Opportunity and Discovery in Science
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Thank you very much President Coleman, and thanks to the organizers for inviting me to speak at this celebration of African-Americans in physics. The University of Michigan has a long and proud tradition of support for students and scholars from diverse backgrounds, and I am honored to participate in its celebration.

As I prepared these remarks, I was not sure what others would say about the significance of Elmer Imes' contribution to physics, but I would like to add a few thoughts of my own before I turn to other topics. I do not mean to slight the contributions of Willie Hobbs Moore, but the work of Imes was so unusual for its time as to warrant special attention. Imes' did his work on the infra-red spectra of diatomic molecules between 1915 and 1918. Recall that the quantum of action had been introduced by Planck in 1900, but no one knew what to make of it until Einstein began to use quantum ideas to explain other phenomena in 1905. Einstein was the first to suggest, in 1907, that Planck's formula relating energy to frequency might apply to vibrations in systems other than atoms. Recall that at this time the electron had been discovered, but not the nucleus. Bohr's model did not appear until 1913, and was by no means accepted immediately by the scientific community. In the same year Paul Ehrenfest first applied quantum ideas to rotational states of a diatomic gas to derive its specific heat, an issue very similar to Einstein's earlier work explaining deviations from the law of Dulong-Petit summarizing the temperature dependence of the specific heat of solids. And here we have Elmer Imes working on diatomic spectra two years later, seeking independent evidence of quantum behavior in vibrating systems.

In view of the overwhelming strength of experimental and theoretical physics in Europe at this time, you might be surprised that any American work could compete for attention in that exciting time just before World War I. America was a full participant, however, in the industrial revolution that had blossomed nearly a century earlier. The enabling technologies it produced of electric power, photography, the liquefaction of gases, and of course high resolution spectroscopy, were all available to the small but growing American science community. What is perhaps surprising is that an *African-American* should have been among the distinguished contributors.

But perhaps we should *not* be surprised, because one of the very striking features of the great quarter-century of discovery in physics at the beginning of the past century is precisely its cultural inclusiveness. To be sure, Germany dominated. But important results and brilliant researchers came from most corners of the globe. Ernest Rutherford, a wheelwright's son from New Zealand who worked at McGill in Canada before going on to England; Satyendra Nath Bose was working on quantum theory in Calcutta at the time of Elmer Imes's dissertation work; Yoshio Nishina was also beginning his studies during this period in Japan. Neils Bohr's institute in Copenhagen was famous for welcoming and supporting physicists from all over the world, and many brilliant careers can be traced to his generous influence.

It seems to me that in whatever culture access to education appears, its people quickly acquire the capacity to contribute to science. In view of many examples from other parts of the world, we should not be surprised at Imes's ability to make discoveries at the forefront of his field. Cultural or ethnic background does not predispose one toward or away from science, as far as I can tell. The unusual aspect of Imes's contributions is the access he had to the educational prerequisites for success.

"Access" of course, is not enough. It is rare for opportunities to appear magically and to be seized effortlessly. I do not know enough about Imes's early history to comment on his ambition or his industry or his persistence, but I know that all these are necessary to succeed in science, even when the opportunities present themselves. It is clear, however, that access to education, particularly to graduate education, was difficult for African-Americans in the early years of the twentieth century. We can be grateful to the University of Michigan for its policies that made it possible for Imes's ambitions and hard work to bear fruit. Imes's discoveries could not have been made without the opportunities created by this university.

As a long-time teacher and researcher and academic administrator, I have had many occasions to ponder the pre-requisites for discovery. And now I find myself in a position where people expect me to have answers. Certainly educational access is important, but it is just as certainly not enough. The equation for success has many terms – and some of them are random variables. One important factor is continuity of preparation, or in plain language, an adequate education at every grade level. Educators have zeroed in on grades three through eight as particularly critical for science and math instruction. The whole rationale of President Bush's education initiative "*No Child Left Behind*" is to strengthen the educational experience in these critical grades so doors to productive careers will remain open.

In my view, teaching science is very difficult, and the challenge of going beyond simple access and motivating young people to do the hard work to become scientists is enormous. I do not have any magic answers about how to do this, but I do have some thoughts about science and teaching that I would like to share with you. Some of these are from remarks that I made yesterday at a "*Science Education Summit*" convened by Secretary of Education Roderick Paige. This was a successor to last year's "*Math Education Summit*" where I also spoke, and said, among other things, that mathematics is the language of nature – an idea first clearly stated by Galileo, who said the book of nature lies open for all to read, and it is written in the language of mathematics.

The idea that mathematics is the language of nature immediately raises the question: *What is nature?* I suppose that is obvious to most people. We use the word "nature" to refer to everything that exists outside ourselves, and sometimes even to ourselves since we are part of nature too. Nature encompasses the stars and planets, earth, sky, and water. It includes the smallest things and everything that can be made from those things, whatever they are, living or inert. And nature includes not only the animals, vegetables, and minerals, but also their behavior – how they interact with each other and all the rest of nature; how they grow and age and interact and disperse in the endless course of time. The Universe of nature is a grand place, our ultimate home. Each of us wants instinctively to understand our role within it. And that instinct emerges spontaneously when as children we learn the names of things and what they mean to us.

"*No Child Left Behind*" acknowledges this instinctive curiosity of children, and strives to sustain it through best teaching practices during the learning years. We have a responsibility to all children to give them the tools for understanding the world they live in. One of those tools is science. I think there is confusion about science, and I think being clear about it would help us teach it better.

Mathematics – the language of nature – is not science, nor is nature herself science. Science is something else. Science is not the names of plants or the bones of the body. Richard Feynman, now something of a popular science icon, told a story about his boyhood when his father taught him about birds on long walks in the mountains. Probably everyone in this audience knows the story. Feynman's friends made fun of him because despite these sessions, he did not know the names of any birds. His father told him "You can know the name of [a] bird in all the languages of the world, but when you're finished, you'll know absolutely nothing whatever about the bird. You'll only know about humans in different places, and what they call the bird." What Feynman *did* learn were the behaviors and habitats and unique characteristics of the birds themselves. Along the way he learned something about science. Many people, myself included, have difficulty remembering names, but we are able to function well enough in society despite that handicap. So there is something more to know than names.

And yet naming things is necessary for science, because science is ultimately a social activity and the ability to communicate unambiguously what we are talking about is essential to the progress of science. The point is not that naming things is unimportant – it is essential. But it is not science.

I could go on for hours about what science is not. Like the names of things however, much of what science is *not* is nevertheless important for actually doing or applying science. Science is not simply a description of things, no matter how accurate. The people of ancient Sumer in what is now Iraq, the earliest civilization known, made accurate observations of the stars and planets, but they were not scientists. But accurate observation is essential to science. Science is not simply a collection of facts about things, partly because what we mean by a "fact" is rather slippery and bound up with the concept of "truth." Is the statement that "this footprint was caused by a tyrannosaurus rex" factual or not? How do we tell? And yet whatever definitions we choose, facts are undeniably a part of science.

"*Science*" has become a word loaded down with meanings. At its core, however, science is a way of continually improving our understanding about nature. It is a method, a practice, even for some a way of life. *And it is based on examining nature to test our ideas*. This conception of science requires us to assume there *is* a nature that consistently "answers" the same questions the same way. All our experience indicates that is correct, that nature is reliably consistent, as long as we are careful about what questions we ask. But nature is most marvelously intricate, harbors many mysteries, and often fools us with superficial appearances. Science does not answer all questions that we may ask, nor many questions we need to answer.

Nor does it give us truth. Science does not even tell us how nature works. *What science does is test our ideas about how nature works.*

When I became Director of Brookhaven National Laboratory in 1998, Department of Energy officials asked me to introduce "performance based management" practices in the Laboratory. At first, I was only vaguely aware of what that meant, but it soon became clear that I was expected to have well defined plans, to execute work according to the plans, and if the work turned out differently than expected, to change the plans for the next time around. Management experts call this the *cycle of continuous improvement*. It goes with a mnemonic that can be traced back to America's quality management guru W. Edwards Deming: *Plan, Do, Check, Act*. I like that way of doing things. That is the core method of science, and I explained it to our scientific staff that way. The same ideas form the basis of the *President's Management Agenda*, promulgated by President Bush to improve the performance of all government agencies. [Earlier this afternoon, Ford Motor Company executive Dr. Gerhard Schmidt described Dr. Hobbs Moore's work at Ford based on Deming's ideas.]

I have given a lot of thought to why every organization does not embrace this so obviously sensible method. The reason seems to be that making plans and checking performance against them requires a lot of time, not to mention thought, and changing your ideas about how things should be done encounters huge psychological resistance. Doing science, in other words, is neither intuitive nor easy. It requires *background knowledge* to make useful plans or hypotheses, *discipline* to execute work or experiments that conform to the plan, *patience* and *attention to detail* to observe and document the results, and a combination of *humility* and *creativity* to abandon preconceptions and forge a new path forward.

I claim that learning science – real science – breaks down our resistance to new ideas and builds confidence in our ability to learn from experience. Along the way, it teaches us that many things we think we know about the world are provisional, and must be tested continually against what we actually see happening around us. To learn these lessons and apply them for ourselves, we must have more than a slogan, we need certain basic skills and knowledge. We need the language of science, the descriptive framework, the history of previous failed attempts, and the skills of observation. Without these prerequisites, attempts to draw inferences from observation may actually be counterproductive.

I recall a painful incident from my eighth grade science class. We were learning about weather, and during a class discussion I remarked that I thought warm air was more moist than cold air. I don't recall my reason for saying so. Others in the class disputed it. The teacher herself (not trained in science) was skeptical but proposed an experiment. We moistened two handkerchiefs and placed one on the steam radiator that was heating our classroom, and the other outside the window in the frigid winter air. The inside handkerchief dried and the other remained wet. Everyone in the class immediately clamored that the experiment had proven me wrong. The handkerchief in the warm air was dry, and that in the cold air was wet, so the warm air is dryer, right? The teacher solemnly declared that the experiment had decided the question against me. I was devastated, and my further arguments were dismissed by all as sheer stubbornness. Of course I was right, but I didn't immediately understand how to argue my case. Everyone else, including the teacher, had read the experiment wrong. It was a bitter lesson for me, and it took me years to get over my anger at myself for not being quick-witted enough to state my case properly.

This is what teacher education is all about. Science is not a simple thing. It occurs in complex settings where even simple questions lead quickly to deep ideas. (Example: Why is the sky blue?) Its methods are not entirely obvious, and even simple experiments require skill in execution if they are to give unambiguous results. For many students the laboratory portion of introductory science courses is a lesson in frustration. The lab activities are very different from the "book learning" and the contrived problems students do for homework or on exams. The real world is messy, and students approach it with a wide diversity of prejudices based on their personal experiences.

As a young physics professor I was approached by some artists to give a course on "science and technology for art." It would be open only to art students in the University of Southern California's School of Architecture and Fine Arts, and I agreed to the project. At one point, I brought the students into a traditional physics laboratory to learn about electricity. There were oscilloscopes, power supplies, signal generators, and so forth on all the lab benches. The artists were fascinated by this equipment, hooking wires here and there, making sparks, and turning knobs to see what would happen. They were excited and having tremendous fun. I was stunned by their reaction. It was totally different from my experience with students studying to be scientists or engineers. By contrast, faced with the same setup, the science students were shy with the equipment. They wanted to know if what they were seeing was what they were supposed to see. The art students cared little about what they were supposed to see. They discovered things about the equipment in ten minutes that the science students would not discover for weeks.

This striking difference in the laboratory behavior of young artists versus young scientists made a deep impression on me. I interpreted the difference as originating in prior experience. Students who aim for an art degree may have much more experience with materials and equipment than their science-oriented counterparts. The artists were more pragmatic than the scientists, more fluent with the messiness of the real world, more prepared to learn its behavior so they could use it for expression. The art students did not become scientists, but they learned about the phenomena and quickly mastered them for their own purposes.

What the art students did *not* learn was the conceptual structure that tied together the various elementary phenomena that made the equipment work. They did not know about Ohm's law, or the math of oscillating circuits, or Newton's laws of motion. So they failed to perceive the deeper harmony of nature that science knowledge brings. Their artist's views of the connectedness of real things failed to penetrate the surface, and their projects, while intriguing and sometimes beautiful in appearance, employed the superficial phenomena for effect, and ignored the deeper beauty of the underlying laws.

This sense of deep connectedness in nature, of reliable patterns of cause and effect that we can learn from careful observation, is one of the great rewards of science education. It is an experience that gives power, and reduces the alienation so many seem to have from the world of inhuman things in our environment. Let me close with another personal experience.

When I was a child in grade school I had a toy box full of junk that I would string together to make "inventions." One evening I made a "ray gun" with an old battery, cardboard, light bulbs, wires, and so forth, all wrapped up with tape. As I was chasing my older sister through the house, shooting away, my father asked to see what I had made, and how it worked. Of course it was just junk, in my eyes. But my father said "Watch this." And he taped the wires in a certain way to the battery and to the light bulb. When he pressed two wires together, the bulb lit up! I was floored. In that instant, my whole world changed. I could literally *see* the logic of what he had done. A window opened in my mind onto a vast landscape of possibilities. From that moment I stopped seeing things around me as passive, disconnected shapes – as junk – and I began to see that things have functions and relationships that may not be obvious. The conviction that I could understand these things motivated me to work to acquire the skills and tools I needed to go farther.

Young people are motivated to learn science because they are fascinated by the things they see in nature. As they learn that nature displays regularities, and probably hides as much as she discloses, they are motivated by the idea that they might discover something new, and see or know something that no one has seen or known before. Such optimism needs to be protected and nurtured at every stage. But it also needs to be guided by teachers and mentors and like-minded peers. Some few men and women of genius, like Einstein, can go it alone, but most of us need help. As our society becomes more complex, more technologically intensive, more globally competitive, our very quality of life depends upon increasing the technical capabilities of our entire population. We cannot afford to adjust our opportunities to the high achieving minority of students who come to us eager to learn science. We must extend the opportunity to learn science to every sector of our population, even if it means changing ways of teaching that have long traditions. We have Planned, Done, and Checked, and we know we have to change something. Now we need to Act.

In closing, I want to thank Professor Homer Neal, whom I knew as an effective, creative, and caring Provost at Stony Brook University, and to all others who helped to arrange this celebration of two extraordinary people and the institution that provided them the opportunity for discovery.

Thank you.