Ultra Energy-Efficient Systems in Biology, Engineering and Medicine

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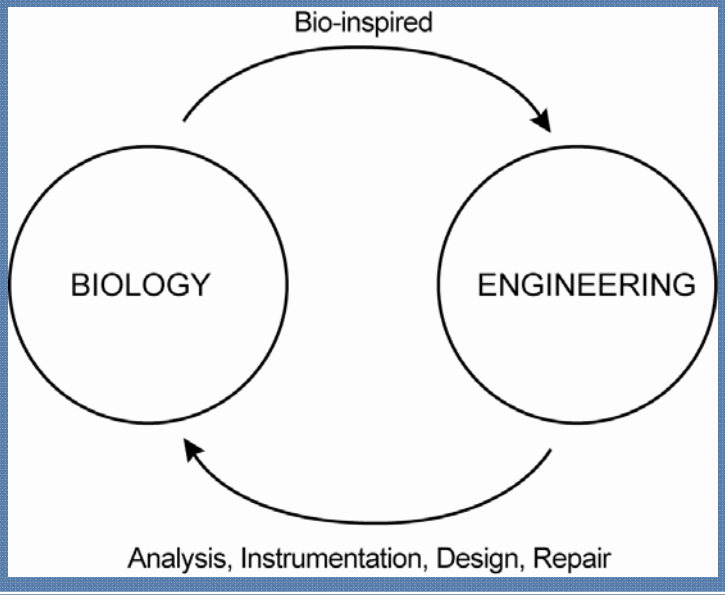
The Big Picture of my Talk

1. Ultra-low-power medical implants.
2. Glucose-powered energy-harvesting medical implants.
3. Highly efficient synthetic DNA-Protein circuits in living cells.

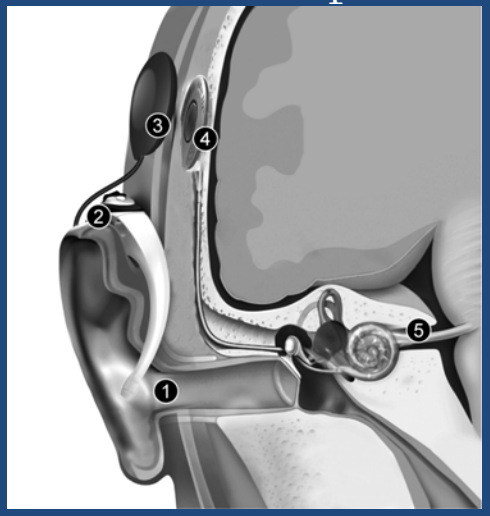
1) Interfacing with the electrochemical nervous system;
2) Electrochemical energy generation;
3) Mapping chemical to electrical circuits and vice versa



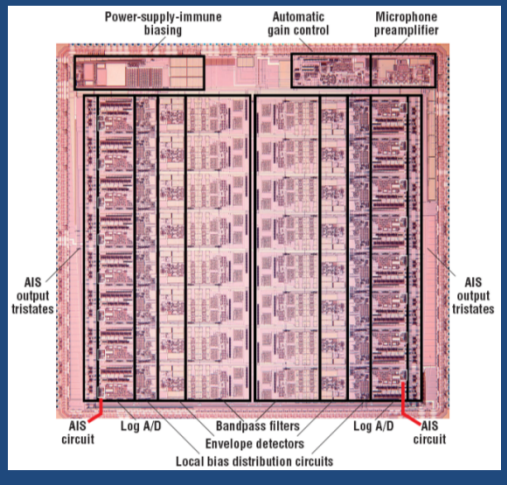
Cochlea-Inspired Asynchronous Interleaved Sampling (AIS) Cochlear-Implant Processor

Can improve power AND performance by an order of magnitude.

Cochlear Implant



AIS Cochlear-Implant Processor

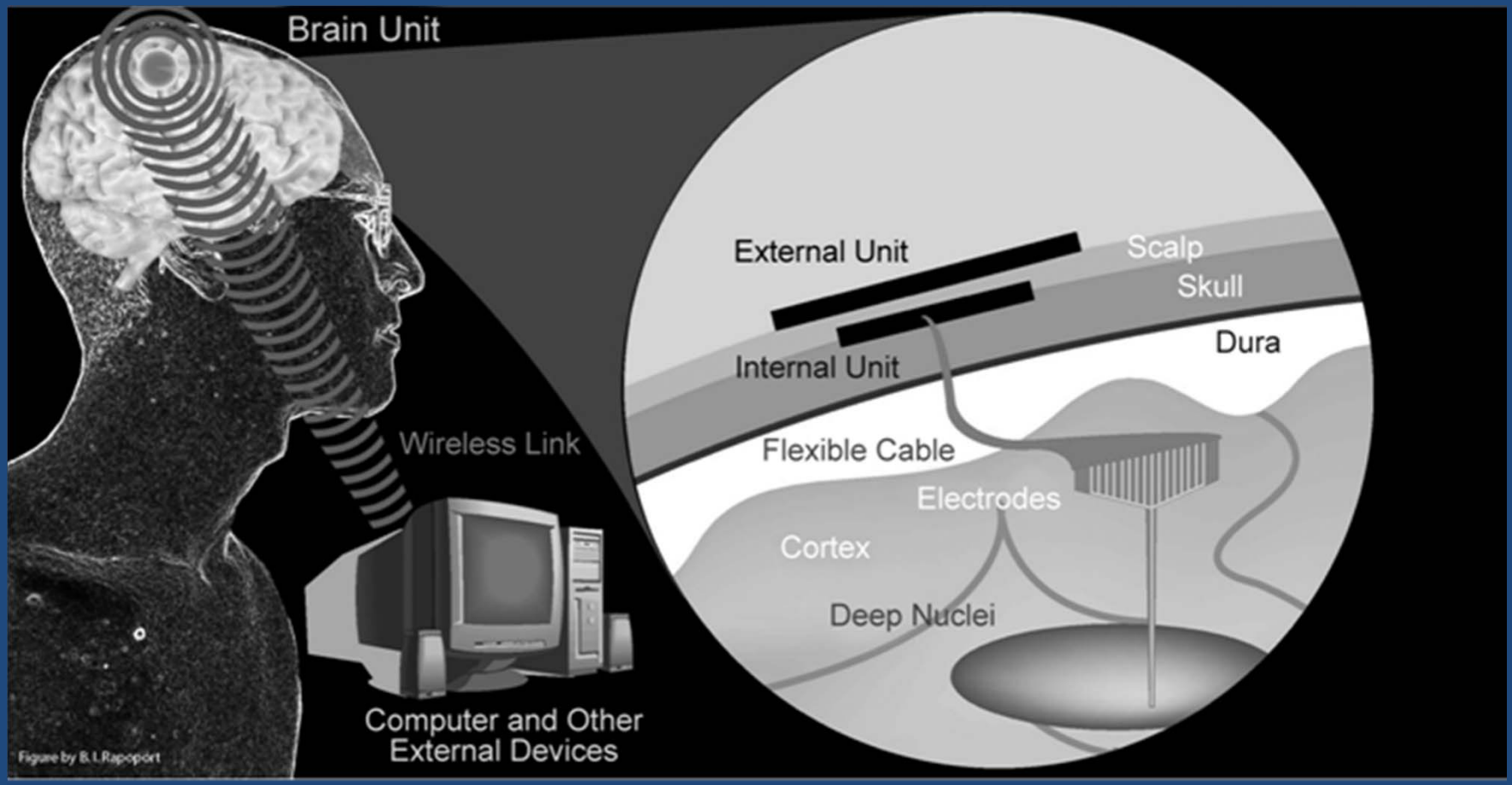


Original

Envelope Only (CIS)

AIS (Envelope + Phase)

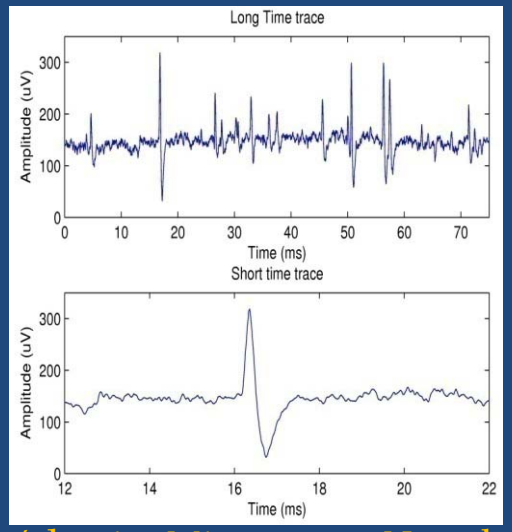
Brain-Machine Interfaces (BMIs) of the Future



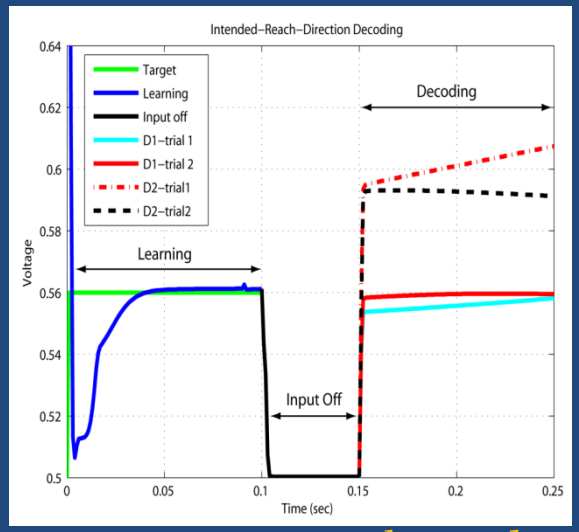
Sarpeshkar, Rahul. *Ultra Low Power Bioelectronics*, CUP, © 2010.

Applications in Paralysis, Parkinson's Disease, Epilepsy, Blindness, Stroke, ...

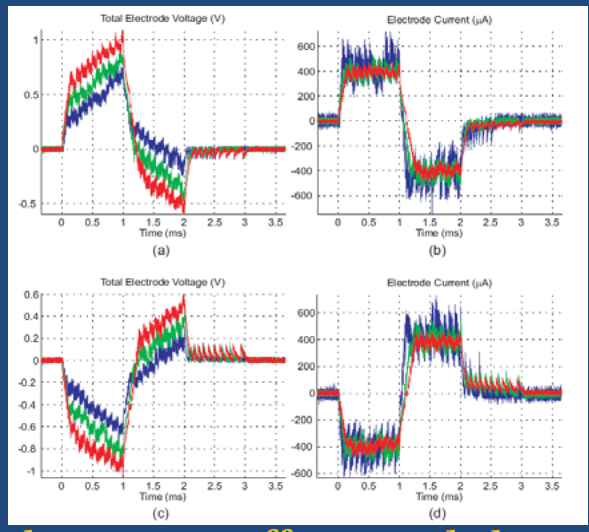
Circuits for Ultra-Energy-Efficient BMI's



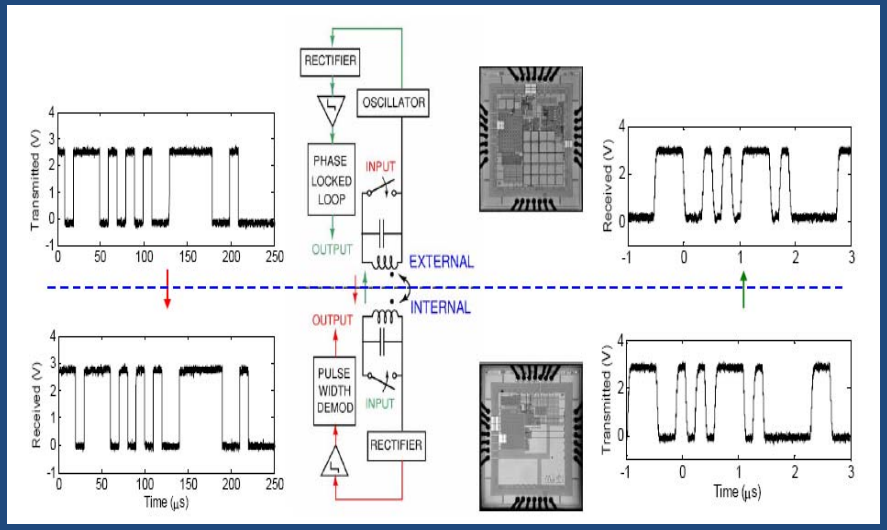
Adaptive Micropower Neural Amplifier



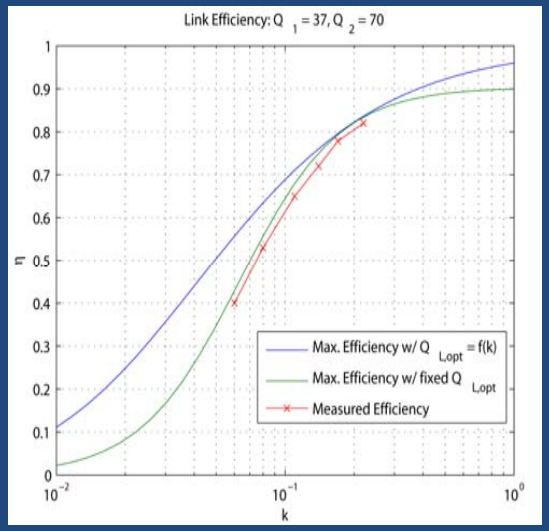
Micropower Neural Decoder



Ultra-energy-efficient 'adiabatic' energy-recycling neural stimulator



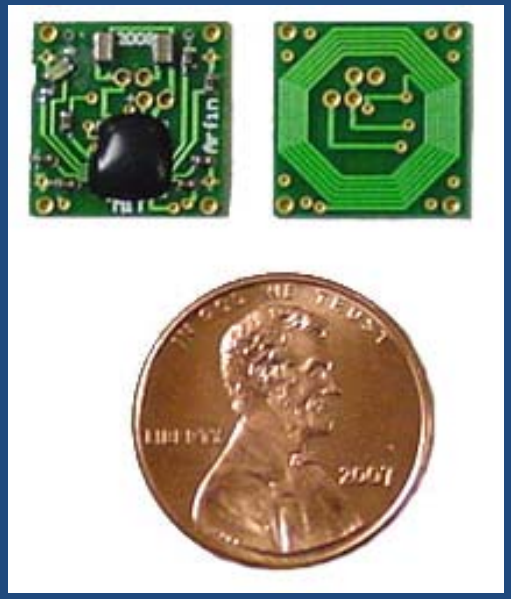
1 nJ/bit Impedance-Modulation Wireless Telemetry System

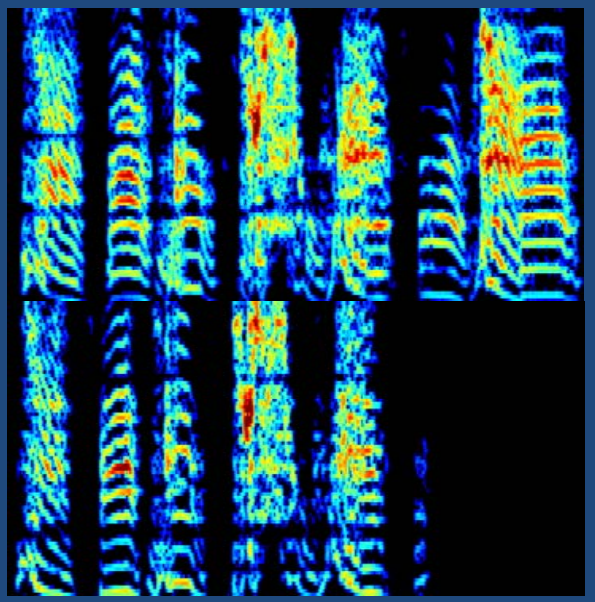


Optimally Efficient Wireless Recharger

In-vivo testing of Systems

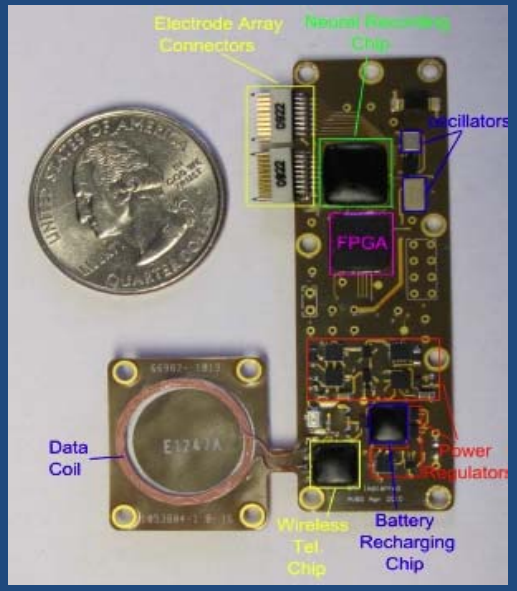
Wireless Neural Stimulation

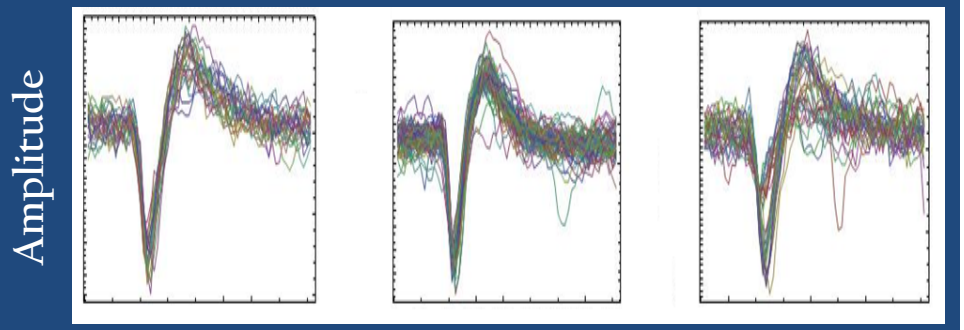




Bird Song Data

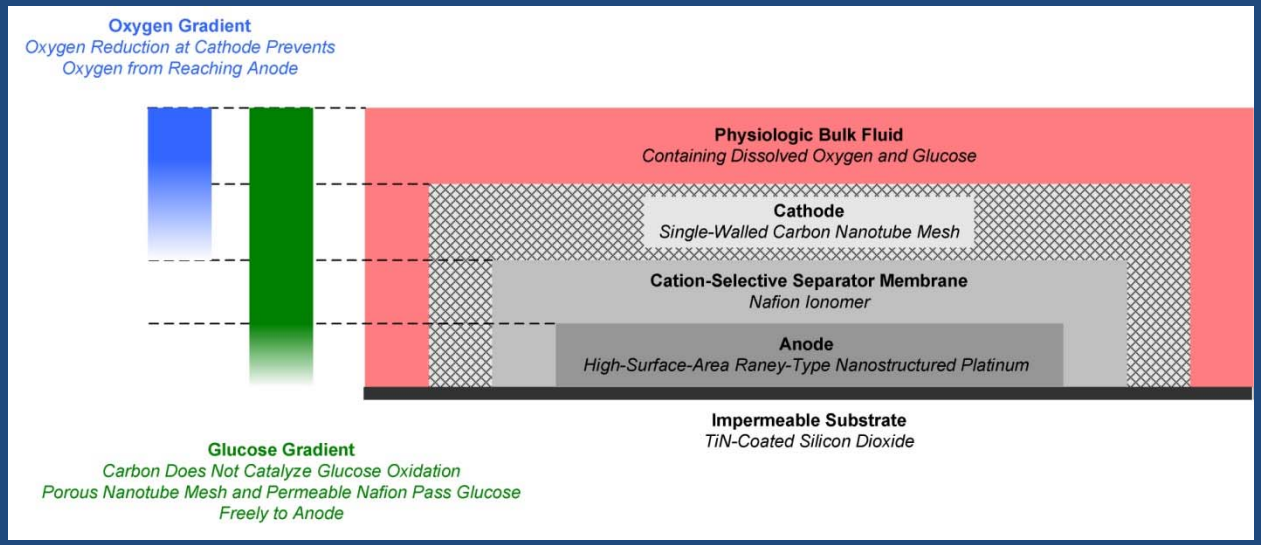
Wireless Neural Recording



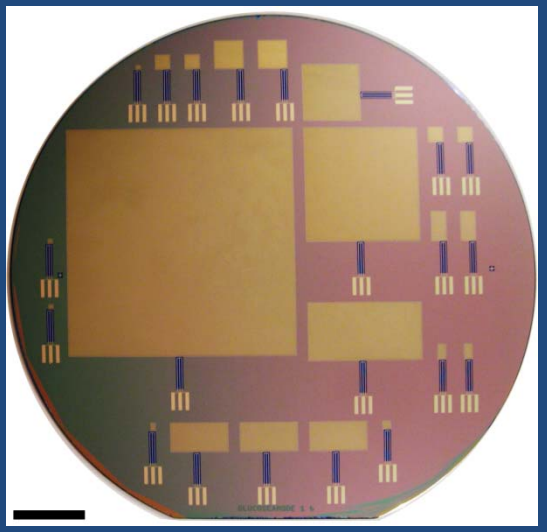


Monkey Action Potential Data

The Future of Biomedical Implants: Energy-Harvesting Glucose Fuel Cell

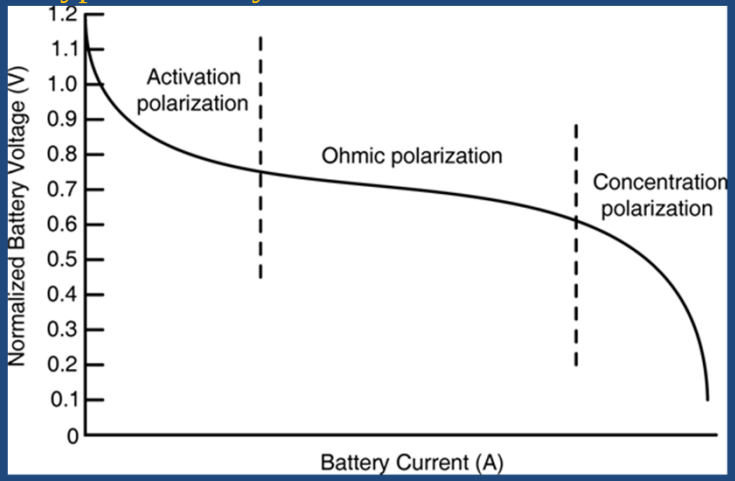


Powered by Glucose in Physiologic Fluids

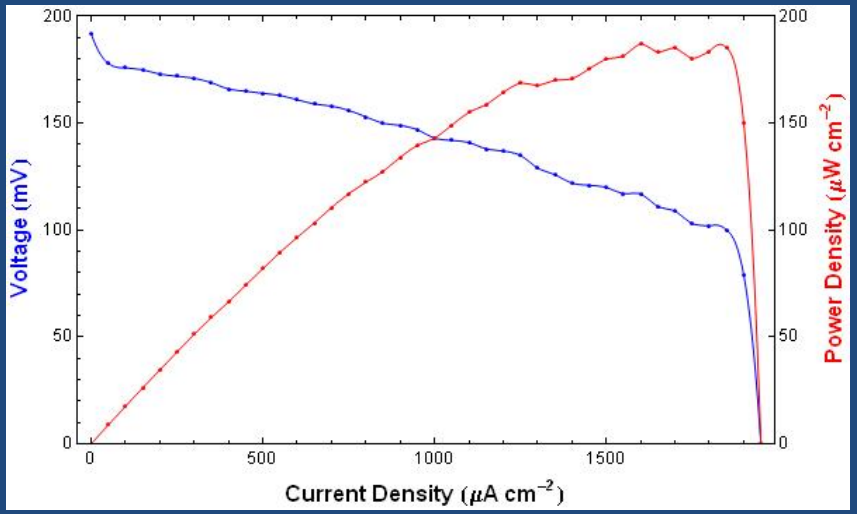


CMOS-Compatible Fabrication

Typical Battery or Fuel Cell Characteristics



Glucose Fuel Cell Characteristics



Sarpeshkar, Rahul. *Ultra Low Power Bioelectronics*, CUP, © 2010.

Cells are 'Mixed-Signal Nanotechnology Supercomputers' that compute directly with molecules

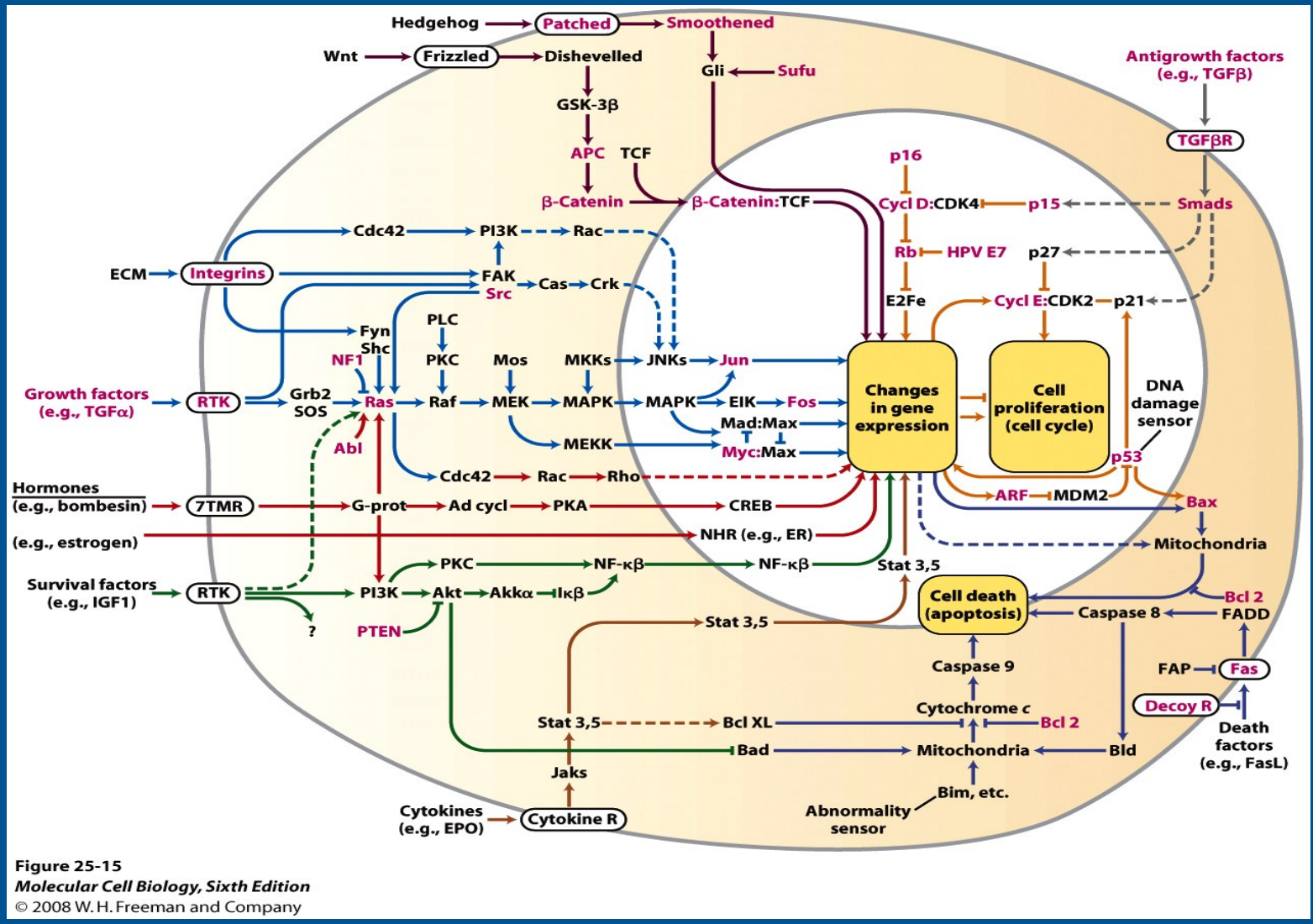
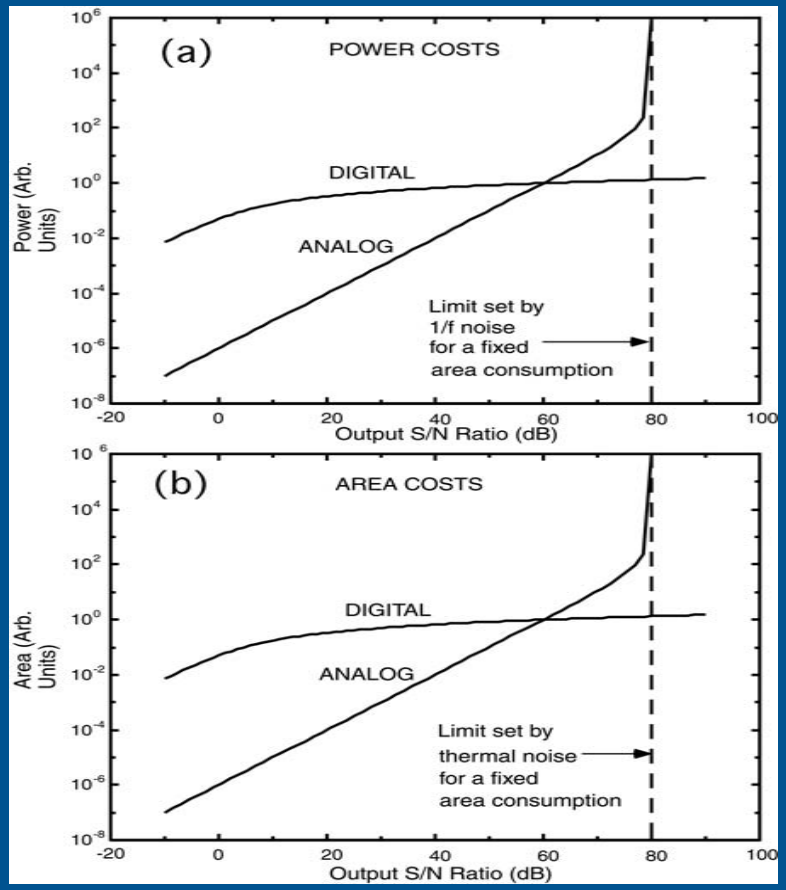


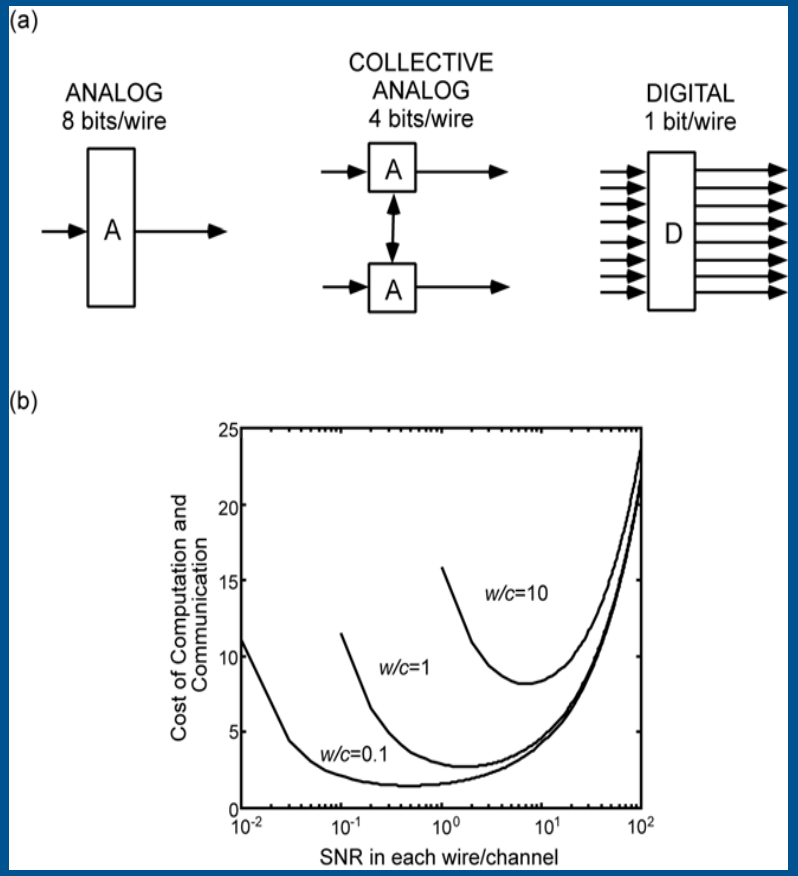
Figure 25-15
Molecular Cell Biology, Sixth Edition

ANALOG	DIGITAL
1. Compute on a continuous set of numbers, e.g., [0,1], graded protein production from low to a maximum level.	1. Compute on a discrete set, e.g., {0,1}, protein produced at a maximum level or not present at all.
2. The basis functions for computation arise from the physics and chemistry of the computing devices such that the amount of computation squeezed out of a single genetic, RNA, or protein circuit is high.	2. The basis functions for computation arise from the mathematics of Boolean logic such that the amount of computation squeezed out of a single genetic, RNA, or protein circuit is low.
3. One wire or channel can represent many bits of information.	3. One wire or channel always represents one bit of information.
4. Computation is sensitive to the parameters of the molecular circuits.	4. Computation is less sensitive to the parameters of the molecular circuits.
5. Noise is due to thermal fluctuations in molecular devices.	5. Noise is due to round off error and temporal aliasing.
6. Signal is not restored at each stage of the computation.	6. Signal is restored at each stage of the computation
7. Robust at final and decisive outputs	7. Robust in every device and signal

Adapted from *Ultra Low Power Bioelectronics*, R. Sarpeshkar, CUP 2010

Analog Versus Digital: The Genius of Biology



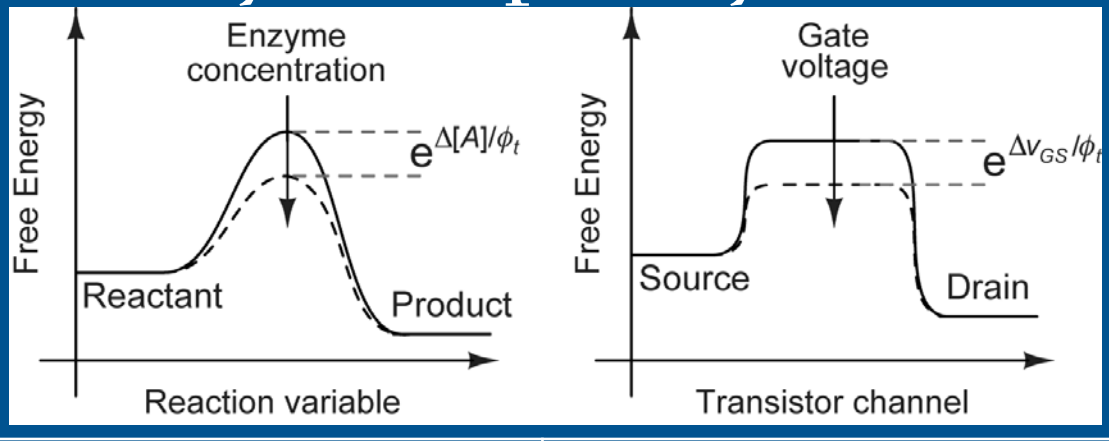


The relatively low-precision environment of cells makes analog computation efficient

Biology uses collective analog computation to achieve incredible efficiency.

R. Sarpeshkar, *Ultra Low Power Bioelectronics*, CUP, 2010

Cytomorphic Systems

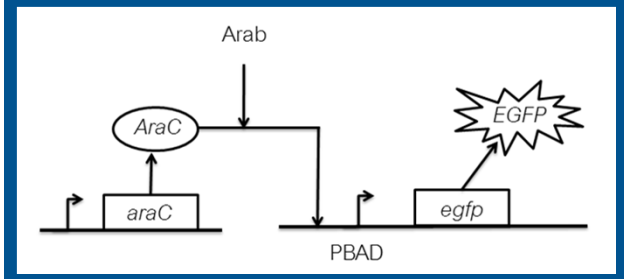


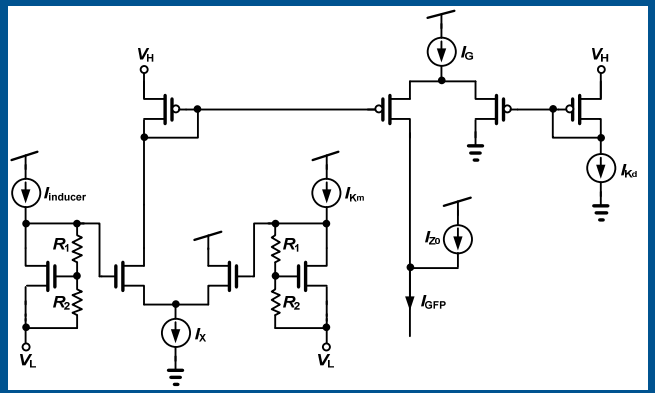
Chemistry	Electronics
Molecular flux	Electron flow (current)
Chemical potential	Electronic potential (voltage)
Enzyme potential exponentially controlling reaction rate	Gate voltage exponentially controlling current level
Flux balance analysis	Kirchhoff's current law (KCL)
Thermodynamic energy balance	Kirchhoff's voltage law (KVL)
Stochastics of molecular shot noise	Stochastics of Poisson shot noise

Log(molecular concentration) + Energy = Log(current) + Voltage
= Electrochemical Potential

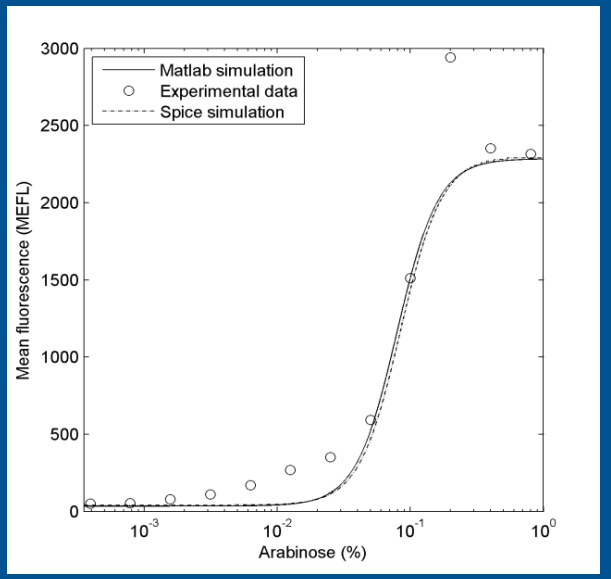
Experimental Data from *E. coli*

ACTIVATOR

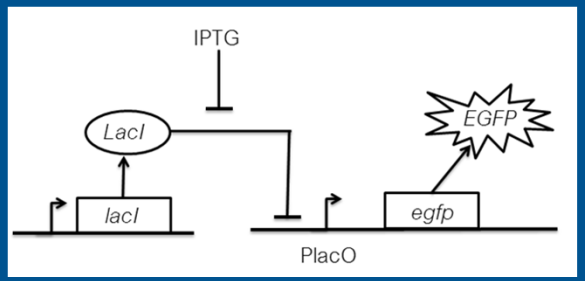


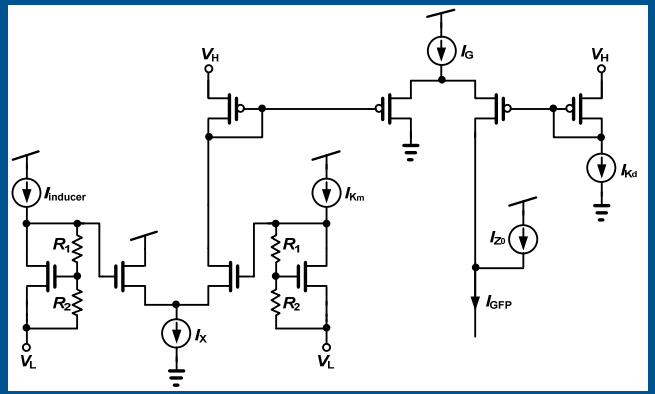


$$I_{GFP} = \frac{I_G}{1 + \frac{I_{K_d}}{I_X}\left(1 + \left(\frac{1}{I_{inducer} / I_{K_m}}\right)^m\right)} + I_{Z_0},$$

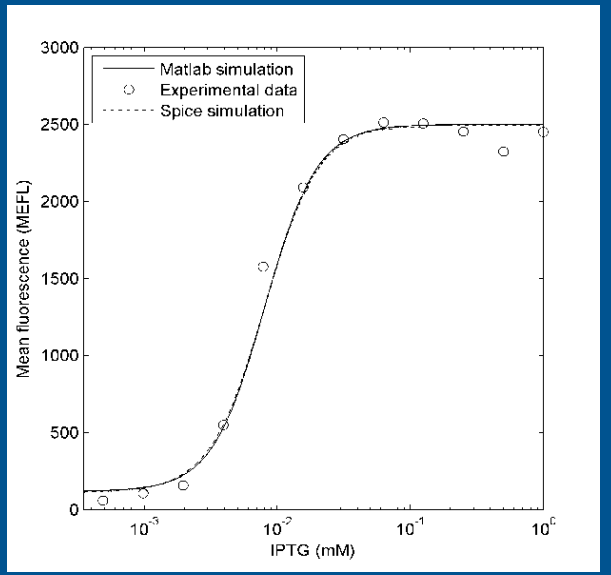


REPRESSOR



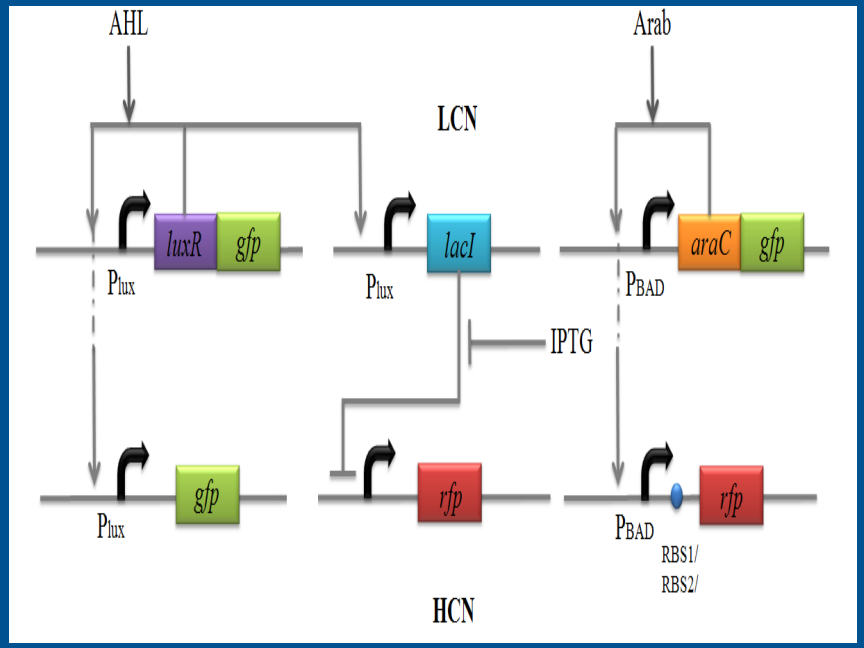


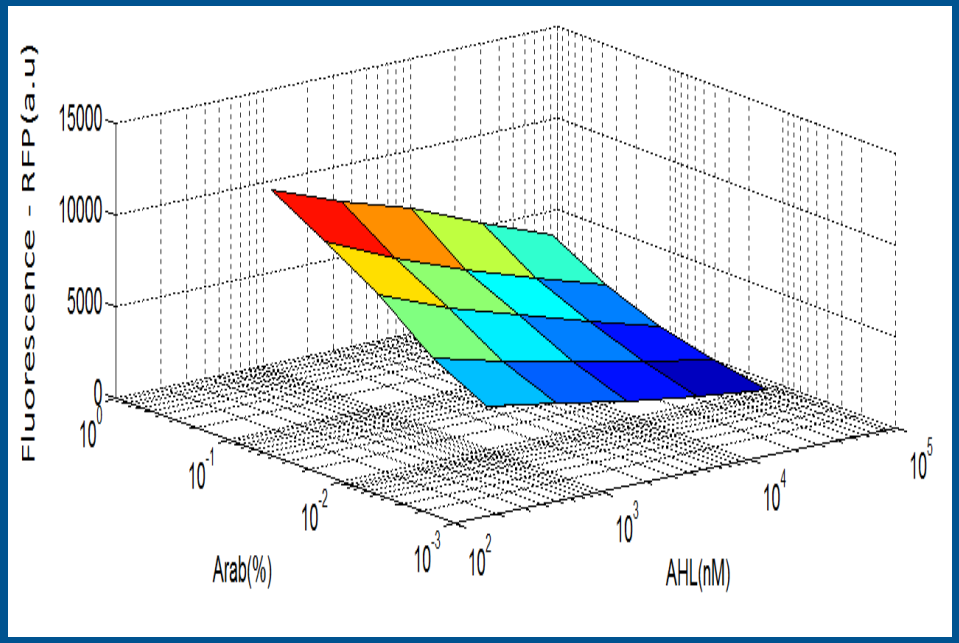
$$I_{GFP} = \frac{I_G}{1 + \frac{I_X / I_{K_d}}{1 + \left(I_{inducer} / I_{K_m}\right)^m}} + I_{Z_0},$$



Daniel et al, BioCAS 2011

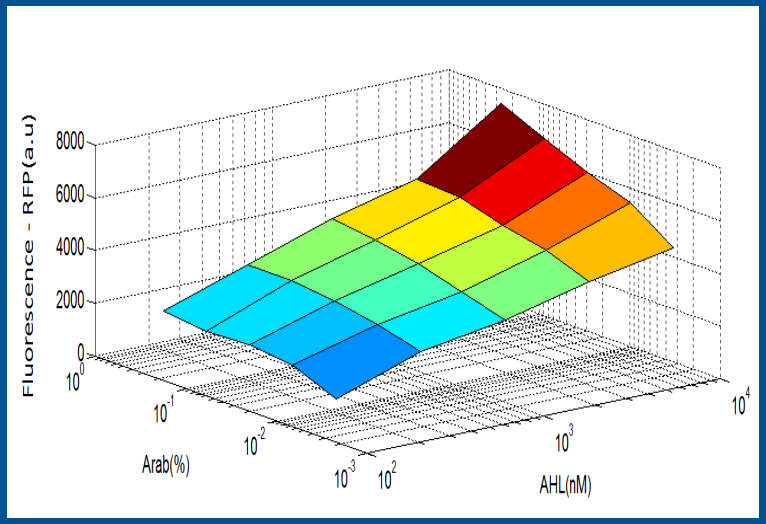
PF-Shunt, KCL, and Repression: Log-Linear Subtraction



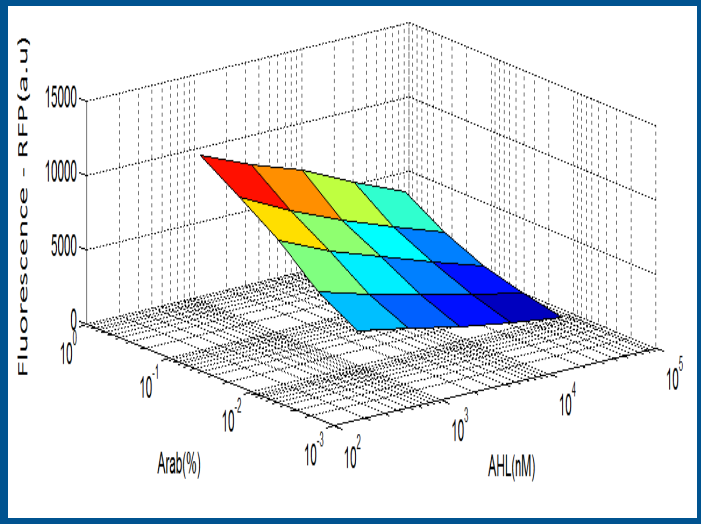


Daniel et al, NATURE, doi:10.1038/nature12148, May 2013

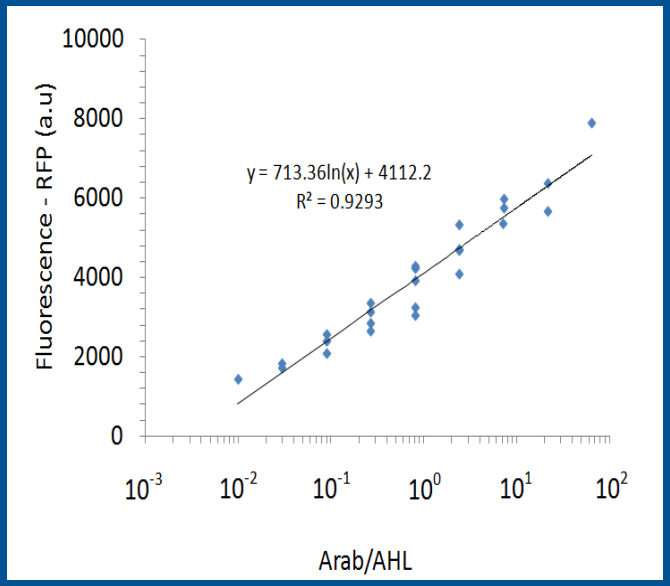
Synthetic Analog Computation in Bacteria



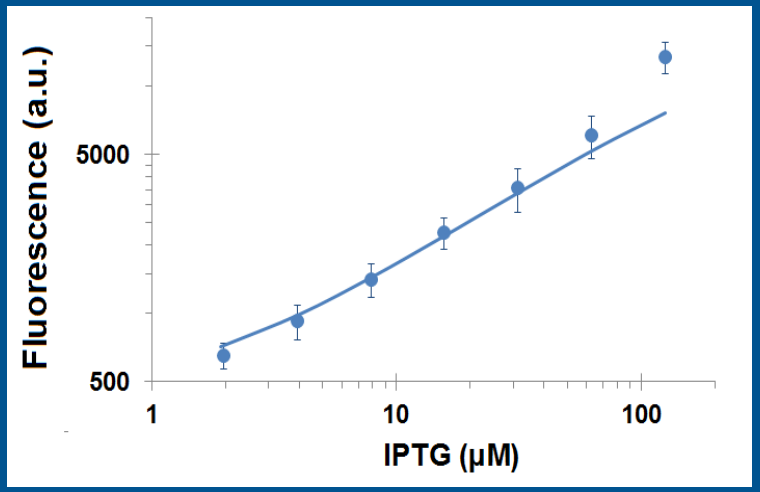
Addition



Subtraction



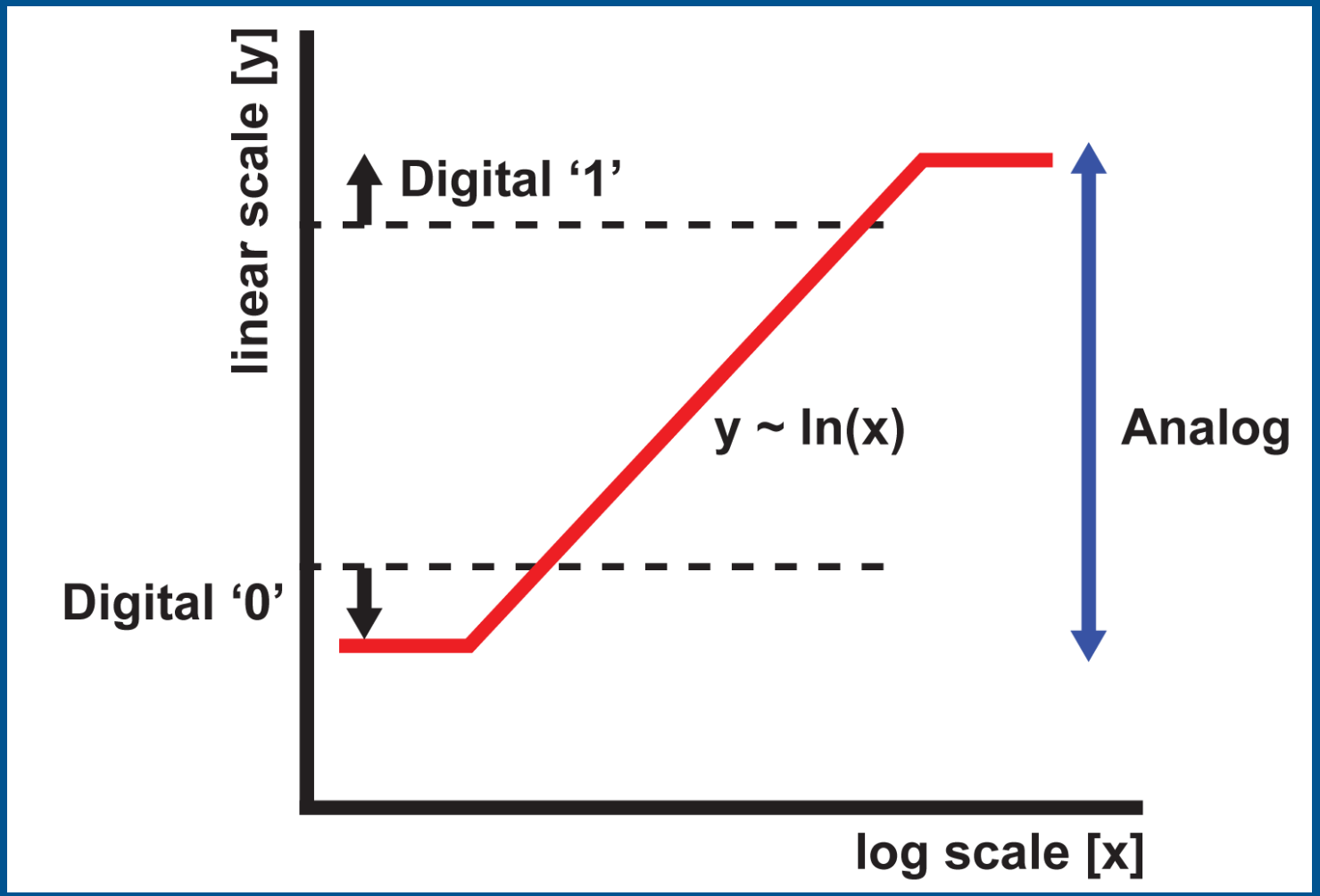
Division



Square Roots & Power Laws

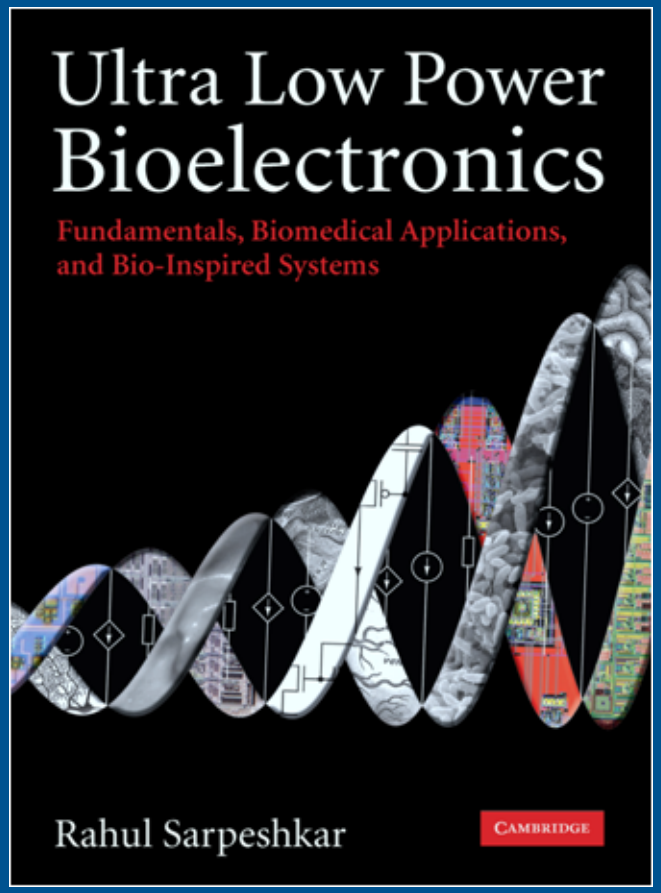
Daniel et al, NATURE, doi:10.1038/nature12148May 2013

Analog Circuits Include Digital Circuits as a Special Case



Daniel et al, NATURE, doi:10.1038/nature12148, May 2013

An Analog Circuits Approach to Biology



Chapter 24, 'Cytomorphic Electronics: Cell-inspired Electronics for Systems and Synthetic Biology'

Daniel et al, Synthetic Analog Computation in Living Cells, NATURE, doi:10.1038/nature12148, May 2013

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