To Learn About Nature Look to Nature Itself

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On a dinner cruise through Matsushima, in early summer 1999, I filled my plate at the buffet and sat down at an empty table. I soon was joined by six colleagues. Looking around the table, I realized that I was surrounded by six of the most important leaders in the field of hearing research. Then I realized that the majority of them were electrical engineers by training and commented on that fact. It turned out that five were trained as electrical engineers. The sixth, trained as a physiologist, spent his career to date collaborating with an electrical engineer at MIT's Research Laboratory of Electronics. And he is an excellent engineer in his own right. By their biomedical colleagues, all six are considered to be biologists of the first rank. But each of them, at core, remains an engineer. What each of them does is *reverse engineering*—reverse engineering of systems, devices, communication strategies, and signal processing strategies designed by nature rather than by other engineers.

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I. REVERSE ENGINEERING

Finding a table full of electrical engineers at a hearing research conference might be memorable, but it is not unexpected. As is true in many biomedical fields, hearing research has a large proportion of practitioners trained as engineers. Increasingly, since the late 1960s, this has included individuals trained as biomedical engineers; but it also includes large numbers trained as electrical or mechanical engineers. Reverse engineering of biological systems undoubtedly has been going on as long as there have been engineers. As a neurobiologist, I am most familiar with reverse engineering in neuroscience, so I will focus on that. Along with many others, individuals such as K. S. Cole, A. V. Hill, B. Katz, and N. Rashevsky made it a flourishing enterprise in the 1930s. It came to a halt during World War II, but emerged as strong as ever in the late 1940s and early 1950s. This postwar effort led to Nobel prizes for reverse engineering of the cochlea (Bekesy, 1961), reverse engineering of the neural spike (Hodgkin and Huxley, 1963), reverse engineering of visual transduction (Hartline, Granite, and Wald, 1967), and reverse engineering of the synapse (Katz, von Euler, and Axelrod, 1970).

The reverse engineers in these cases had training in physics or biophysics rather than engineering. But by the time these prizes were awarded, the engineering professions themselves had begun to promote the

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concept. Electrical engineers had a long history of advancing biology and medicine through new concepts in instrumentation and clinical devices. This enterprise clearly was the main thrust of the AIEE Committee on Electrical Techniques in Medicine and Biology and the IRE Professional Group on Medical Electronics. But in 1963, those two groups merged to form what is now the IEEE Engineering in Medicine and Biology Society. The broadened implications of that new name were underscored by a special biomedical electronics issue of the Proceedings of the IRE (Volume 47, Issue 11) published four years earlier. In addition to discussions of instrumentation, it contains landmark reverse engineering—including "What the frog's eye tells the frog's brain," by J. Lettvin, H. Maturana, W. McCulloch, and W. Pitts, and "Stability, oscillation, and noise in the human pupil servomechanism," by L. Stark. Five years after the merger, in 1968, a special issue of the Proceedings of the IEEE (Volume 56, Issue 6) was devoted entirely to reverse engineering in the nervous system. Among its articles are "Neural coding in the bullfrog's auditory system, A teleological approach," by L. Frishkopf, R. Capranica, and M. Goldstein, and "The oculomotor control system—A review," by D. Robinson. Along with the earlier Lettvin *et al.* piece, the first of these landmark articles inspired the founding of neuroethology, now a thriving subdiscipline of neuroscience dealing with the neural bases of natural behavior. The second, along with the earlier Stark paper, demonstrated the power of control system thinking in biology as well as the power of being able to develop your own sophisticated instrumentation for your own physiological experiments. They inspired generations of reverse engineers in physiology.

The special issue of 1968 was edited by Tom Weiss (trained as an electrical engineer) and his doctoral mentor Walter Rosenblith (trained as a communication engineer). In summer 1959, Rosenblith had hosted a "symposium on principles of sensory communication," the contributions to which were published in 1961 under the title "Sensory Communication." This volume summarized neurosensory reverse engineering activities of the 1950s and was a profound inspiration for several generations of reverse engineers. In the Electrical Engineering Department at MIT, Rosenblith pioneered research training in neurosensory reverse engineering, an enterprise that was continued by Weiss and several others, and that continues to thrive today. Moise Goldstein and Robert Capranica (both academic descendants of Rosenblith), pioneered neurosensory reverse engineering training at Johns Hopkins University and Cornell University, respectively. Larry Stark and David Robinson pioneered neuromotor reverse engineering training, Stark first at the University of Illinois, Chicago Circle, then at the University of California at Berkeley, Robinson at Johns Hopkins University. The academic descendants of these pioneering reverse engineers can be found in industry, government laboratories, and academic engineering and life-science departments in all corners of the globe.

Neurosensory and neuromotor reverse engineering are major components in what is now called neural engineering, which in turn is a major component of *neural systems and rehabilitation engineering*, an area to which the IEEE Engineering in Medicine and Biology Society dedicates a quarterly journal. Neural plasticity (ability of the nervous system to learn or to adapt by rewiring itself) is a quintessential theme in this area. Just as most computer scientists of the 1960s seemed not to foresee the power of the consumer market to drive cutting edge computer technology, many or most of my 1960s colleagues in neural reverse engineering did not foresee the power of neural plasticity to enable realizable neurosensory and neuromotor prosthetics. This was not true, however, of James C. Bliss and John G. Linvill or Carter C. Collins and Paul Bach-y-Rita. The effectiveness of their 1960s visual prosthetic devices depended on blind subjects learning to translate images presented as vibro-tactile patterns into identifiable mental images. Cochlear implants (first attempted in the early 1970s) and retinal implants (first attempted in the last decade) do not involve substituting one sense for another, but nonetheless depend heavily on neural plasticity and training for their effectiveness.

Plasticity is quintessential to another form of engineering, what one might call "neural enhancement engineering." Teachers and athletic coaches and trainers all might be considered neural enhancement engineers. The empirical work of Michael M. Merzenich and colleagues on rewiring in the brain (1990s and earlier) and on brain-fitness-training software based on rewiring, and developed over the past decade, illustrates cutting edge neural enhancement engineering at its best. And it is a wonderful example of fulfillment of both ends of Francis Bacon's ideal, "To learn about nature, look to nature itself, and then use what you have learned for the betterment of humankind."

II. THE PROCEEDINGS OF THE IEEE 50TH ANNIVERSARY PREDICTIONS AND THE FUTURE

In the May 1962 issue of the Proceedings of the IRE, two biomedical engineers, Lee B. Lusted and V. K. Zworykin, made predictions about the state of their field in 2012. Now that we have arrived at 2012, we can see that they both anticipated the impact of telemedicine and medical informatics, and that Lusted also anticipated the growing impacts of medical genomics and minimally invasive surgery. Regarding prosthetics involving the nervous system, Lusted seems to predict hardware-tissue connection with greater axon-by-axon precision than we find in 2012. This is the sort of prediction that the more optimistic of my early-1960s colleagues might have made. The more pessimistic of them considered any need for axon-by-axon precision to be an almost insurmountable barrier. Neural plasticity came to the rescue. It seems clear now, however, that tissue regeneration and tissue-based implants will become increasingly competitive with hardware-based solutions. With regeneration, precise axon-by-axon connection or repair may well be approximated or achieved by 2062. What we now know about neural plasticity, however, tells us that even in healthy, uninjured individuals, axon-by-axon functional maps are ephemeral—the nervous system is always changing.

By 2062, there will be a large family of prosthetic systems and devices that interface transcutaneously with the nervous system and in that sense are noninvasive. There also will be a large and growing family of such (noninvasive) systems and devices that provide enhanced motor or sensory performance rather than prosthesis. By 2062, implantable items for cognitive rehabilitation (e.g., cognitive prosthetics) should be emerging. Most likely, these will be tissue based (perhaps some form of stem cell therapy). Success with such items will lead to trials in uninjured (nonhuman) brains—for cognitive enhancement. Advances in cognitive training and, especially, in interactive cognitive training software, however, will make that the preferred alternative for cognitive enhancement in human subjects. For Lewy body and Alzheimer dementia, prevention ultimately will be the solution; but the time required for verification of a prevention treatment's efficacy may mean that 2062 is too soon to expect it in common medical practice.

Accompanying the predictions of Lusted and Zworykin in the May 1962 issue of the Proceedings of the IRE is a discussion by Marcel Golay that comes very close to anticipating the "rapture of the geeks" (see IEEE Spectrum, June 2008). This is a presumption that consciousness will emerge at some point ("the singularity") in man-made machines as they become increasingly complex, self-taught, and interactive with the world around them. In his discussion, Golay stresses the importance of the scientific method and the demarcation between science and pseudoscience, which remains a central issue in modern culture. Among engineers, on the other hand, that demarcation likely is well settled. It seems clear that the concept of *the singularity* will promote vigorous discussion of another demarcation—between axiomatic science (e.g., mathematics) and natural science (e.g., physics and neuroscience). Will presence or absence of consciousness be provable in the formal mathematical sense, or will they be merely inferable in the natural science sense? In other words, will there be a definitive test for consciousness? The natural scientist in me tells me that, in 2062, the answer to that last question still will be "no." ■