FROM PARTICLE PHYSICS TO COSMOLOGY

Charles Baltay

College Years

My academic life started at Union College where I was a freshman physics major in the class of 1958. Without much imagination I started out taking Freshman Physics, which that year was tought by Professor Harold Way, the chairman of the Union College physics department. Being a naïve freshman, I assumed that the purpose of college was to study hard, so I did just that, and scored a 100 on the first physics exam. As time went on, however, I joined a fraternity, discovered girls, and learned important skills like how to tap a keg of beer. My grades went from As to Bs to Cs, the gentlemen's index at Union College at that time (don't tell anybody I said this, but Union was a bit of a party school at that time). So I had a great time in college.

In the fall of my senior year, Harold Way called me into his office and asked if I had any intention of going on to graduate school. I answered without much enthusiasm that I supposed so. He then asked what I thought of Yale, and I said I thought that was OK. He then went on to explain that there was an annual meeting of the American Physical Society in New York every January. He had a good friend, Bill Watson, who was the chairman of the Yale physics department, whom he had met for lunch every year at the APS meeting. He asked if I wanted to join them this year, which I said I would be delighted to do. So we went and had a very nice lunch. At the end of lunch Bill Watson turned to me and said, "You are in, Charlie." That's how I got into Yale Graduate School. I never filled out an application form, never took GREs and such. Apparently, Harold Way and Bill Watson had a deal that whenever Way had a student at Union who he thought would succeed at Yale, he recommended that student to Watson, and so far they all had done well at Yale. I guess in those days department chairs at Yale could get away with admitting students that casually (not now!).

Charles Baltay, the Eugene Higgins Professor Emeritus of Physics and Astronomy, received his PhD in physics from Yale University in 1963. He performed research as a professor at Columbia University in elementary particle physics and served as director of Nevis Laboratories of Columbia University from 1979 to 1985. He returned to Yale University in 1988 and served as chair of the Department of Physics from 1995 to 2001. He served as co-spokesman of the SLD project at the SLAC Linear Accelerator from 1983 to 2003. His recent research at Yale is in experimental astrophysics and cosmology, focusing on learning about the nature of dark energy and the accelerated expansion of our universe. In collaboration with the Perlmutter group at Berkeley, Professor Baltay is involved in the NASA Nancy Grace Roman space mission, having served as co-chair of the Science Working Group commissioned to develop the Roman mission concept.

Graduate School

At Yale I started taking physics more seriously. I chose a thesis topic in the then nascent subfield of elementary particle physics with Jack Sandweiss and Horace Taft as my thesis advisers (Horace was the grandson of President Taft and was later dean of Yale College). Jack and Horace had many friends at other universities, and so as I was finishing up my thesis, they made a few phone calls. As a consequence, Professor Mel Schwartz from Columbia University called me, inviting me to visit at Columbia. I did that and gave a talk on my thesis work. At the end of the afternoon Sam Devons, the chair of the Columbia physics department, offered me a position in the department, I guess on the strength of my recommendations from New Haven. I declined the offer, saying that I was quite happy to continue at Yale. Mel Schwartz, however, not about to give up on me that easily, said that as it was getting late, instead of driving back to New Haven I should stay over at his home in Irvington that night. Columbia has a research lab, called Nevis Labs, in Irvington, New York, on the banks overlooking the Hudson River. The next morning Mel drove me around showing me the beautiful mansions overlooking the Hudson, telling me that that's where I would live if I came to Columbia. Well, that was nice, so I called Sam Devons, the chairman, and told him that I changed my mind and that I would like to come to Columbia that September. I did not want to be a postdoc, so they created a new position for me, and I started as an instructor, teaching a course right away. It did not take long to figure out that my salary and the cost of those mansions along the Hudson were inconsistent by a few orders of magnitude, so my young family settled happily in a third-floor apartment near Nevis Lab.

Years at Columbia

At that time T.D. Lee, a theorist, was the honcho in the Columbia physics department (he won the Nobel Prize when he was twenty-nine for discovering parity violation). He was wonderful in taking junior faculty under his wing, mentoring us in our thinking and taste in physics. He instilled in me at an early age the ambition to go for the study of frontier topics that had the chance of changing the way we understand our science in a fundamental way. The department at that time had a tradition of gathering for a Chinese lunch every Friday. Soon after I arrived at Columbia, T.D. invited me to come to a Friday lunch with the department. We sat at a big table in a local Chinese restaurant. Looking around the table absolutely blew my mind. There were eight Nobel Prize winners (past or future) sitting at the table who were faculty of the Columbia physics department at that time! Halfway through lunch, one of them turned to me and said, "Baltay, you come highly recommended. What do you think we should do next?" Like a dumb jerk, I said we should do A, B, and C. He looked at me and in front of that whole crowd said, "That's the dumbest thing I ever heard!" That was my introduction to Columbia; it was a tough physics department at that time. Once you were in, however, they were extremely supportive. I had tenure within four years.

The Chinese lunches were both socially and intellectually the highlights of life in the Columbia physics department. With such a famous faculty, we very often had very famous visitors. I recall one Chinese lunch where I happened to be sitting next to our visitor that week, Werner Heisenberg (a German physics professor, the discoverer of the Heisenberg Uncertainty Principle and one of the inventors of quantum mechanics). Since the 1920s, Heisenberg was "God" in physics, until the 1940s when he became the devil, since he led the effort to develop the atomic bomb for Germany. He was often called "Hitler's Oppenheimer." Since a lot of the Columbia faculty worked on the Manhattan project previously, the relations around that lunch table were frostier than absolute zero. It was interesting that the feeling was mutual. Heisenberg found significant fault with the American scientists who worked on the Manhattan Project. He asked how any decent scientist in good conscience could develop such a horrible weapon for any administration, as it was inevitable that it would spread around the world eventually. He maintained that he accepted the job of developing the bomb for Germany so that he could slow it down, until hopefully Hitler would be gone, and the project could be forgotten. At some point Prof. I.I. Rabi, former chair of the Columbia physics department, making fun of Heisenberg, said to him derisively, "You could not even get the amount of plutonium needed for a bomb right." I recall Heisenberg looking at Rabi and saying, "Rabi, you know that I know how to do that calculation correctly. I overestimated on purpose to make developing a bomb seem much harder than it was." That was one of the more interesting lunches I have been at.

Early Years

I started this story with my freshman year at Union College. The real beginning however was my birth in Budapest, Hungary, back in 1937. In 1945 we moved west with my whole family to escape from the Russian occupation of the country. We ended up in a very pretty Alpine town, Kempten, in Bavaria, where we lived for five years until we came to the US in 1950. Due to the difficulties of education during the war, out of the eight grades of elementary school, I attended four. That was a good thing as it left my mind uncluttered for more interesting things later. In the US, I started high school, and in my senior year was admitted to Princeton, MIT, and Union College. I chose Union as the one that offered me the largest scholarship. My adventures from there I discussed above. The wonderful thing about the US is that anyone from anywhere in the world is welcome. I never felt any disadvantage because of my origins. On the contrary, Hungarian physicists were in good repute. There is a story, true or not I don't know, with a US federal science advisory comittee with Wigner, Szilard, Teller, von Neumann, Telegdi, and others sitting around a conference table, when one of them remarked, "Gentlemen, wouldn't it be simpler if we just spoke Hungarian?"

The Standard Model of Particle Physics

The 1970s and 1980s were an exciting time for particle physics. Starting out in the 1960s as a relatively new field, much experimental progress was made in the next two decades. In that period a fairly detailed understanding of the field, called the Standard Model of Particle Physics, was arrived at. It started with the unification of the electromagnetic and the weak nuclear forces. The major achievement in physics in the previous century, the 1800s, was the unification of electricity and magnetism through the efforts of Coulomb, Oersted, and Faraday culminating in the electromagnetic force neatly summarized by Maxwell's equations. At the end of that process, physics consisted of the gravitational and the electromagnetic forces. Shortly thereafter, two new forces, the strong nuclear force holding the atomic nucleus together and the weak nuclear force that causes radioactivity, were discovered in the early twentieth century. Now, physicists are a simple-minded folk, believing that the basic laws of physics should be simple and elegant. As Rabi once said, if something looks too complicated, you don't understand it. The central question in physics thus was the issue of why are there four independent forces. Einstein, after developing relativity, spent the rest of his life trying to unite the other forces in what he called the Unified Field Theory. He did not succeed, mainly because he did not have sufficient experimental information in his lifetime.

It was not until the 1970s that Steve Weinberg, a theorist at Harvard, developed a theory uniting the electromagnetic with the weak nuclear forces into what became the so-called electroweak force. In 1972, my research group at Columbia set out to do an experimental test of the key predictions of the Weinberg Model. This involved scattering neutrinos off electrons, using the newly built particle accelerator at Fermi Laboratory near Chicago, Illinois. But, as behooves such a hot topic, European groups at the CERN Laboratory in Geneva, Switzerland, set out to do a similar experiment. This became a horserace, asking who gets there first. As it turns out, CERN got a result first, *but* they got the wrong answer. Their result ruled out the Weinberg Model. Steve Weinberg called me every other day after that, "Charlie, what do you guys see at Fermilab?" A month later we got our result, which agreed with the predictions of the Weinberg Model. The key parameter of the model was the Weinberg angle, whose value was not defined by the model but had to be measured experimentally. This parameter was of crucial importance since all subsequent quantitative predictions of the model were dependent on the value of this parameter. We obtained a measurement of the Weinberg angle to be 0.23, enabling the model to make quantitative prediction from then on. The CERN group later acknowledged that they had overlooked an important effect that threw their result off the correct value.

The bi-annual International Particle Physics Conference was held in Tokyo that year. Steve Weinberg was scheduled to give the final concluding talk of the conference, declaring victory for his model. I gave the talk before Steve, presenting the experimental evidence for his model. The following year Steve was awarded the Nobel Prize.

The Weinberg Model was the heart of the theoretical synthesis we now call the Standard Model of Particle Physics. The Stanford Linear Accelerator Center (SLAC) built the two-mile-long electron accelerator (atom smasher) near the Stanford campus in Palo Alto, California. I was co-leader of the experiment in the 1980s and 90s using this accelerator to carry out precision measurements of the parameters of the standard model. We obtained the best measurements worldwide of the Weinberg angle to be 0.23 to a precision of a part in a thousand, in agreement with our earlier measurement from the neutrino scattering experiment a decade before.

Coming Home to Yale

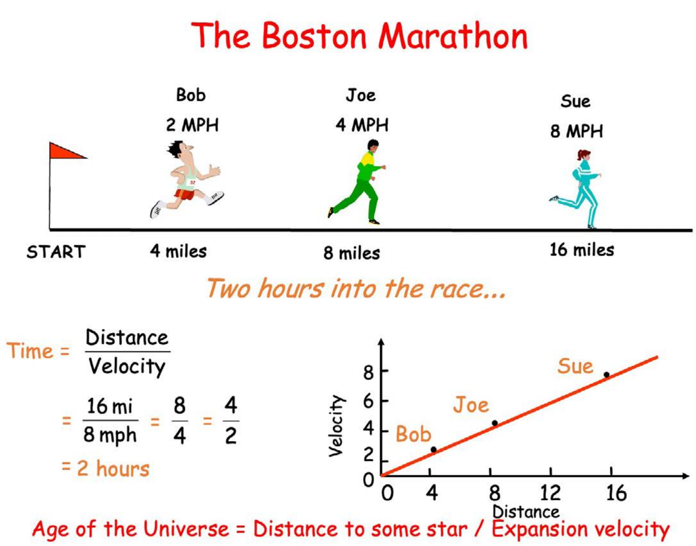
Throughout those years I was very happy at Columbia. The intellectual atmosphere set by T.D. Lee, I.I. Rabi, and others was influential in motivating me to do interesting things. In the late 80s, however, Horace Taft, my former thesis adviser at Yale, passed away from a heart attack at the young age of fifty-seven. The Yale physics department subsequently offered me his position. Even though I was very content at Columbia, this opportunity to carry on in Horace Taft's position was too nostalgic to turn down (also sailboat racing on Long Island Sound was attractive compared to New York City). I remember when telling T.D. Lee of the Yale offer. I said to him, "T.D., please do me a favor and let me go without a fuss." This he did not do, and against my wishes, doubled my salary and offered me a named chair at Columbia. This turned out well since Yale had to follow suit and then some, so I came home to Yale as the Eugene Higgins Professor of Physics in 1988 and have been here ever since.

Over the years, I served on every departmental and university committee imaginable. I served as director of undergraduate studies, director of graduate studies, department chair, etc. I sat on the University Budget Committee when Alison Richards was provost and enjoyed interacting with her immensely. David Swensen was often on the Budget Committee. I recall one meeting when he discussed having borrowed some eight billion dollars, at a variable interest rate. I naively asked him why he would borrow billions when he had a twenty-four-billion-dollar Yale endowment. He looked at me and said, "Charlie, I make 15 to 20 percent on the endowment but pay about 5 percent interest on loans. What would you do?" We also kept bugging him when he would go from variable rate to fixed rate interest on the Yale debt. He kept replying, "no, not quite yet." Upon returning to Yale, we had just built a house here near New Haven and had a variable rate mortgage. My wife kept pushing to convert to a fixed rate, but I kept saying, "no, not quite yet," parroting Swensen. Then at one meeting Swensen said the time has come to convert to fixed rate. I went home that night and felt very wise to say the time has come to convert to a fixed rate. We did that, and that was the lowest fixed rate ever since. Being on committees can be useful sometimes.

The Excitement of Cosmology

The following decades, starting with the 1990s, turned out to be a relatively slow period for particle physics. With the standard model established as precision science, really new experimental information had to wait for much higher energy accelerators than were available at that time. Some such instruments were under design and construction but were relatively far off. In the meanwhile, there was a multitude of new data and excitement in astrophysics and cosmology. New, large, ground-based telescopes had been commissioned, and space observatories, gathering qualitatively new kinds of data without the obstruction of the Earth's atmosphere, had become a reality. With Einstein's Theory of General Relativity, which is really a modern theory of gravity, we were in a position to make scientifically tight calculations about the behavior of the universe. Even Steve Weinberg's mind turned to cosmology. He wrote a book called *The First Three Minutes*, which presented in his usual clear style the current knowledge of the development of the universe in the short period after the Big Bang. He was kind enough to send me an early copy of this book. The fascination of the subject was overpowering. For the past two thousand or more years, cosmology has been a subject for the religion and philosophy departments. Since Einstein's relativity and the influx of a wealth of modern data, however, cosmology became a topic for the hard sciences.

Until the middle of the last century, it was generally believed that the universe was in a static state, unchanging from past to future generations. It was not until Hubble's discovery that we learned that this is not true: the universe is in a state of uniform expansion. What Hubble observed using the Doppler effect and redshifts was that all distant galaxies were moving in a direction away from us. In addition, the further a galaxy is from us, the faster it is moving away from us. He summarized this by an expression (v = Hd), which is now called Hubble's Law, where "v" is the recession velocity, "d" the distance, and "H" is a constant of proportionality, called Hubble's Constant. This discovery was a huge revision of our thinking about our universe, upsetting the two-thousand-year-held conviction that the universe is static and unchanging. Hubble's discovery implies an expanding universe and a universe that was created or came into being at a given location at a time some thirteen billion years ago – the Big Bang. To see this more clearly, let's look at an analogy with the Boston Marathon, sketched in the figure below.



What we see in this marathon is that all of the runners take off at the starting point at the same starting time. At any later time, the ones that run faster will have gotten further away. This is just Hubble's Law stated backwards, i.e. the further a runner is from the starting line the faster they are running. Turning the clock backwards implies that all of the runners, i.e., all components of the universe, started at the same time from a small region of space, the starting line. This is what we now call the Big Bang Model. This model also gives us an estimate of the age of the universe as the distance of some galaxy from us divided by its recession velocity, which comes out to be about thirteen-and-a-half billion years. In the picture of the marathon above, Sue at sixteen miles running at eight miles per hour tells us that the age of the marathon is two hours.

In the above discussion, we considered the expansion velocity of the universe to be a constant in time. Given our present laws of physics in which gravity is an attractive force between all masses, we expect that the backward pull of gravity will slow down the expansion, just as a baseball thrown up in the air will be slowed down by gravity. The amount of this deceleration depends on the total mass density of the universe, which we do not know very well. It was therefore a high priority to try to measure the change in the expansion velocity of the universe looking back in time, i.e. measure the expansion history of the universe. The relevant time scales are billions of years. It is hard to measure something a billion years ago, and experiments that last a billion years in the future are hard because graduate students don't like to take that long for their theses, and we know we cannot do experiments without graduate students. The velocity of light comes to our rescue. Light has a finite velocity. Light from a heavenly object, like a supernova, that is for example (3 times 10 to the 22nd power) meters away takes three billion years to reach Earth. Thus the light we observe today on our telescope was emitted three billion years ago, and the nature of that light can tell us the expansion velocity of that supernova three billion years ago. Observing a large number of supernovas at different distances then can trace out the expansion velocity over some period in the past. Such an experiment was carried out by Saul Perlmutter and team at Berkeley and independently by Adam Riess and team from Harvard. Both groups found the startling result that the expansion velocity was smaller in the past and is faster today, i.e. we live in a universe with an accelerating expansion.

This situation is in contradiction with the currently understood laws of physics, which, as discussed above, predict the expansion of the universe to be slowing down. All this is reminiscent of a hundred years ago. Around the year 1900, physicists thought they had a good understanding of the classical theory of physics in terms of Newton's laws of mechanics and Maxwell's equations of electromagnetism. Soon after that, detailed studies of atomic physics showed that atoms behaved in a way not allowed by those classical laws. The outcome was that in the next two decades quantum mechanics and relativity theory had to be invented, completely revising our understanding of physics. We face a similar situation today where we have to face a thorough revision of our laws of physics to explain how the universe is behaving.

Having Fun in Physics

What fun! The challenge that the discovery of the accelerated expansion of the universe poses for fundamental physics is hard to resist. At this point in the early 2000s, I dropped everything else I was working on to concentrate on this exciting issue. A group of us academics, including Saul Perlmutter, the discoverer of the acceleration of the universe, got together to consider what the best approach would be to study the physics of the accelerating universe. The result of these discussion was our proposal to build a space mission, a large telescope launched in a high earth orbit, to allow observations of the cosmos without interference of the Earth's atmosphere. After numerous reviews by committees of the US Department of Energy, a prominent supporter of basic science, the President's Science Advisor, NASA, etc., the mission was approved as the WFIRST space mission, the name indicating its priority among the large NASA missions. A number of us academics have been on a science definition team to design the mission and develop the specifications thereof. The mission is now under implementation by NASA with an intended launch date in mid-2026. Our group of scientists is busy in the meanwhile developing the data analysis plans and the required software. As is NASA's recent custom, the mission has been renamed after a noted astronomer, in this case becoming the Nancy Grace Roman space mission. All this has been a tremendous learning experience for me; I feel like a starting graduate student learning a new science of cosmology and space exploration.

All in all, I consider myself very fortunate to have been on the Yale faculty all these years. A European friend once said to me that an American university professor is the last free person on Earth: you have no boss, no one ever tells you what to do, you get to follow what excites you intellectually, you get to work with other very smart people, and you make a living having fun.