Basic Energy Sciences 2018: A Future Retrospective
In Memoriam Iran Thomas
"The Promise of Nanotechnology"
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Predicting the future is a chancy business, especially when the subject is exploring the unknown. But that is what we ask the people to do who are entrusted with spending public funds for research. Fortunately, the course of science is constrained in interesting ways that make this not an impossible task. I did not know Iran Thomas as well as many of you did, but my impression was that he had an instinct for how science works, and to peer a mere fifteen years into the future would have been for him no trouble at all.

We are living through an exciting time for science, especially in what the Department of Energy calls "Basic Energy Science." I think of it as the science of the part of our world dominated by the electromagnetic, as opposed to the strong or the gravitational, interactions. That covers most of the phenomena important for humans, and serves as a model for all the rest. The immediate future of science in this immense domain promises to be a rich one, and I look forward to hearing other visions at today's symposium. My own thoughts about this future begin with a phenomenon in the recent past.

As the 20th century drew to a close, so too did the first rash exuberance of speculators in applications of the new technologies based on the Internet – what we now call the "dot-com bubble." From January to December 2000, more than 130 Internet companies had folded in the U.S. and Europe, and in November they went out of business faster than one per day. By 2002, Department of Commerce officials estimated 500,000 lost jobs and $2 trillion in lost market value in the telecommunications and technology sectors of the U.S. economy.

As the bubble burst, however, the technical revolution that made it possible continued to roll forward. Unlike the tulip mania that swept Holland in the 17th century, with which it is often compared, the dot-com phenomenon was based on a real and lasting change in the technology infrastructure of the world economy. I am neither an economist nor a historian, and I no more understood what was happening at the time than anyone else, but the ingredients were clear enough, and they offer some insight into near-term future developments in science and technology.

What particularly intrigues me about the dot-com bubble was how completely the futurists and technical visionaries failed to anticipate it. Some visionaries had accurately anticipated technical aspects of the future we now inhabit – the science fiction author William Gibson comes to mind – but none predicted the singular set of social behaviors that led to the dot-com phenomenon. The point is that technical evolution is easier to predict than the social consequences thereof. Which gives you some idea of how I plan to handle my assignment this morning to speak about the promise of nanotechnology. The fact is that the most important

consequences of nanotechnology are social, and they are unpredictable in the sense of that word that physicists understand. We cannot ignore the social impacts, and must be prepared to discuss them and deal with them as they become more apparent. But prediction is too difficult.

Some things about the future of science *can* be predicted, however, and quite accurately. I think Iran Thomas had a valid vision of the future of his field, and acted deliberately to help bring about the important capabilities we have today – capabilities that form the infrastructure for the technical revolution taking place around us. Before I say more about them, I would like to point out four aspects of science that make prediction possible. I am not talking about solving Schrödinger's equation, but about anticipating the technical context of future science.

1. The first aspect is that in the long run the growth of science is progressive and irreversible. There are no business cycles in science. (But there are occasional dead-ends.) The advancing front of science does not reject its past, but absorbs it. This progressivism, unusual among human enterprises, can be explained only by the objective reality of the natural world. Discovery in science is somewhat like geographical discovery. Nature is there for us to search out. We map her features with mathematical structures on a conceptual globe whose geometry reflects the laws of Nature. What makes science somewhat predictable is first of all that the ground we gain according to the methods of science is never lost. Everything we do next in science must accommodate everything we have already done, and so by necessity the new ground is somewhat familiar.

2. The second aspect is that science rarely jumps from the continent of the known to an isolated island in the unknown. Physicists think of Einstein's theory of gravity as an exception to this rule, and Ed Witten has said that string theory is a bit of 21st century physics that landed by accident in the 20th century. These are rare exceptions. Scientific understanding tends to extend out from its current base. And the means of extension are the technologies we use to magnify our powers of perception. It is no accident that modern experimental science grew up with the industrial revolution. Through much of the 19th century, science remained in debt to technology. With the discovery of the laws of electricity and rapidly developing chemical knowledge, the balance became more nearly equal. With the advent of quantum mechanics in the first quarter of the past century, science began to drive technology. But empirical science necessarily employs existing technology. Consequently the advance of science is tied to the advance of technology. New tools create new opportunities for discovery, and new discoveries enable new tools. This is particularly true in the Basic Energy Sciences.

3. The third aspect is that science has well-defined structures intrinsic to its operation. It requires tools; it demands sharing of information throughout the community; its cycle of hypothesis, experiment, comparison, and revision entails social structures and psychological attitudes among its practitioners. And these structures are conservative. They change slowly. Even at today's unprecedented pace, the change is slow enough to predict fifteen years ahead and more.

I might interject here that when it comes to the public understanding of science, it is these structural features of how science works and what is required to sustain it that are most important, but least heeded by science popularizers and publicists. It is nice to think of teaching

everyone about the subject matter of science, but most people will not become scientists themselves. Even those who do will not succeed unless they learn this structural/social side of their profession. It's more fun to focus on the science than on how science itself behaves, but there is much more to science than the highly visible and sometimes romantic work of discovery. How can we convince science journalists that part of the story of discovery is the chain of decisions that fund its pursuit? The greatest need for public education in science is not about the facts and concepts of science, but about the machinery of science, and what it takes to keep it running.

4. The fourth aspect, of course, is that Nature herself has a structure that does not change at all, only our knowledge of it. In the domain of electromagnetism, the place where humans dwell, we think we know the basic rules. We call them Quantum Electrodynamics, or "QED." Whatever we learn in the domain of Basic Energy Science had better be consistent with these rules. The basic rules, of course, permit an unimaginably huge diversity of structure – the entire natural world of animals, vegetables and minerals – and centuries of exploration will not exhaust the possibilities. The unusually accurate status of QED makes it reasonable to invest heavily in first-principles calculations – actually simulations – of physical, chemical, and biological phenomena. Knowing definitely the underlying rules, and possessing sufficiently powerful computers and algorithms, enables us in practice as well as in principle to discover new phenomena in "computer experiments."

These four aspects of science: progressive in the long run, incremental through technology, and structured in execution and in content, provide a very strong basis for forecasting and planning. Fifteen years from now, we will still be solving Schrödinger's equation; we will still be using fundamental particles – photons, electrons, neutrons – as probes to sense material properties; we will still use accelerators and lasers to generate them; we will use inexpensive computers to control equipment, manage data, write reports, and communicate with our colleagues. Fifteen years from now, the things we study will still be made of atoms.

So what will be new? If everything will look pretty much as it does now, where will the excitement be? What I have said so far is very abstract. The simple and stable rules – the laws of motion – can lead to overwhelmingly complex and dynamic behavior. At this point in my remarks, I have to make a strategic decision about what to say. There is simply too much detail There are too many possibilities. The vista of science now potentially unveiled by powerful new technologies of computing and atomic scale manipulation is so immense that it is changing fundamentally the balance of importance among traditional fields. This morning I am not going to get into much detail, since others in today's symposium, and especially this audience, know more than I do about them. So I will simply mention some avenues of endeavor that seem significant to me: a physicist by training with a long interest in these fields.

I see four avenues along which discovery will take place.

1. First, the exploration of phenomena in systems with huge numbers of degrees of freedom coupled in a complex way. Some systems with many degrees of freedom are easy to describe: an ideal gas, for example, where randomness eliminates the need for detail, or the opposite extreme of perfect crystals, where all you need to know is the location of atoms in a single unit cell. But

intricate coupling among degrees of freedom rapidly increases the mass of information required to describe and understand behavior. This is what I call the frontier of complexity. It includes the extraordinary structures of life, in all their hierarchical glory, from DNA to organisms. And it includes the more exotic visions of nanomachinery. There is an inevitable convergence of biology with chemistry and physics here, and we are just beginning to explore the boundaries. The necessary underlying technology includes instrumentation for imaging, manipulating, and simulating matter at the atomic scale. This includes large x-ray and neutron sources on the one hand, and on the other, massive computing and data storage capacities.

This is the really interesting domain of nanotechnology, a term that could be used to characterize molecular and cellular biology as well as the inorganic structures for which the term was invented. It is no accident that nanotechnology has remained a priority in this administration, and it will continue to be a priority for federal funding for the foreseeable future. Experience has shown us that entirely new phenomena emerge in systems of increasing complexity. As Phil Anderson has said, "More is different."

Commercial applications of nano-scale technology are already important in optical and magnetic devices. I expect they will become important in chemistry as well, particularly in phenomena such as catalysis that occur at surfaces. Microstructures for controlling photons, such as photonic bandgap systems, will also continue to be developed and integrated with electronic devices.

2. This control over microscopic properties brings control over a material degree of freedom that has remained relatively unexploited in the past. The second avenue of discovery that seems interesting to me is the taming of the electron spin degree of freedom. The catchy name "spintronics" suggests the potential of these studies, which have already spawned economically significant applications in magnetic memory devices. Magnetics in general has much to gain from the new nano-capabilities.

3. The third avenue is the extension of quantum coherence into the meso- and macroscopic domains, and its exploitation in new technologies. Many of the tools required to probe and exploit complexity are relevant here. Increased understanding of decoherence, the crucial process that divides quantum from classical behavior, is an essential part of this effort. There are two interesting approaches to this problem. One is to work with increasingly perfect systems at very low temperatures to extend quantum coherence to macroscopic scales. The other is to shrink the size of entire systems to scales where coherence is more easily achieved and sustained. Nano-control of material properties is essential to both approaches. Practical applications of quantum coherence are greatly expedited by clever ideas that are emerging for dealing with states of partial decoherence.

I think the problems of achieving and sustaining quantum coherence in complex systems are so difficult that technologies based upon them will be very limited even fifteen years from now. Some quantum information processing applications may be realized sooner, but the vision of quantum computing will, I believe, take decades to be realized. Because all matter is governed by quantum mechanics, however, and because of the new nano-capabilities, many new

systems will be discovered or invented during the next decade that display interesting quantum coherence properties.

It is in this category that "cold atom" physics lies, a field whose practical applications will be realized gradually in much the same way that laser applications gradually emerged after the laser appeared in 1960. It took more than fifteen years for lasers to find truly widespread commercial application, first in eye surgery and military target designators, but the largest commercial market for lasers in the early days was in art displays.

4. The fourth avenue is the continued exploration and exploitation of the fourth dimension of atomic-scale phenomena, the time dimension. The atomic time-scale is measured by the period of optical oscillations, or the rate of electron transitions in chemical reactions. The first steps toward control of temporal phenomena at this scale occurred with the invention of the laser. Today we are seeing the emergence of optical pulse control where the pulses themselves are on the order of or less than this scale. Apparatus that combines pulsed beams of electrons and photons continues to be extremely interesting, from conventional particle accelerators to free electron lasers, laser particle accelerators, and probes of extremely fast atomic processes. I see a convergence here of accelerator physics with optical and molecular beam technology. Richard Feynman's famous lecture "There's Plenty of Room at the Bottom" focused on the opportunities for structures with small spatial scales. We must not forget that size has four dimensions, and the time domain still has much unexplored territory.

There is one other intriguing possibility for the future that is impossible to forecast. According to the Standard Model, the fields whose excitations we observe today as elementary particles have components that have frozen out in the current state of the universe. That is, our entire universe today is an immense condensed matter system, with fluctuations. The keystone Higgs mechanism of the Standard Model has its origins in condensed matter theory, itself a product of Basic Energy Science. One of the surprise discoveries of the previous quarter-century is just how complex the Standard Model is. The ground state of the quark-gluon sector, for example, which is responsible for quark confinement and most of the observed mass in conventional matter, is a vacuum condensate with very complicated space-time structure. The most important function of the Higgs field is to produce a condensate that couples with other matter. Is it possible that the tools and explorations of nanotechnology can provide new concepts that give insight into these complex structures of the Standard Model? Might there be a relation between the complex topologies of string theory objects and the intricate foldings of nano-objects?

Iran Thomas would have been proud indeed if he could have known that the capabilities he endeavored to provide to science were to reach so far into the corners of our universe. He would certainly be proud of the array of phenomena that have already sprung from his labors. I am sorry he is not here to enjoy our reflections upon them.