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What a biologist should know about Physics*

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If the truth were told, I know very little about biology beyond what I learned in high school. I know a little more about physics. So, the question in the title of the talk –*What a biologist should know about particle physics and cosmology*– has a simple answer: nothing about cosmology is of the least professional importance to the biologist, nor is relevant any fundamental discovery in particle physics that has been accomplished in the last thirty years. The last relevant advances I can point to are the discovery of positrons in 1932 —the year of my birth—, the discovery of nuclear spin, and the production of synthetic radioactive isotopes. All of these go back many years. The «should» in my title is by way of a cultural suggestion, rather than professional advice. And yet, there is every reason for the modern biologist to understand a lot more of physics than has been the case in the past.

The limits of Biology and Physics

Unlike physics, biology is a very specific discipline. Life is limited in space so far as we know to the surface and crust of the Planet Earth, which I estimate to comprise about 10^{-60} of the volume of the observable universe. I will presume that there is no life anywhere else. There may be, but we may never find it. The other aspect of biology is that it is limited to a very short period of time. There was no life more than four billion years ago, and yet most of the interesting things in the universe have been long before that: atoms, nuclei, stars were created long before that and so were galaxies.

Life entered the scene in a very late stage in the history of universe. Size is also relevant. Biology seems to span enormous distances, from the size of an atom (10^{-8}cm) –because atoms are surely important biologically– to the size of a whale (10^{4}cm), which is twelve powers of ten. But twelve powers of ten are not really a great deal if compared with the difference between the size of the universe and the size of the hypothetical superstring, which is sixty powers of ten.

Biology is a limited discipline, limited in size, limited in time, trapped between geology on one side and chemistry on the other. A very small discipline but a very significant one, because we are alive and we are very concerned with the study of life. I would say that biology is by far the most relevant of all scientific disciplines. And I would also argue that particle physics and cosmology-my beloved disciplines-are the least relevant disciplines in science.

The future of Biology

We are all aware of the recent advances in biology, including genetically engineered food, genetically modified food and cloned sheep or a cloned mice or –heaven forbid– cloned people! These advances have whipped up a veritable firestorm of controversy, especially in Europe. Some of the fears of these new developments in the biological sciences are rational, whereas others are absurd. But we have not seen anything yet. And neither cloning nor genetically modified foods are advances that reflect the enormous and accelerated potential in modern biology. Biology is now emerging from being an art to becoming a science as well as a force majeur in social change and in economic development. Biology is becoming today what the physical sciences were a century ago. There are several reasons for this tremendous explosion of knowledge. And they have to do with the growingly interdisciplinary nature of modern biology. For example, today's physicists have learned how to manipulate individual atoms and assemble them in novel ways such as they have never been assembled before. Along with other scientists, they are learning the precise molecular processes underlying gross molecular behavior. A colleague of mine at Harvard explained to me how, atom by atom and molecule by molecule, the rotary engine that drives the flagellum of a single cell organism works. There is a rotary motor, and the method by which it works is known. Biochemists can ring the 1001 different changes of a known biologically active molecule in the search for a drug that does the trick without causing ill effects. For example, mole-

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cular biologist Walter Gilbert is now launching a company that hopes to produce a memory-enhancing drug: a kind of drug that people of my age would like to take so that we could remember peoples' telephone numbers. And he told me that this drug exists: there exists a drug that just does that, except it makes you throw up, so that is a bit of an expensive price for a better memory. But as soon as he or his colleagues learn how to get rid of one of those attributes of the drug, and keep the other, he will make a lot of money and I will be able to remember lots of things!

Chemists are finding less expensive ways to produce rare biological molecules and they are creating remarkable new molecules and materials that have never before existed. High-energy physicists are used to dealing with huge data samples and data streams. They invented the world wide web to transmit data among remote collaborators. But of course that has become rather important to other people as well. The world wide web is a gift from the particle physicists to society. And computer scientists now have made it possible to deal with data that are far larger than anything that has ever been put on paper in the history of the human species. We can do remarkable things, and these developments are slightly relevant to biology. But future developments will require closer collaborations among scientists from many disciplines. There will be a new breed of scientists-the renaissance scientist-armed with the appropriate skills from all of the physical, biological and mathematical disciplines.

We will soon understand and have mapped the human genome. That will be a first step to a wonderful new frontier. To use that information will be a tremendous challenge, but it will be both an ethical and scientific challenge. Let me imagine an example. Should the prospective parent be advised-and offered the possibility of an abortion-if the pregnancy would result in a child with devastating deformity? Many of us would say yes. But, what if the child would simply have a tendency to a dread disease, a tendency to diabetes, or a tendency to colon cancer, or cardiac myopathy? Should the child be aborted? Or what if the child were likely to be born with a less than stellar intelligence or with a tendency to talk back to his parents? Should it be aborted? Where do you draw the line? I think that modern bio-scientists will have a desperate need for clear ethical guidelines, but this is not a subject I can competently address. The study of ethics in biology will surely become a major issue. Instead, let me predict the future of biology, not in the next ten years or the next one hundred years but over the course of the centuries to come. I have listed a few simple «discoveries»:

1. CADAT

CADAT is Computer Assisted Diagnosis and Treatment. Imagine a patient coming to a doctor presenting with kidney cancer. The tissue would be biopsied, analysed, and the precise mutation responsible for the disease would be identified. In CADAT-1, which we can expect very soon, the physician consults a data bank, determines the historically optimal treatment for this disease and applies that treatment. That is a small advance. A much bigger advance would be CADAT-2, in which a patient-specific drug would be created, some drug tailor-made for that cancer and that patient. It will be created, administered and the disease will be cured.

2. Pharms

A Pharm is a place where you grow genetically modified plants that will serve as inexpensive drug manufacturing facilities. Why should you build the factory to make drugs when you can just as well design a plant that will produce that drug? So Pharms are pharmaceutical factories that we can grow.

3. Elderpal

I have an elderly relative, a stepfather-in-law who is 96 years old, and here is something that he could certainly use. It may take a while to build a conscious computer although we will certainly do that, if not in a hundred years, then in a thousand years or ten thousand years. We already know how to make computers that can play chess better than we can. We can even make computers that pretend to be psychoanalysts, rather poor psychoanalysts. It would not be much harder to take a computer and pack its program with all sorts of specific biographical trivia so that it could act as a sympathetic companion for elderly or lonely persons. I call that Elderpal: a little computer that talks about what the children were like fifty years ago, reminds him of his diseased friends and relatives. A very nice device, indeed.

4. Autolescence

Autolescence will be a medically induced process by which a patient is induced to regrow whatever replacement cells, arms, legs, fingers, teeth or organs that he or she may need. I think that what frogs can do, what newts can do, we can learn to do it better. So, why to have a kidney transplant when you can grow your own kidney?

5. Eugerontics

Sooner or later, not next year, but a bit later than that, we shall be able to live as long as we please. Not just 80 years, or 100 years, but 200 years, or 300 years, or however many years we choose. Eugerontics is a new science that will become necessary once the problem of ageing is solved to deal with all these. It will focus on human life beyond the first or second century, and it will replace the no longer relevant disciplines of gerontology or geriatrics.

6. Seesero

Let's get a bit more futuristic. A Seesero is a seemingly sentient robot that we shall send into space. We are not going to send people into the stars any more. The Americans have sent humans to the moon but it is unlikely that it will be done again. Seeseros are the seemingly sentient robots that we shall send into space as proxy explorers. And perhaps miniaturised, made very tiny, we shall send them into our bodies to diagnose disease and maintenance.

7. Trusero

Trusero is of course the truly sentient robot, the robot that will evolve and self-replicate, and they will be our inheritors when we are no more.

The growing of Cosmology and particle physics or Cosmology and particle physics are one

Those are some of the things that biology can give us in the next century or the next millennium or perhaps in the next million years. Let me turn to a subject that I do know something about. Let me change the subject to talk about what I understand: particle physics and cosmology. Two sciences: one studies the largest things in the universe; the other studies the smallest things in the universe. These two disciplines, however, have very much in common. Let me give six examples of how these two sciences have grown up together and have always been linked. Let me give the following examples through quotations.

«We live under an ocean of air.» This is a quotation translated from the Italian of Evangelista Torricelli. He is the person who discovered and first produced the vacuum on Earth. He produced the barometer, he discovered the origin of air pressure and why suction pumps cannnot pump water more than 30 feet or so. He discovered also how a baby sucks milk from his mother, how a siphon works, and how we breathe. But all these down-to-earth discoveries were cosmological in nature. They all followed from his truly cosmological discovery that the air does not exist throughout space, and that we live under a very thin and very fragile ocean of air. That was in 1642: Cosmology and particle physics are one.

«If I have seen further it is by standing on the shoulders of giants.» A quotation from Isaac Newton, extracted incidentally from a letter he wrote to his arch-rival Hooke on February 5, 1675. Robert Hooke was the person who really did discover the inverse-square law of force, which Newton stole. It must be remembered that Hooke was a dwarf, less than 4 feet tall. «We see so far –said Newton– because we stand on the shoulders of giants-not a dwarf like you.» But Newton synthesized the laws of motion of heavenly bodies with the laws of motion on Earth. We have heard about the apple falling on his head. Did the apple teach him about the Moon, or did watching the Moon teach him about the apples? We shall never know, but there again the two sciences-those of the large and the small-were unified in the mind of Newton.

Auguste Comte (1798-1857) was a philosopher, not a physicist, nor a biologist. He claimed that we cannot learn the chemical composition of the stars. By 1861 –four years after his death–, however, we were learning the chemical composition of the stars! Philosophers should learn never to say never. We were learning the chemical composition of the stars because the science of physics on Earth and physics in the stars is one and the same. Spectroscopes were discovered, photography was discovered, and modern telescopes were developed. Those instruments were put together to measure stellar light spectroscopically and to measure the chemical composition of stars.

Saint Exupery wrote: «You are responsible for anything you tame.» I am thinking here of nuclear energy. In the 19th and early 20th centuries there was a dispute between biologists and geologists on the one side, who said that the Earth was very old, 100-million year at least, and physicists, who said that it could not possibly be more than 10-million years old because the Sun could not burn for more than 10 million years. It could not burn chemically. It was thought that the source of solar energy was gravity. And gravity does not have enough energy to power the Sun for so long. Now we know that the source of solar energy is nuclear energy. And by learning how the nuclei of atoms behave, we learn how the stars shine. In the 1930s again another example of how cosmology and particle physics are one.

«There are more things in heaven and Earth than have dreamed us in any philosophy,» said Jean Calvin, and indeed there are. Cosmic rays are energetic particles that come from distant parts of our galaxy. Some of them may even come from other galaxies. And they have been these messengers from the stars. They were the method by which we learned the first fundamental facts about elementary particles. Many of the first particles that have funny names like muons, pions and positrons, and strange particles which play major roles in the history of particle physics were first discovered in cosmic rays. We still wonder what exactly produces cosmic rays. There are riddles not yet solved connected with cosmic rays. The universe can teach us about particles, whereas particles can teach us about the universe.

The last concern about Ouroboros (the mythological snake that eats its own tail in an endless circle) is the connection between the large and the small, the unification between the study of the universe and the study of the particle. Some of the most convincing evidence for the Big Bang comes from the studies on the abundance of chemical elements on Earth and in the heavens. And much of what we know about neutrinos-one of the several varieties of elementary particles-was first deduced from studying the effect of the neutrinos upon the expansion of the universe in the first minutes, and how they would effect the synthesis of elements. Cosmologists first taught us that there could not be more than four kinds of neutrinos in nature. Today we believe that there are just three. It is in fact difficult for me to explain how close the modern superstring theory truly identifies the study of the universe with the study of elementary particles. Let me summarize some of the aspects that these two disciplines have in common, apart from the fact that they grew up together.

Meta-questions

There are various kinds of questions that scientists ask, and this is relevant to the special status of cosmology and particle physics. There are what I like to call «intrinsic questions.» An intrinsic question is one that can be answered in terms of known scientific principles, that can in principle be answered. For example, we can ask the chemist: «Can you calculate the atomic spectrum of the iron atom?» The answer is: «No, it is much too complicated, it is not worth doing.» In principle, however, we know how to do it. Can we explain the molecular principles, the physical principles explaining high temperature superconductivity? Some ten years ago it was discovered how to make superconductors that work at temperatures of liquid nitrogen, but they are slightly mystifying. We know the fundamental principles that underlie the behavior of matter on Earth. We can understand how embryos differentiate and become organisms. It is all a matter of quantum mechanics and the Schrödinger equation, and the electromagnetic interactions among the large number of particles. It is very complicated, it will take a long time, but we know the underlying principles: there are no mystical forces to be discovered. The laying on of hands or the applications of magnets, however, are not to do anything to cure or prevent diseases. And the principles that underlie acupuncture seem irrational. Those people in France who dilute drugs over and over until there is not a molecule left of that drug, put them in bottles and sell them as homeopathic medicines for lots of money, operate under principles that do not exist. We know the fundamental laws that are relevant to all of the basic sciences such as chemistry, biology and geology. We understand how pulsar signals are produced. They are not little green men as they were suspected of being. There are no little green men as far as we know. However, we are looking for them too.

The second kind of question is the historical question, which has to do with how things got to be the way they are. How did the rabbit evolve from whatever precursor there was to the rabbit? How did the Earth get its moon, or how did giraffes develop their long necks? Or, which were first, stars or galaxies? And when did they evolve? When did the human language first appear? And how old is the Earth? Questions like these can often be answered indirectly. Some obvious meta-questions of the past are: How does a suction pump lift water? That was Galileo's question, answered by Torricelli. Why do the planets move as they do? Answered by Newton. What is burning? Answered by Lavoisier. But Lavoisier was mistaken in his answer to that. He thought that it was a substance, «caloric,» and that was not true. It took another fifty years or so, before it was shown that heat is a form of motion. What are atoms made of? Answered around 1900-1910, after Joseph John Thomson discovered the electron in 1897, and Niels Bohr wrote his trilogy on the constitution of atoms and molecules in 1913. What are atomic nuclei made of? We could not answer that question until we discovered the positron in 1932.

All of these were in their day meta-questions. But today there are no meta-questions in chemistry or biology. There are hard questions. There are questions that we do not know the answer to such as how to cure cancer, what is consciousness, can we duplicate consciousness with a computer? In principle, we ought to be able to figure them out. But we have no meta-questions except in the two domains of cosmology and elementary particle physics. And there are lots and lots of meta-questions, although they are not terribly relevant. What we are learning today about the universe and its tiniest constituents is unlikely-I would say impossible-to have the least practical importance directly. And yet as one of my favourite authors, Primo Levi has written «A world in which only useful things are studied would be sadder, poorer and perhaps even more violent that the one fate has allotted us... I believe that what is being discovered about the infinitely large and the infinitely small is sufficient to absolve this millennium.»

The cost of particles physics and Cosmology or the luxuries of particle physics and Cosmology

Particle physics and cosmology have another feature in common: they cost a lot of money. Let me give a couple of examples: the superconducting collider, which the US government cancelled, had cost more than 2 500 million dollars before it was cancelled. It would have cost another 8 000 million dollars to complete. I certainly feel that the cancellation was unwise. The device that a good friend of mine is responsible for, called LIGO (there are actually three of such devices, two in the United States and one in Italy), will be used to search for gravitational waves, which have never before been seen. This devices cost about 300 million dollars. The accelerators that do exist –the establishment at CERN– certainly cost about 1 000 million dollars to create.

Accelerators are expensive things, so are orbiting laboratories. The Hubble space telescope, which incidentally is a joint European-American project, is wonderful too but it also costs hundreds of millions of dollars. And there are other extremely expensive devices up there in space that are essential, for we cannot do cosmology and particle physics without them. These expensive «toys» that we play with, that cost hundreds of millions of dollars, will yield neither miraculous cures nor inexpensive space travel. They will neither give us mind-to-mind communication nor produce better mousetraps. Investments in particle physics or cosmology are extremely unlikely to create wealth. Besides, they will certainly consume a lot of wealth, like Grand Opera. I think that we should try to regard these sciences that I love as optional science, as luxuries, that a rich society can choose to afford if it wishes. Questions such as what are the ultimate constituents of matter, how our universe arise, why the laws of physics are what they are, and how many dimensions there are really to space-time, if there is really a space-time dimension, are not relevant. However, they are interesting and satisfy human curiosity. The fact that our society and sometimes even banks are willing to support them generously is-I think-a testament to the culture, the good taste and the curiosity of our species.

Great archievements during the 20TH century

I would like to emphasize how exciting my discipline is and always has been. So let me end reminding you that science is not dead and science will never die. It is possible to find at least one example of a great discovery in each decade of the 20th century and in different fields. I will give examples from particle physics and from cosmology.

1900. Special relativity was discovered by Albert Einstein, and in 1911, cosmic rays (those particles that teach us so much about the universe) were first observed by Austrian scientist Victor Hess.

1910. The atomic nucleus was discovered, and Einstein continued and invented his general theory of relativity. One for simple things on Earth, and one for complicated things like gravity.

1920. The theory of quantum mechanics was developed. A marvellous and mystifying discipline. At the same time, Mr. Hubble, an astronomer, discovered that the universe is expanding.

1930. For better or for worse, nuclear fission was discovered. And also nuclear fusion was understood as the mechanism by which stars get their energy.

1940. Quantum mechanics «got married» to relativity to form what is called quantum electrodynamics or quantum field theory, which explains nature in many instances to up to and beyond ten decimal place precision. Also in the 1940's, radio astronomy developed as a secondary consequence of World War II and the use of radar.

1950. It was discovered that nature «knows» the difference between left and right. This was radical, because the law of conservation of parity had been one of the pillars of theoretical physics. Also in the 1950's, in cosmology we learn how simple nuclei were synthesized in the early universe, in the hot Big Bang.

1960. There was an explosion of newly discovered elementary particles; literally hundreds of particles were discovered and they were assembled in a discipline called the eight-fold way. But also in the 1960's, cosmic background radiation was discovered in New Jersey. The cosmic background radiation is the last whimper of the Big Bang. And by seeing it, or sensing it, or hearing it, we saw, heard or sensed the last whimper of that great explosion that created the universe.

1970. saw the creation of the Standard Model of the elementary particle physics, which works too damned well, and it also saw the discovery of the Standard Model of cosmology, which also works rather well.

1980. saw the growth of superstring theory, which is too complicated for me to either criticise or understand. And it also saw the discovery of dark matter-rather the confirmation of earlier observations-which told us that almost all of the matter in the universe is of a kind that is not described by the Standard Model. We do not know what the dark matter is. It is a big challenge for future generations of particle physicists and cosmologists.

1990. We discovered that neutrinos have mass. A joint Japanese-American collaboration in Japan proved that some of these ghostly particles that we have known about for half a century, the neutrinos, do have mass. And also in the 1990's the wrinkles in space and time, the tiny seeds that were to become galaxies and clusters of galaxies, that is-to be technical-the fluctuations in the cosmic background radiation were first observed.

And furthermore, in the 2000, what will we see? At the Large Hadron Collider at CERN we will certainly see the Higgs boson or whatever it is in nature that is responsible for particles having mass. And we shall also see in the 2000's the gravitational waves at this very expensive gravitational wave detector, which I have already mentioned, one in Washington State, one in Louisiana, one in Italy, called LIGO.

What will be the major discoveries of the 21st century? Let me quote Shakespeare and say that «If you can look into the seeds of time, / And say which grain will grow and which will not, / Speak then to me, who neither beg nor fear / Your favours nor your hate.» Maybe we can forecast some goals to be achieved in the next few years, even in the next few decades. Great discoveries, however, may come out of serendipity, as it has happened throughout history. Human mind is frequently a lonely hunter.

About the author

Sheldon L. Glashow was born in New York in 1932. He obtained his doctorate at Harvard University and he has worked in various research establishments such as CERN (European Centre for Nuclear Research) in Geneva, CalTech (California Institute of Technology) and the Universities of Stanford and Berkeley in the USA, among other prestigious centres. At present he is pursuing his research at Harvard in the field of theoretical physics, on matters such as the beginning and end of the universe, the nature of fundamental particles, and other subjects.

In 1979 he was awarded the Nobel Prize for Physics, together with Abdul Salam and Steven Weinberg, for their work on the theory of the unification of weak and electromagnetic forces between elementary particles. This study was a notable advance in the development of one of the key issues in particle physics: the unification of the four fundamental forces in nature –electromagnetism, gravity, and weak and strong nuclear interactions– in one coherent theory.