to be ported to synthetic biological circuits in a rigorous fashion, and biology to be simulated by analog circuits in an ultra-fast fashion. Thus, it has the potential to revolutionize the conceptual, computational, and therapeutic aspects of biology and medicine.

http://www.rle.mit.edu/acbs/

TEN UNIVERSAL PRINCIPLES FOR LOW-POWER DESIGN:
ANALOG, DIGITAL, BIOLOGY, ELECTRONICS, CARS