Ultra Low Power Biomedical and Bio-inspired Systems

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Biological systems are incredibly energy efficient and compute with unreliable and noisy components to perform reliable and precise computations. For example, the brain computes with a staggering energy efficiency of approximately 0.2 fJ/floating-point operation, and the cell, which is even more energy efficient, uses only 20 kT per active biomolecular operation (Sarpeshkar 2010). Similarly impressive numbers for the energy efficiency of the eye, ear, and organs of the body may be found in (Sarpeshkar 2010). The creation of circuits that are inspired by biology can lead to novel architectures and systems that have applications outside of biology. Such circuits can also be immediately applied to repairing biological systems when they do not work, i.e., in neural prosthetics. This talk will illustrate how the synergy between biological and electronic circuits has led to ultra-low-power and noise-robust systems for the deaf, blind, and paralyzed and to advanced ear-inspired radio receivers. It will conclude by discussing *cytomorphic* or cell-inspired systems that establish an important bridge between electronics and chemistry (Sarpeshkar 2010). Such systems lay a rigorous foundation for an analog circuits approach to systems and synthetic biology, fields highly important in the future of medicine and biological engineering.

A rigorous comparison of the pros and cons of analog versus digital computation (Sarpeshkar 1998) reveals that analog computation, which exploits freely available physical basis functions in the underlying technology that are not necessarily logical or linear to compute, is more energy efficient than digital computation at low precision and vice versa (Sarpeshkar 1998). Biology exploits this insight to compute in a novel and highly energy-efficient *collective* *analog* or *hybrid* fashion that is not purely digital or purely analog but an intimate combination of both (Sarpeshkar 2010). Engineering systems can take inspiration from biology to also compute in this fashion, and can improve energy efficiency by delaying digitization after an optimal amount of analog preprocessing (Sarpeshkar 2010).

One example of a bio-inspired collective analog system is the *RF cochlea* (Mandal 2009), an electronic chip which takes inspiration from the spectrum-analysis of the inner ear or cochlea, to create an energy-efficient and ultra-fast broadband radio-frequency spectrum analyzer. This chip exploits the fact that the ear's spectrum-analysis architecture is the fastest and most hardware-efficient known to man, faster than a digital Fast Fourier Transform or an analog filter bank. It efficiently maps the partial differential equations that describe fluid-membrane-hair-cell interaction in the biological cochlea at kHz audio frequencies to inductor-capacitor-amplifier interaction in the RF cochlea at GHz frequencies. The resulting broadband RF-cochlea chip operates with 20x lower hardware cost than a traditional analog filter bank or with 100x lower power than a system that directly digitizes its RF input to perform spectrum analysis. The RF cochlea is useful as a front end in advanced cognitive or software radios of the future (Sarpeshkar 2010).

The use of analog circuits to perform energy-efficient spectrum analysis is also useful in *bionic ear* or *cochlear implant* processors for the profoundly deaf. Cochlear-implant processors compress spectral information present in a microphone signal in a nonlinear fashion such that it is suitable for charge-balanced tonotopic current stimulation of a cochlear electrode array implanted near the auditory nerve. For example, a digitally programmable analog cochlear-implant processor described in (Sarpeshkar 2005) lowered power consumption by 20x over a conventional A-D-then-DSP design, enabled flexible 86-parameter programming in a patient who understood speech with it on her first try (Sarpeshkar 2006), was highly robust to several sources of noise including transistor mismatch, *1/f* noise, power-supply noise, RF cross talk, thermal noise, and temperature variations, and is at or near the energy-efficient optimum even at the end of Moore's law. Thus, this processor is amenable to fully implanted and low-cost systems of the future: Its 251 *m*W power consumption enables it to function on a small 100 mA h battery with 1000 wireless recharges for 30 years. A more advanced 357 *m*W bio-inspired *Asynchronous Interleaved Sampling* (AIS) cochlear-implant processor utilizes a novel bio-inspired method of nerve stimulation similar to that present in the auditory nerve. It enables fine-time encoding of phase information in a signal without requiring a high sampling rate (Sit 2008). Hence, it enables music information to be encoded in an energy-efficient fashion without requiring a high number of electrodes or requiring high stimulation power consumption, a bottleneck in the field of cochlear implants. It is also important for improving speech understanding in noise. Similarly, a companding algorithm inspired by tone-to-tone suppression and gain control in the cochlea has led to improved speech performance in noise (Turicchia 2005), (Oxenham 2007).

Recent work has reported an ultra-energy-efficient adiabatic energy-recycling neural stimulator that can lower power dissipation of nerve stimulation in implants for the deaf, blind, paralyzed, or in other neural, cardiac, or muscle-stimulation applications by a factor of at least 2x-3x (Arfin 2011). Such work can be combined with state-of-the-art micropower neural amplifiers that operate near the fundamental limits of physics (Wattanapanitch 2007); with 1 nJ/bit near-field RF telemetry systems that enable transcutaneous wireless bidirectional data transmission in implants (Mandal 2008); with energy-efficient wireless recharging that circuits that operate at the limits of physics set by coil quality factors (Baker 2007); with novel highly area and power efficient battery recharging circuits (Do Valle 2011); with highly energy-efficient bio-inspired processors for neural decoding (Rapoport 2010); with highly energy-efficient imagers and novel cochlear-implant-inspired image-processing algorithms (Turicchia 2008); with bio-inspired analog vocal tracts for speech and hearing prostheses that perform well in noise (Wee 2011); and with blocking-capacitor-free highly miniature precision neural stimulation (Sit 2007). The integration of several such ultra-low-power and bio-inspired innovations can enable ultra-low-power, low-cost, highly miniature, and fully implanted neural prosthetics for the deaf, blind, paralyzed, and other conditions to become a reality (Sarpeshkar 2010). Examples of complete working systems that successfully stop a bird from signing via wireless neural stimulation (Arfin 2009), that perform wireless recording from a monkey (Wattanapanitch 2011), and that summarize system aspects of design (Sarpeshkar 2008), (Sarpeshkar 2010) discuss practical engineering constraints needed in such devices.

As these examples illustrate, analog and bio-inspired circuits have enabled and are continuing to enable noise-robust, highly miniature, and ultra-low-power operation in neural prosthetics, a necessity to reduce advanced research to practical clinical applications (Sarpeshkar 2010). In fact, the deep and astounding mathematical similarities between a form of electronics termed *subthreshold electronics* and chemistry (Sarpeshkar 2010) suggest that the impact of electronics on the future of medicine may not be confined to neural, cardiac (Turicchia 2010), or muscular prosthetics but in fact could be much broader: It could encompass a whole new way of thinking about biological circuits, simulating them, designing them, and fixing them.

The average 10 *m*m cell is a marvel of nanotechnology, performing 10^7 energy-consuming biochemical operations per second, in its stochastic, nonlinear, feedback 30,000-node gene-protein and protein-protein network with just 1 pW of power (Sarpeshkar 2010). Efficient precise computation with noisy components is achieved via clever nonlinear, feedback, and hybrid analog-digital strategies in cells in biology (Hahnloser 2000) as it is in the most advanced ultra-low-power analog electronic systems of today. Circuits in cell biology and circuits in electronics may be viewed as being highly similar with biology using molecules, ions, proteins, and DNA rather than electrons and transistors. . The striking mathematical similarities between chemical reaction dynamics and electronic current flow in the subthreshold regime of transistor operation including the Boltzmann stochastics of current flow (Sarpeshkar 2010) imply that one can mimic and model large-scale chemical-processing systems in biological and artificial networks very efficiently on an electronic chip at time scales that could potentially be a million times faster. This key idea has been built on to show how to create current-mode subthreshold transistor circuits for modeling arbitrary chemical reactions in protein-protein (Mandal 2009) and gene-protein networks (Mandal&Sarpeshkar 2009), (Sarpeshkar 2010).

The latter work shows that we can potentially attempt to simulate cells, organs, and tissues with ultra-fast highly parallel analog and hybrid analog-digital circuits including molecular stochastics and cell-to-cell variability on large-scale 'supercomputing' electronic chips. Such molecular-dynamics simulations are extremely computationally intensive especially when the effects of noise, nonlinearity, network-feedback effects, and cell-to-cell variability are included. Stochastics and cell-to-cell variabililty are highly important factors for predicting a cell's response to drug treatment, e.g., the response of tumor cells to chemotherapy treatments. In turn, analog circuit-design techniques can also be mapped to design and create synthetic-biology circuits that have been shown to be in accord with biological data (Danial 2011). Thus, they can impact the treatment of gene therapies in diseases like cancer and diabetes, or impact the understanding of how such circuits malfunction, thus leading to better drug therapies.

The deep links between energy and information allow one to articulate information-based principles for ultra-low-power design that apply to biology or to electronics (Sarpeshkar 2010). Engineering can aid biology through analysis, instrumentation, and repair (medicine). Biology can aid engineering through bio-inspired design. The positive-feedback loop created by this two-way interaction can amplify and speed progress in both disciplines and shed insight into both (Sarpeshkar 2010).

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