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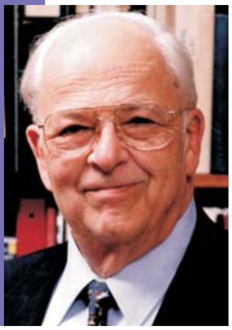

Theory in particle physics: Theological speculation versus practical knowledge

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To me, some of what passes for the most advanced theory in particle physics these days is not really science. When I found myself on a panel recently with three distinguished theorists, I could not resist the opportunity to discuss what I see as major problems in the philosophy behind theory, which seems to have gone off into a kind of metaphysical wonderland. Simply put, much of what currently passes as the most advanced theory looks to be more theological speculation, the development of models with no testable consequences, than it is the development of practical knowledge, the development of models with testable and falsifiable consequences (Karl Popper's definition of science). You don't need to be a practicing theorist to discuss what physics means, what it has been doing, and what it should be doing.

When I began graduate school, I tried both theory and experiment and found experiment to be more fun. I also concluded that first-rate experimenters must understand theory, for if they do not they can only be technicians for the theorists. Although that will probably get their proposals past funding agencies and program committees, they won't be much help in advancing the understanding of how the universe works, which is the goal of all of us.

I like to think that progress in physics comes from changing "why" questions into "how" questions. Why is the sky blue? For thousands of years, the answer was that it was an innate property of "sky" or that the gods made it so. Now we know that the sky is blue because of the mechanism that preferentially scatters short-wavelength light.

In the 1950s we struggled with an ever-increasing number of meson and baryon resonances—all apparently elementary particles by the standards of the day. Then Murray Gell-Mann and George Zweig produced the quark model, which swept away the plethora of particles and replaced them with a simple underlying structure. That structure encompassed all that we had found, and it predicted things not yet seen. They were seen, and the quark model became practical knowledge. Why there were so many states was replaced with how they came to be.

A timelier example might be inflation. It is only slightly older than string theory and, when created, was theological speculation, as is often the case with new ideas until someone devises a test. Inflation was attractive because if it were true it would, among other things, solve the problem of the smallness of the temperature fluctuations of the cosmic microwave background radiation. Inflation was not testable at first, but later a test was devised that predicted the size and position of the high angular harmonic peaks in the cosmic microwave background radiation. When those were found, inflation moved from being theological speculation to a kind of intermediate state in which all that is missing to make it practical knowledge is a mathematically sound microscopic realization.

The general trend of the path to understanding has been reductionist. We explain our world in terms of a generally decreasing number of assumptions, equations, and constants, although sometimes things have gotten more complicated before they became simpler. Aristotle would have recognized only what he called the property of heaviness and we call gravity. As more was learned, new forces had to be absorbed—first magnetic, then electric. Then we realized that the magnetic and electric forces were really the electromagnetic force. The discovery of radioactivity and the nucleus required the addition of the weak and strong interactions. Grand unified theories have pulled the number back down again. Still, the general direction is always toward the reductionist—understanding complexity in terms of an underlying simplicity.

The last big advance in model building came a bit more than 30 years ago with the birth of the standard model. From the very beginning it, like all its predecessors, was an approximation that was expected to be superseded by a better one that would encompass new phenomena beyond the standard model's energy range of validity. Experiment has found things that are not accounted for in it—neutrino masses and mixing and dark matter, for example. However, the back-and-forth between experiment and theory that led to the standard model ended around 1980. Although many new directions were hypothesized, none turned out to have predicted consequences in the region accessible to experiments. That brings us to where we are today, looking for something new and playing with what appear to me to be empty concepts like naturalness, the anthropic principle, and the landscape.

Theory today

I have asked many theorists to define naturalness and received many variations on a central theme that I would put as follows: A constant that is smaller than it ought to be must be kept there by some sort of symmetry. If, for example, the Higgs mass is quadratically divergent, invent supersymmetry to make it only logarithmically divergent and to keep it small. The price of this invention is 124 new constants, which I always thought was too high a price to pay. Progress in physics almost always is made by simplification. In this case a conceptual nicety was accompanied by an explosion in arbitrary parameters. However, the conceptual nicety, matching every fermion with a boson to cancel troublesome divergences in the theory, was attractive to many. Experiment has forced the expected value of the mass of the lightest supersymmetric particle ever higher. The Large Hadron Collider at CERN will start taking data in 2008 and we will know in a couple of years if there is anything supersymmetric there. If nothing is found, the "natural" theory of supersymmetry will be gone.

An even more interesting example to an amateur theorist like me is the story of the cosmological constant. Standard theory gives it a huge value, so large that the universe as we know it could not exist. It was assumed that if the cosmological constant was not huge, it had to be zero. Unlike supersymmetry, there was no specific symmetry that made it zero, but particle physicists expected one would be found eventually. No one took seriously the possibility of a small cosmological constant until supernova observations found that the Hubble expansion seemed to be speeding up. Naturalness seemed to prevent any serious consideration of what turned out to be the correct direction.

At the time Sheldon Glashow, John Iliopoulos, and Luciano Maiani developed the GIM mechanism, the naturalness concept was not in the air.[1] They realized that suppressing flavor-changing neutral currents required restoring a certain kind of symmetry to the quark sector. They added the charmed quark to create that symmetry, and the experiments of my group and Sam Ting's showed the charmed quark was there.

The score card for naturalness is one "no," the cosmological constant; one "yes," the charmed quark, though naturalness had nothing to do with it at the time; and one "maybe," supersymmetry. Naturalness certainly doesn't seem to be a natural and universal truth. It may be a reasonable starting point to solve a problem, but it doesn't work all the time and one should not force excessive complications in its name. Some behaviors are simply initial conditions.

For more than 1000 years, the anthropic principle has been discussed, most often in philosophic arguments about the existence of God. Moses Maimonides in the 12th century and Thomas Aquinas in the 13th used anthropic arguments to trace things back to an uncaused first cause, and to them the only possible uncaused first cause was God.

The cosmological anthropic principle is of more recent vintage. A simplified version is that since we exist, the universe must have evolved in a way that allows us to exist. It is true, for example, that the fine structure constant α has to be close to 1/137 for carbon atoms to exist, and carbon atoms are required for us to be here writing about cosmology. However, these arguments have nothing to do with explaining what physical laws led to this particular value of α. An interesting relevant recent paper by Roni Harnik, Graham Kribs, and Gilad Perez demonstrates a universe with our values of the electromagnetic and strong coupling constants, but with a zero weak coupling constant.[2] Their alternative universe has Big-Bang nucleosynthesis, carbon chemistry, stars that shine for billions of years, and the potential for sentient observers that ours has. Our universe is not the only one that can support life, and some constants are not anthropically essential.

The anthropic principle is an observation, not an explanation. To believe otherwise is to believe that our emergence at a late date in the universe is what forced the constants to be set as they are at the beginning. If you believe that, you are a creationist. We talk about the Big Bang, string theory, the number of dimensions of spacetime, dark energy, and more. All the anthropic principle says about those ideas is that as you make your theories you had better make sure that α can come out to be 1/137; that constraint has to be obeyed to allow theory to agree with experiment. I have a very hard time accepting the fact that some of our distinguished theorists do not understand the difference between observation and explanation, but it seems to be so.

String theory was born roughly 25 years ago, and the landscape concept is the latest twist in its evolution. Although string theory needed 10 dimensions in order to work, the prospect of a unique solution to its equations, one that allowed the unification of gravity and quantum mechanics, was enormously attractive. Regrettably, it was not to be. Solutions expanded as it was realized that string theory had more than one variant and expanded still further when it was also realized that as 3-dimensional space can support membranes as well as lines, 10-dimensional space can support multidimensional objects (branes) as well as strings. Today, there seems to be nearly an infinity of solutions, each with different values of fundamental parameters, and no relations among them. The ensemble of all these universes is known as the landscape.

No solution that looks like our universe has been found. No correlations have been found such as, for example, if all solutions in the landscape that had a weak coupling anywhere near ours also had a small cosmological constant. What we have is a large number of very good people trying to make something more than philosophy out of string theory. Some, perhaps most, of the attempts do not contribute even if they are formally correct.

I still read theory papers and I even understand some of them. One I found particularly relevant is by Stephen Hawking and Thomas Hertog. Their recent paper "Populating the Landscape: A Top-down Approach" starts with what they call a "no boundary" approach that ab initio allows all possible solutions.[3] They then want to impose boundary conditions at late times that allow our universe with our coupling constants, number of noncompact dimensions, and so on. This approach can give solutions that allow predictions at later times, they say. That sounds good, but it sounds to me a lot like the despised fine-tuning. If I have to impose on the landscape our conditions of three large space dimensions, a fine structure constant of 1/137, and so on, to make predictions about the future, there would seem to be no difference between the landscape and effective field theory with a few initial conditions imposed.

Although the Hawking and Hertog paper sometimes is obscure to me, the authors seem to say that their approach is only useful if the probability distribution of all possible alternatives in the landscape is strongly peaked around our conditions. I'll buy that.

To the landscape gardeners I say: Calculate the probabilities of alternative universes, and if ours does not come out with a large probability while all others with content far from ours come out with negligible probability, you have made no useful contribution to physics. It is not that the landscape model is necessarily wrong, but rather that if a huge number of universes with different properties are possible and equally probable, the landscape can make no real contribution other than a philosophic one. That is metaphysics, not physics.

We will soon learn a lot. Over the next decade, new facilities will come on line that will allow accelerator experiments at much higher energies. New non-accelerator experiments will be done on the ground, under the ground, and in space. One can hope for new clues that are less subtle than those we have so far that do not fit the standard model. After all, the Hebrews after their escape from Egypt wandered in the desert for 40 years before finding the promised land. It is only a bit more than 30 since the solidification of the standard model.

References

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