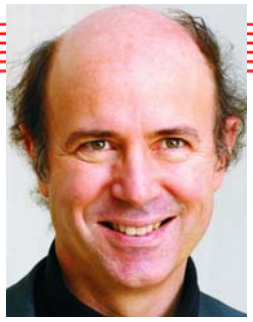
Reference Frame

On Absolute Units, III: Absolutely Not?

Frank Wilczek



Max Planck's concept of absolute units, that is, units constructed from fundamental parameters that appear in universal and immutable laws of physics, invites a question: Are there such laws?

Absolute units have their natural home in a program whose roots go back to Pythagoras: to calculate the major properties of the physical world we observe in terms of a few input parameters. (He declared, "All things are number.") Given a system of absolute units, we can express all other physical quantities as pure numbers, which we must aspire to calculate theoretically.

Twentieth-century physics marked, in large part, the triumph of that Pythagorean program. We discovered and validated powerful standard models of fundamental physics and cosmology, which suffice to accommodate all existing observations. The standard models contain a few tens of numerical parameters. Many of those parameters are pretty esoteric, having been introduced only to describe the properties of short-lived particles produced at accelerators. I count 10 that are of wide significance for present-day phenomena in the natural world. Six are from microphysics: the electromagnetic and strong coupling strengths α, α_s, Fermi's constant G_F for the weak interaction, and the masses m_e, m_u, and m_d of the electron and light quarks. Four are from cosmology: the dark matter, dark energy, and baryon mass densities relative to photon number, and the amplitude of the primeval fluctuation spectrum. So while we didn't finish the job of calculating all things as pure numbers, we got the major exceptions down to 10 or so.

More recently, however, the triumphant march of Pythagorism has stalled. There are a few isolated bright spots—most notably, the unification of couplings (see the article by Savas Dimopoulos, Stuart Raby, and me in PHYSICS TODAY, October 1991, page 25)—that are very promising and important, but on the whole, progress has been extremely limited. There's even been some slippage, in that many of us hoped to avoid introducing dark energy, but now observations seem to demand it. With frustration mounting, prominent theorists have begun to express serious doubt about whether ultimate success is possible.

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Seeds of doubt

Several specific features of our model of the world invite us to speculate that the basic laws of physics might appear markedly different elsewhere:

▶ We know that what appears to our senses as empty space is in reality a richly dynamical medium, full of symmetry-breaking fields, condensates, and virtual particles. Properties of the particles we observe, such as the masses of the proton and electron, depend essentially on their interactions with that medium. The material media we are familiar with in ordinary life, and in condensed matter physics, exist in different phases and often contain defects and inhomogeneities. Why shouldn't the cosmic medium?

▶ In quantum mechanics, the wavefunction of an object typically describes many different consistent behaviors that might occur and assigns them each a nonzero probability. Why shouldn't the wavefunction of the universe?

▶ In Big Bang cosmology, the origin of the observed universe is a singular explosive event, whose precise nature is unclear. Why couldn't such explosions occur repeatedly and in varied forms?

Occasions of doubt

Those questions might seem more appropriate for metaphysicists than for physicists. Why should we worry about the academic possibility of other worlds when we could be doing fruitful work toward understanding ours? And the doubts those questions raise might lie dormant, were not our world's numerical parameters so peculiar in ways that we might not expect for numbers that are uniquely determined by universal abstract principles.

One way they're peculiar is that several of them are outlandishly large or small. I discussed that fact extensively in the previous column of this series (PHYSICS TODAY, January 2006, page 10). But, as I also discussed, we know of several mechanisms in physics and mathematics that generate very large or small pure numbers through simple, natural operations.

A more disturbing fact is that the parameters have messy values. So it is hard to imagine a simple framework in which they can be calculated. Quark and lepton masses and mixing angles, in particular, have eluded calculation despite decades of intense effort. Even the parameter that specifies the number of families—the whole number 3—remains mysterious. When the muon was discovered, I. I. Rabi asked, "Who ordered that?" His question continues to resonate, undamped, with ever-increasing amplitude. Could a beautiful, logically complete formulation of physical law yield a unique solution that appears so lopsided and arbitrary? Though not impossible, perhaps it strains credulity.

But the most disturbing fact, if you're a believing fundamentalist Pythagorean, is that several of the parameters appear to have values that are fine-tuned to bring forth a universe that contains complex condensed structures, including life as we know it. If the electron or down quark were a bit lighter, or the up quark a bit heavier, then electrons and protons would combine into neutrons (emitting neutrinos). A world of neutrons does not support stellar burning, complex chemistry, or even the collapse of nebular clouds into solid structures. Make those masses slightly lighter, and deuterium becomes unbound, with catastrophic consequences for the workings of stars and production of nuclei more complex than hydrogen. More subtly, as Fred Hoyle famously argued,[1] small changes in the fine-structure constant would upset the balance of nucleosynthesis in stars, effectively eliminating either carbon or oxygen. Likewise in cosmology, the road leading to life in anything like the form we know it threads a narrow path through hostile territory in parameter

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space. Significantly larger fluctuation amplitudes would lead to black holes rather than to user-friendly galaxies; significantly smaller background densities would bring forth only diffuse gas clouds, and so on.

It is logically possible that parameters determined uniquely by abstract theoretical principles just happen to exhibit all the apparent fine-tunings required to produce, by a lucky coincidence, a universe containing complex condensed structures. But that, I think, really strains credulity.

Failure modes

Fine-tunings of this sort are the stuff of theology's Argument from Design.[2] According to that idea, either a designer carefully fine-tuned the values of parameters left free by the fundamental laws, or the laws themselves were carefully designed to have a unique solution with the desired fine-tuned values for the parameters.

In biology, Charles Darwin's theory of evolution by natural selection undermined the analogous Argument from Design. In chemistry, quantum theory did the job. (The chemical Argument from Design may be less famous than the biological version, but it is—or rather was—a powerful argument. Both Isaac Newton and James Clerk Maxwell used it! Those greats realized that the laws of classical physics could not explain the foundation of chemistry—that is, the existence of a few types of atoms with definite, reproducible properties, available in vast numbers of copies. They argued that such atoms would have to be deliberately manufactured.) It's possible that the physical Argument from Design will suffer one of those fates, to be undermined by selection or quantum theory.

Selection requires variation. Despite the possible seeds of doubt I mentioned above, as recently as 30 years ago it might have seemed whimsical, if not perverse, to entertain the possibility that standard model parameters were anything but universal, immutable characteristics of physical reality, for two reasons. First: the fact that the same laws act everywhere and everywhen in the observed universe is a central result of observational cosmology, attested most impressively by the fixed, universal pattern of spectral lines. Second, insofar as the standard model of fundamental physics describes reality—and it does, precisely, under an extraordinary range of circumstances—it tells us what can vary in space and time, and what cannot. The parameters we're discussing, of course, are just those that, according to the standard model, don't change.

Inflationary cosmology changes our perspective on the first barrier to selection, the uniformity of the observed universe. By making it plausible that the part of the universe accessible to observation today might have developed from expansion of a tiny patch of space, inflationary cosmology explains the uniformity of what we see, while suggesting that truly distant regions (arising from other patches) might be quite different. Inflation is a broad scenario rather than a specific theory, but its success has motivated theorists to look for ways in which concrete extensions of the laws of physics might license multiple big bangs. Many ways have been found, including some that are amazingly simple,[3] reasonably modest extrapolations from what we know.

Ideas about symmetry and unification change our perspective on the second barrier to selection, the apparent fixity of standard model parameters. Axion physics shows that at least one numerical parameter of the standard model, the so-called θ parameter of quantum chromodynamics, might be—I'd say probably is—a dynamical quantum field. It has settled into quiescence—that is, assumed a universal, constant value—for conventional energetic reasons. Unified models with supersymmetry (and for that matter water ice and spin glasses) provide examples with many different metastable ground states that have closely comparable energy. Superstring theory goes much further in the same direction. In each of those theoretical frameworks, the mathematical mechanism for producing many candidate worlds is that the space of solutions to a coupled system of nonlinear equations can suffer a combinatorial explosion. Dropping the jargon, what this means is that the medium that is empty space has competing candidate phases, and there is no obvious physical sense in which one is better than another.

Evidently, once-powerful objections to considering variation of fundamental parameters have lost their force. Let me be clear that we're not concerned here with time variation of parameters in our part of the universe. There are very strong experimental constraints on that sort of variation, and it's not what the preceding paragraphs suggest. The suggested variation refers to places that are far away in physical space, or possibly in Hilbert space, and inaccessible to current observation. If parameters vary in this way, then the Pythagorean program fails. We won't be able to calculate unique values of the parameters by solving the equations, for the very good reason that the solutions don't have unique values.

Bug into feature

Of course, the very real possibility that we can't calculate everything in fundamental physics and cosmology doesn't mean that we won't be able to calculate *anything* beyond what the standard models already achieve. It does mean, I think, that the explanatory power of the equations of a "theory of everything" could be much less than those words portend. To paraphrase Albert Einstein, our theory of the world must be as calculable as possible, but no more.

The idea that we find ourselves in one of many possible universes, each with different values of some basic physical parameters, has its positive sides as well. Famously—or notoriously—it could help explain the fine-tunings required for life. Most of the alternative universes would not have those fine-tunings, but there'd be no one around to notice. That sort of anthropic reasoning can be used constructively to make predictions if we tie the conditions necessary for life to other, superficially unrelated phenomena. Hoyle's prediction of a resonant energy in carbon nuclei was an example of that kind. Several others, relating more directly to the values of standard model parameters, are currently under discussion.

Eastern religions and science fiction writers agree that it is wondrous and awesome—not to mention correct—to contemplate an abundance of universes. I'll close with a quote from Olaf Stapledon's *Star Maker*[4]

> So I, in the supreme moment of my cosmic experience, emerged from the mist of my finitude to be confronted with cosmos upon cosmos, and by the light itself that not only illumines but gives life to all. Then immediately the mist closed in on me again.

References

1. See review by C. Hogan, *Rev. Mod. Phys.* **72**, 1149 (2000).
2. S. Barr, *Modern Physics and Ancient Faith*, U. of Notre Dame Press, Notre Dame, IN (2003).
3. A. Linde, *Particle Physics and Inflationary Cosmology*, Harwood Academic Publishers, New York (1990).
4. O. Stapledon, *Last and First Men, and Star Maker: Two Science-Fiction Novels*, Dover, New York (1968). *Star Maker* originally appeared in 1937. ■