The Heartbeat of Science

By Larry R. Faulkner

Ed. Note: *The following article has been excerpted from the comments made by Dr. Faulkner during the Edward Goodrich Acheson Award Address presented at the ECS meeting in Phoenix, Arizona this past fall. Dr. Faulkner is President of The University of Texas at Austin, and has long been active in the Society. He served as president from 1991-92, received the Society's Young Author Award in 1976, and was named a Fellow in 1993.*

It is a wonderful honor to join the roll of members of this Society who have been chosen to receive this award. Recognition by peers for contributions made to the health of science is among the greatest satisfactions that can be drawn from the scientific enterprise. Recognition at this level by a Society that has so faithfully served my science for almost a century adds great warmth to the occasion. This is a remarkable organization, worthy of the investment that you are making in it. I hope that, at the close of your scientific career, you are as proud of it as I am.

By the nature of its charter, the Edward Goodrich Acheson Award is given to members of the Society who have been around for a while—"senior members," one might say. Alas, I must admit that I am no longer a young turk, no longer even in mid-career. A person in my shoes, obligated now to address you on a serious topic, runs a great risk of entrapment in the past.

When I started to develop this talk, I thought I might work with the title, "Impressions from the Golden Age." (How's that for entrapment in the past?) The idea was simply to recognize that, during the years of my career, science has passed through a remarkable time of advance. How striking it has been! How different is the base of knowledge and the tools taught to chemistry undergraduates now, by comparison with the contents of the curriculum I had. We certainly have had a Golden Age, and we are probably still in it. I thought I might explore with you just what we have learned from that time about the conditions that can bring about a new golden age, or that might be needed to extend the one we have.

But I began to think about the fact that science has a rhythm: It pulses and consolidates, pulses and consolidates. This is certainly true of individual fields like physical electrochemistry or battery technology; and as the separate cycles of separate fields reinforce each other, science as a larger enterprise pulses, too. This is what I mean by the heartbeat of science. I am old enough to have seen several cycles in each of my own domains.

When I use the word "science" here, I mean to include technology. And I mean to have technology understood as quite a bit more than information technology.

What makes the heart beat? What can keep it beating in a healthy way?

In my mind, the big forward pulse in each cycle always comes from the advent of an exceptionally valuable tool, technique, or insight. Consolidation follows as it is used to explore a broad range of systems or phenomena, and as theory is critically tested. In a healthy field, the consolidation is thorough enough and well enough targeted to critical issues to lay the foundation for the next major invention: another new tool or technique, or an illuminating insight. And the cycle repeats.

In periods of rapid advance, the heart beats fast. New tool leads to quick, broad application, which leads to insight, which suggests new techniques and new tests, and on and on.

Let me illustrate with some experiences. I was born into science as a graduate student with Allen Bard at the University of Texas in the 1960s. The powerful tool that drove that era was the operational amplifier, which radically changed the experimental repertoire of electrochemistry. It led to new techniques, like cyclic voltammetry, which led in turn to very broad exploration. New insights arose. Important among them was the concept that an electrode surface is a chemical entity, not just a physical one. In the early 1970s, this led to the idea of deliberate synthesis of chemical structures on a surface, and the field of modified electrodes exploded. It was greatly advanced by the tools from surface science, which were brought into electrochemistry at about the same time. Electrochemists began to think smaller, and by the early 1980s, they were interrogating tiny spaces with tiny electrodes. As these ultramicroelectrodes were applied broadly, new phenomena were seen, and insights followed about how they could be used to extend measurements into very short time domains or into systems of high resistance. By the middle 1980s, the new piezoelectric positioning technology used in scanning tunneling microscopy had been brought into electrochemistry and was driving many advances, including the characterization of surfaces at active electrodes and the invention of new tools, such as scanning electrochemical microscopy.

And all along, there have been parallel advances in critical areas of theory, such as the fundamentals of electron transfer or the treatment of complex mass transfer and kinetic problems. Spectroscopic techniques have also come into the field from time to time and have had a big impact.

To keep the heart beating, the system of science needs to place a fair emphasis on tools, techniques, and insights. But there is fine structure here: Tools and techniques are often essential to advance fundamental insights in any particular area of science, but they are not enough to sustain the heartbeat. They can create a cycle, perhaps even a few in sequence, but in a field where understanding is very fully developed, new tools and techniques confirm what is already known, and new insights are rare. The heart begins to beat slowly, or even comes to a stop. New insight is the essential.

For this reason, the scientific enterprise cannot afford to support work that is oriented entirely to tools and techniques. It needs theorists; it needs people interested in chemical processes, kinetics, mechanisms. It must never forget to ask, "Why?" In our pragmatic age, fascinated as we are with the technology of the possible, there is a temptation to devalue that propensity, especially on the physical side of science.

The heart responds to exercise and adrenaline, too. For the scientific heart, these things are found in the form of public and private investment and social urgency. It is no secret that science operates on money. Wealthy societies invest more, and the pace of

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their science is more rapid. Political or social concerns can inject special conditions into the picture and can quicken the pace markedly, especially if national security is involved. In my time, I have seen many examples, including two big waves of research on electrochemical processes at semiconductors driven by public concerns over energy supplies. Even now, we are seeing an extra push in research on batteries and fuel cells driven by that concern and by the public interest in environmental protection.

The heartbeat of science depends so much on innovation that it is worth our while to try to define elements that can encourage it. Here is my list:

- Talent
- Funding appropriate to opportunity
- Social purpose
- Personal fascination among individuals
- Room for entrepreneurship

An old saying in real estate is that the three most important aspects of a property are location, location, and location. In any field where innovation is at a premium, at the top of the list of desirables are talent, talent, and talent. In science, as in opera or baseball, there is indeed such a thing as talent; and in science, as in opera or baseball, there is no substitute. The health of science depends above all on drawing into it people with the talent to bring about the innovation that sustains the heartbeat.

I have spoken already about funding and about the role of social purpose. Let me add here a point about the latter. Not everything in science needs to be focused on application. Indeed history proves that critical, insight-giving fundamental work often provides the largest new stimuli for further progress. But a clear social purpose (including profitable business) does motivate many individual scientists and helps to build scientific communities around large, important goals.

My favorite in this list of elements, rarely mentioned otherwise, is personal fascination. Albert Einstein once wrote to a young student, "Science is a wonderful thing if one does not have to earn one's living at it." With this pithy remark, he expressed the pleasure that a committed soul gains just from doing science for the fascination of it, without worry over the nuts and bolts of scientific enterprise—proposals and publications, agencies and committees, budgeting, and personnel. While we cannot escape those nuts and bolts—after all many of us do earn our living at science—we can give higher place to fascination. Fascination is among the highest and best of human motivations. A great fraction of creativity in science, the arts, and many other fields derives from it. In a cynical, pragmatic world, it simply evaporates from the human soul. Invaluable indeed it is, and we should find deliberate ways to honor it, to cultivate it, and to allow it to flower.

The last element on my list is room for entrepreneurship. In the 1920s, John Dewey wrote, "Every great advance in science has issued from a new audacity of imagination." With this remark, Dewey placed an emphasis on the dual importance of the individual and venturesome thought. Powerful new ideas germinate in the minds of individuals. Colleagues can help develop them, but room needs to remain in science for individuals to think and to develop their ideas. And there ought to be room to start new ventures, new schools of thought or investigation. There must be mechanisms, too, for the unsuccessful ones to fail.

In the glow of our golden age, are there reasons for concern over the vitality of science? I think so, and I would like to give you my list:

- Graduate education takes too long and is too oppressive.
- The attention span of the community is too short.
- Granting procedures are overcoded.

In the United States, the average time required to earn a doctoral degree in science has lengthened markedly—by two years or more—over the past three decades. Moreover, the emphasis has shifted from development of the student to production of publications and meeting abstracts. Results have always been important. After all, it was Michael Faraday whose motto was "Work. Finish. Publish." But publications have not always been everything in graduate school. When students of ambition, energy, and talent look at the current system of graduate education, many opt for other ways to develop a career, ways that allow them to see quicker results and to become professional more quickly. Moreover, the system is so tightly focused that it tends to eradicate fascination in students as they proceed, and that is a real shame. We need to find ways to shorten graduate education and to breathe life back into it. Perhaps elevating the professional standing of postdoctoral appointments would be a valuable parallel effort.

My second concern is that the attention span of our community is too short. This has happened because making a living from science has become too complicated. Einstein would not do well at all. Too many nuts and bolts. Too many proposals, committees, publications. Too little time to think. The Internet hasn't helped that. To address this ill, I suggest that the scientific societies and a key academic organization such as the Association of American Universities seriously engage the issue of fragmented, repetitive publication and overcommitment of scientists. Whatever they learn about the academic side should be at least partly applicable to industrial science. Without changes in editorial and review practices in important journals and without changes in policies concerning career advancement of scientists, there will be no progress here. But it is important to make progress. The current system does not make the best use of talent, and it discourages creativity. It does encourage innovation, but more in the mode of change of fashion, rather than substantial invention leading to broad impact.

My last point concerns the practices of granting agencies, which may be the most important factor of all, because they have a substantial effect on the current nature of graduate education and on the factors leading to a short attention span. Key agencies should surely be engaged in the process that I suggested earlier concerning fragmented publication and overcommitment of scientists. My expression was that their procedures are "overcoded," which is a way of saying that processes are cumbersome, require too much overall effort from all parties, and often are aimed at accomplishing too many things in a single process. The result is a system that can lead investigators away from science and into insubstantial arrangements with colleagues or students just to satisfy specifications of what a contemporary proposal ought to be about. It ought to be about science.

I am sympathetic with program officers who staff the agencies. This is not a story about them. My experience is that they work in good faith to do the right thing for science and for the nation. But they work under boundary conditions defined by Congress, policy boards, or advisory committees, all of whom act with little understanding of the way in which small requirements roll up into an overall system that is far less than optimal.

And it is not altogether a bad system. In my experience, it allocates resources fairly well to scientists who manage to do a lot of science with those resources. But I think the system could achieve the same results with much less effort by all of the parties, and perhaps in a way that could also increase the scientific attention span and do a better job of encouraging serious innovation. Such measures as broader use of reviewed preproposals, lengthened terms for grants, and mechanisms for consolidating grant support are all worthy of consideration.

Balancing these concerns are some bright things that can keep the heart of our science beating for some time to come. I will cite three:

- Important new domains, such as nanoscience and nanotechnology are so broad as to be surely rich areas for new applications, tools, techniques, and insights.
- The advent of very powerful new computational tools will open important new approaches for the understanding of complex materials and systems.
- The vitality of science is broadening geographically as democracy extends itself, education becomes more highly valued, and wealth develops.

We live in very interesting times, with spectacular opportunities as well as daunting challenges. Some in each category are so great as to involve all humankind. We can neither realize the opportunities nor meet the challenges without science. Those of us here can take pride and satisfaction in that realization, but we also must realize that science is itself an organism that must sustain and renew itself. Precisely because science is indispensable, we in the scientific community need to keep a careful watch on the health of science itself. ■