Aims of Education XVII 2009-2010
Answering the Big Questions
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Foreword by James L. Doti
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Chapman University took a "quantum leap" – literally as well as figuratively – in 2008 when we brought a new team of physicists and computational scientists to the campus to launch an initiative that will be vital to the future of Chapman: the new Schmid College of Science. Yakir Aharonov, Ph.D., a member of that team, is one of the most highly regarded scientists in the world.

A theoretical physicist of the first order, Professor Aharanov was the co-discoverer of one of the foundation principals of modern physics, the Aharonov-Bohm Effect, and is the winner of the prestigious Wolf Prize in Physics. Because it is often decades after a vital discovery that the Nobel Prize in Physics is awarded, the excitement is growing here that Professor Aharonov will one day very soon be accorded that highest of honors. While there is no completely precise way to predict who will be awarded Nobels, Professor Aharonov was named a Thomson Reuters Citation Laureate last fall, which has often been a highly accurate prognosticator that the Nobel will follow in the next few years.

But, typical of this soft-spoken, serious researcher, he takes all this very much in stride. The discoveries – and the paths to discoveries – mean more to him than any award ever could. He is a man of passionate curiosity who continues to find new and creative ways of looking at the universe and solving problems that no one else has believed could be solved – as he explains so well in this seventeenth annual "Aims of Education" speech to our 2009 Opening Convocation of freshmen and their families.

Nobel laureate Sir Anthony Leggett once said that Yakir Aharonov "is the most distinguished living exponent of the theory of the foundation of quantum mechanics." We are thrilled and honored that he is researching – and teaching undergraduate as well as graduate students – here at Chapman University. The sky truly is the limit for the Schmid College of Science, and the discoveries that Professor Aharonov and our gifted scientists will make here are sure to continue to astound us all.
-James L. Doti

Answering the Big Questions

Thank you very much for the introduction. I also would like to take this opportunity to welcome all the new students and their families to this wonderful university. Chapman University rightfully prides itself as being one of the most individualized and outstanding institutions of higher education in this country.

I am indeed honored to be asked to speak about the very interesting subject of education to the students, parents, faculty, Senator McGovern and the many other guests assembled here.

Many scholars have devoted their career to researching the art and science behind being a good educator. I have not participated in these exciting areas of research. Therefore the best thing I can do is to tell you about my own experience and the main lessons that I learned, especially those experiences that are relevant to distinguish between what I believe to be a good education and a bad education.

I am not a young person; most likely I'm four times older than many of you. Still I am extremely enthusiastic about my scientific research and about the world at large and for this opportunity to address such a young group.

When I delve into my memories, I find many occasions and events pertinent to the main theme of this talk, which is "How can we make education most exciting?" The second is how I kept my fascination alive since my childhood motivation with the deep questions of existence.

When I was a child, before I started elementary school, I had a vivid imagination and a lot of curiosity. I remember that I would approach random people in the street and challenge them to give me puzzles and paradoxes, which I would attempt to solve on the spot. I would also invent many stories that the other children of my age would listen to attentively.

So I was a candidate to be a very good student when I joined elementary school. And indeed, for the first two years things went very well, and I had a very good teacher. He told me interesting stories that made life very nice for me.

But from the third year on, I started to encounter teachers who were teaching knowledge just for the sake of knowledge. They demanded that I memorize all kinds of facts just for the purpose of passing an exam! In other words, they would just teach facts, without trying to make them interesting or creative.

At that point, I started to get worse and worse grades. I felt so bored by that way of teaching that I could almost have become a dropout. Luckily my parents intervened. I knew that we didn't have a lot of money; we were not the kind of family who were well-to-do. Nevertheless, I asked my parents if they could hire private instructors to help me. As a consequence, I managed to survive my high school education (more or less).

There was one bright spot that survived all of that. This was my love for mathematics. I excelled in that subject. Also, outside of my classes I read lots of books about mathematics. That was exhilarating!

Then I had to decide what I would be doing after I finished my high school and military service – and, in particular, what subject I would focus on when I went to the university.

It may surprise you. But physics was one of the subjects I hated most in high school, because it was taught in the same boring way that I mentioned earlier – just memorizing the formulas without really understanding what's going on or their deeper significance. Nevertheless, I decided to study physics for the following reason.

During my time at high school and even before that, I was very interested in the really big questions. Many young children begin to wonder about these profound questions. For example, what is the meaning of life, why are we here, do we have free will, is the world finite or infinite, is time finite or infinite, how did time start? These are all very deep questions.

I continued to be very excited about these questions throughout my time in high school. I was trying to find the answers to these questions by reading all manner of books. For example, I read books on philosophy: Western philosophy, Eastern philosophy, etc. I found that philosophers are very good at asking questions, but they are very bad at giving answers to them.

So I didn't know what to do. Luckily, there was a very nice woman who worked at the library. She knew about my interests. She suggested that I should read two books (luckily they were translated into Hebrew at that time, since my English was poor, even poorer than today). One book was by Sir Arthur Eddington, who was a very famous English astronomer. His book was called *The Nature of the Physical World.*

What impressed me very much about these books was the fact that they asked the really profound questions by using the laws of physics. So that inspired me to study physics.

When I started to study physics at the Israel Institute of Technology, I encountered professors there who still emphasized the acquisition of knowledge just for the sake of knowledge (i.e. without the quest for the greater meaning of that knowledge).

Nevertheless, a miracle happened as a result of my motivation for these really deep questions: I started to develop my own individual, self-inspired approach to my studies. Every time my professors would introduce a new subject, I would try to understand the subject more deeply than was introduced by my professor. I tried to discover if there was some other way to approach the subject, how it was connected to other subjects, etc. The miracle was that when I approached my schoolwork in this way, then I found that acquiring knowledge was much easier.

Instead of just memorizing things, I used the knowledge I acquired to solve the problems that I set for myself. I absorbed that knowledge so well that I still remember it even today. In summary, I discovered that the best way to approach my studies was to create my own personal projects and questions that fascinated me the most. I would then use all the knowledge that I acquired in order to solve these personal projects and questions. I was interested not so much in studying the facts, but in studying what it meant to *understand* in the first place.

Now the time came towards the end of my studies at the Israel Institute of Technology when I had to write a final "thesis" in order to get my bachelor's degree. Again, I wanted to study the really big and deep questions, but I first had to get approval from Professor Nathan Rosen. Professor Rosen was a very famous physicist who was teaching at the Israel Institute of Technology. He collaborated with Einstein and another famous physicist, Boris Podolsky, on one of the most famous articles in modern times.

Professor Rosen asked me what would be the subject of my thesis? I said I wanted to investigate some deep problems connected with quantum mechanics. He said "No, you're not supposed to do that; you're too young. Only older people like myself should work on these kinds of philosophical questions. You should do something that has more practical consequences."

I said “But the only reason I wanted to study physics in the first place was because of my love and wonder for these deep questions!” But my plea didn’t make any impression on him. He refused to accept it. It was a real impasse. I nearly decided to leave the Institute.

Luckily, just at this moment, a new professor of physics arrived at the Israel Institute of Technology. Professor David Bohm was also a very famous physicist. In fact, Einstein had so much respect for Bohm that the two of them became very close friends and collaborators. Einstein was so impressed with Bohm that he declared that Bohm was his “intellectual successor” and his “intellectual son.”

As soon as Bohm arrived at the Institute, and out of his desperation to find somebody who would engage me with my deep questions, I went to visit Bohm. The two of us had fascinating discussions. In response to the research that I was doing, Bohm said, “Oh, beautiful! Let’s work together on these profound questions that you are asking!”

So I finally encountered somebody who was willing to work with me on really deep questions. I followed him to England and completed my doctorate with him.

As a result of my keen interest in the very deep questions, many new and important discoveries were made. Indeed, eventually I was able to discover completely new ways to think about physics. These new approaches helped to make progress on the really deep questions, which motivated me in the first place.

I would like to tell you little bit about some of these discoveries. But, to do this, I may have to try to teach all of physics to you in five minutes!

One of the two biggest revolutions that happened in physics was when quantum mechanics was discovered. What was the revolution about? It revealed something extremely puzzling about nature. Consider two systems that are exactly 100 percent identical; for example, two particles that are exactly in the same location with the same forces being exerted on them (etc). Quantum mechanics showed that one of those particles may go to the left while the other, identical particle, goes to the right. These completely different behaviors occur for no apparent reason whatsoever.

This is the main thing that made Einstein very unhappy with modern physics. He asked why nature should behave in this capricious way? There should be an actual reason why one particle goes to the left and the other, identical particle goes to the right. But quantum mechanics instead said that there was no reason.

In other words, although there was no difference whatsoever between the two particles in the beginning, nevertheless they behaved completely differently later on.

So this looked like a real problem. Einstein said he didn’t believe that “God plays dice” in order to decide whether the particle will go to the left or go to the right. That is, Einstein could not believe that nature would roll a dice, i.e. be capricious, in order to decide how things behaved later in time.

Nevertheless, this state of affairs appears really to be the case. After a century of carefully testing quantum theory, most physicists believe that “God does play dice.” And the theory was very useful: it was the principal scientific revolution of the

20th century and the most successful scientific theory in history. It led to a significant portion of our modern technology, such as computers, lasers, etc.

So, let me give you an example of a "deep question" that I kept asking myself throughout my life: I reformulated Einstein's declaration in a positive way. I asked myself *"Why* does God play dice?" I thought there must be some reason for it.

And then something very exciting occurred to me. Rather than the traditional answer – namely, that nature is capricious; i.e. things happen without any reason or cause – I found that nature gains something very beautiful and exciting by playing dice.

I thought that, perhaps, what nature is trying to tell us is that the information we obtained later in the future (namely, did the particle go to the left or did it go to the right?) may already be relevant earlier in time, i.e. before it went to the left or to the right. This was a very revolutionary idea, that the future is just as relevant for the present as the past is. In other words, when we later found out the two, originally identical particles behaved completely differently, then this later difference was already there before, in the past, but we couldn't actually find it when we arrived in the future.

So I reformulated the laws of quantum mechanics and I said that in order to understand what we meant by the "present moment," we should not only understand the past, but also the information that flows backwards in time from the future, like that movie *Back to the Future.*

I also discovered why nobody noticed this before. You know the old saying, "if your only tool is a hammer, then you tend to treat everything as if it were a nail?" Well, in a sense, that is what physicists were doing; they were using a hammer to observe the world. I found that if you look at the world in a very gentle way, then this beautiful new reality shows up, which is described by information coming back from the future.

Now, this gives us a completely new approach to time. And once you start to think in this way, then this beautiful new reality shows up, which is described by information coming back from the future.

Let me conclude by closing a loop, so to speak. When I went with Bohm from Israel to England to complete my doctorate, I was interested in one of the principal arguments that Einstein gave to support his declaration that "God does not play dice." This was written up in that famous paper I mentioned earlier by Einstein, my professor Nathan Rosen from the Israel Institute of Technology, and Boris Podolsky. They said that a very profound aspect of quantum theory, our most successful theory in history, had to be wrong.

Well, Bohm and I were the first to show that it was really part of reality. This led to breakthroughs that some people believe will allow us to solve technological problems beyond our current imagination.

As you can see by the newspaper clipping below, I had the great privilege to discuss these breakthroughs with Professor Rosen, the man who originally told me not to think about such deep questions. You can see some of the other people who participated in that meeting: from left to right, you see Professor Dirac (who won the Nobel Prize), Professor Rosen, then you see me as a young fellow there, and some other physicists who won the Nobel Prize, and lastly Professor Podolsky.

The work that I started back then by asking the deep questions has continued to this very day and has become one of the most fascinating areas of science.

So what advice can I give to you young aspiring students?

When you become students and progress academically (and in life in general), never give up your enthusiasm and your curiosity. Rather, keep nurturing and developing it. It is the key to your originality and to your success, and, I believe, to much of your happiness.

Asking the right questions is as important as finding the answers. Often the germ of the solution is already evident in the question itself. Never be afraid to ask questions. There is no silly question, only the silly attitude of some who did not have the humanity to admit our "ignorance" and our inability to fully answer some of the truly profound questions.

So open up your eyes and ears. Put out your antennas. And most of all, open up your mind to the world and to the wisdom gained in the past. Open up to the minds of others near you and to the inner voice within you. Hopefully it will guide your way by telling you where your strengths and weaknesses are.

If you are excited about being a scientist, then you have many opportunities here in Chapman's Schmid College of Science. Try to develop your potential and talents to the utmost so as to contribute to your family and to your society. If you think something is important, never give up, even if the subject or question seems too difficult. Keep trying to use all the resources you can bring to bear.

Exercise the muscles of your mind just like an athlete exercises his muscles. In the process, you will grow and expand your willpower as will. Much more important than the specific solution to any given problem is the confidence you gain in the process of trying to solve it.

And to the teachers here, just two general suggestions: try to make your classes as interesting as possible. Never repeat the same identical set of lectures, even when teaching the same material. When it is boring to you, it is even more boring to the students. Rather than using the same old notes, try to derive the same results, *ab inito,* in class – and in the process, you will get the students involved in it as well.

Finally, I found that it is often much more exciting to pose the new subjects and problems in the form of a paradox. While this is particularly easy in physics, I think that in some properly generalized form, it can serve as a paradigm for teaching in general. By emphasizing the aspects of the problem that are particularly unclear, we can make the situation look as paradoxical as possible and thereby arouse our curiosity and bring to bear the power of our mind in order to resolve it. And the deeper the sense of puzzlement or mystery, the higher will be the peaks of enjoyment in the resolution. As a byproduct, you too will learn much more. This is the essence of active learning.

Thank you very much for your attention, and I hope you have a wonderful time here at Chapman.

About the Speaker
Yakir Aharonov, Ph.D.

James J. Farley Professor of Natural Philosophy and Professor of Theoretical Physics, Chapman University

Yakir Aharonov, Ph.D., is without doubt one of the most highly regarded physicists in the world. He has made many seminal contributions to physics and in particular to the most successful scientific theory in history, quantum mechanics. Quantum theory governs the micro-world of atoms and has led to the creation of a large portion of the entire U.S. gross national product, such as computers and lasers.

Dr, Aharonov received the prestigious Wolfe Prize in 1998 for his co-discovery of the Aharonov-Bohm Effect, one of the cornerstones of modern physics. This effect, along with the Einstein-Podolsky-Rosen/Bohm effect, has provided the foundation for work on the development of ultra-powerful computers. Dr. Aharonov is regularly nominated for the Nobel Prize in physics and in 2009 was short-listed as one of the scientists most likely to receive the prize within the next few years.

Dr. Aharonov is one of the leading researchers who serve as Distinguished Research Chairs in Theoretical Physics at the Perimeter Institute in Waterloo, Ontario, Canada. He joins the institute's first Distinguished Chair, Stephen Hawking, and a roster of other eminent scientists in spending extended research visits at the Perimeter Institute each year.

Dr. Aharonov's current research with fellow Chapman team members Menas Kafatos, Ph.D., Jeff Tollaksen, Ph.D. and participants from other universities includes a grant awarded from the Science and Transcendence Advanced Research Series (STAR) for a project titles "Subjective Experience as a Window on Foundational Physics." The aim of the project is to investigate the areas of tension between objective scientific description and our conscious experience.

Professor Aharonov received his undergraduate education at the Technion-Israel Institute of Technology in Haifa, graduating with a B.S.c. in 1956. He continued his graduate studies at the Technion and then moved to Bristol University in England, together with his doctoral advisor David Bohm, where he received his Ph.D. degree in 1960. Prior to his arrival at Chapman in 2008, he served on the faculties of Brandeis University, Yeshiva University, the University of South Carolina, George Mason University and Tel Aviv University. He is professor emeritus at Tel Aviv University and serves as president of the Iyar, the Israeli Institute for Advanced Research.