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Reference Frame

Scaling Mount Planck II: Base Camp

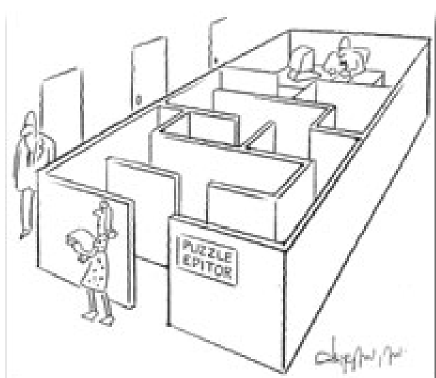
Frank Wilczek

As I explained in an earlier column in Physics Today (Physics Today, June 2001, page 12[*]), if we believe that gravity will be a primary element within a unified theory of fundamental physics, then the classic question Why is gravity so weak? is much better posed in the form, Why are protons so light? And since we have achieved, on the basis of modern quantum chromodynamics (QCD), a detailed and powerful understanding of how the mass of the proton arises, I was able to give a detailed and powerful answer to this rephrased question. What I didn't do was present any serious evidence that my answer is the same as Nature's.

Let me recall very briefly the central points from that previous discussion. Quantum fluctuations in the quark and gluon fields render empty space into a dynamical medium, which, under different circumstances, can either screen out or enhance the power of a source of color charge. Thus the strength of this coupling depends on the energy scale at which it is measured, an effect we call the running of couplings. Operationally, it means that the probability for radiation of color gluons that carry away large amounts of energy and momentum is predicted to decrease as the energy in question increases, or equivalently to increase as the energy shrinks. This behavior has been verified, with quantitative precision, in many experiments. Now because the coupling strength changes only logarithmically with the energy scale, a big factor in this scale is required to make a significant change in the effective coupling strength. Thus a moderate color coupling at the enormously high energy scale that gravity suggests is fundamental (the Planck scale, about 10^{19} proton masses) will only become large and capable of binding quarks together at some much lower energy scale, where quarks bind into protons, and the building blocks of matter take shape. Following this scenario, it is not a difficult stretch to imagine that the running of the QCD coupling produces a relatively tiny mass for protons starting from a much larger fundamental scale, thereby placing the feebleness of gravity in satisfying perspective.

Frank Wilczek

That's a fine sketch, as far as it goes. It's coherent, largely taken from life, and I think quite pretty. But I'd blush to call it a scientific trail guide for an ascent of Mount Planck. It's lacking in context and detail. And, beyond the bare observation that the logarithm of a very large number need not be very large, it lacks sharp quantitative focus. To go further, we need to draw in other parts of physics besides QCD and gravity proper. Do they fill in our sketch? In particular, do they provide specific pointers toward our sought-for peak--the remote Planck scale? Or do they bring out remaining gaps? The answers, broadly speaking, are Yes, Yes--and Yes again. Overall, our sketch will grow much stronger and more coherent. Though holes do appear, I'll save their description for next time. Here let's savor some nice fancy doughnuts that surround them.



To begin, let's appreciate that the running of couplings is a general phenomenon of quantum field theory, not restricted to QCD. Indeed, its historical antecedents can be found in the prehistory of modern quantum field theory. When hints of a deviation from Paul Dirac's prediction for the spectrum of hydrogen were in the air, but before Willis Lamb's accurate measurements, Edwin Uehling in 1935 calculated a correction to the Coulomb potential due to the screening effect of virtual particles, the so-called vacuum polarization. It turns out that vacuum polarization provides a relatively small part of the Lamb shift. But it definitely must be included in order for theory to agree with experiment. This agreement provided early, direct evidence for what we today would call the running of the effective coupling for quantum electrodynamics. In recent times, this effect, and its weak interaction analog, has been richly documented in precision experiments at CERN's Large Electron-Positron Collider (LEP).

Whereas the fine-structure constant α that we observe at vanishingly small energies is very nearly $\alpha(0)$ = 1/137.03599976(50), the value governing high-energy radiation in *Z*-boson production and decay is measured to be $\alpha(M_Z)$ = 1/127.934(27). The numerical value of the fine-structure constant, a conceptual gold nugget ardently pursued by Arthur Eddington and Wolfgang Pauli, has lost its luster. (There is a shiny gold nugget, nonetheless, whose nature will emerge in my next column.)

With both strong and weak couplings in play, it makes sense to ask if there is an energy scale at which they equalize. The answer involves extrapolating many orders of magnitude beyond what has been accessed experimentally. Following the credo "It is more blessed to ask forgiveness than permission," let's try it. Certainly, nothing in the internal logic of quantum field theory forbids the extrapolation. Indeed, by its indication that fundamental dynamics evolves on a logarithmic scale, quantum field theory encourages us to think big. Carrying out the extrapolation, we find a most remarkable and encouraging result. The strong and weak couplings equalize--at roughly the Planck scale! Planck, of course, knew of neither the strong nor the weak interaction, nor of quantum field theory and running couplings. The reappearance of his scale in this entirely new context confirms his intuition about the fundamental character of the Planck scale.

The plot thickens when the remaining fundamental interaction, electromagnetism, is added to the mix. Its coupling also runs, as I've already mentioned. But in comparing this coupling with the strong or weak coupling, a new issue arises. The mediators of the strong and weak interactions are themselves strongly and weakly interacting particles; they have nonvanishing strong or weak charges. This property reflects the nonabelian character of the strong and weak gauge symmetries. The photon, however, is electrically neutral. So whereas for the strong and weak interactions there is a unique, natural unit of charge, for electromagnetism the natural unit is obscure. Should we use the charge of the u quark ($^2/_3\,e$), the d quark (- $^1/_3 e$), the electron (-*e*), or something else? Since, as I've emphasized, small changes in the couplings correspond to big changes in energy scale, our answer for the unification scale is quite sensitive to this ambiguity.

Resolving it requires considerations of another order. Up to this point, I have been able to be rather vague about what actually happens at the Planck scale. We've seen that the strong coupling is not very strong up there, that it equalizes with the weak coupling, and both sorts of interactions become roughly comparable in strength to gravity. But it has not been necessary to speculate about the dynamics of a specific unified theory. Now it's unavoidable.

Unified gauge symmetry, which includes strong, weak, and electromagnetic interactions in a single structure, makes precise comparisons possible. Of course, our answer depends on what unifying symmetry is assumed. The original, simplest, and most natural possibilities were identified by Jogesh Pati and Abdus Salam and by Howard Georgi and Sheldon Glashow. On adopting either of those possibilities, we can make our calculation. And we find that the strong and electromagnetic couplings equalize, again, at roughly the Planck scale! And so do the weak and electromagnetic couplings.

A usably specific unified theory including gravity remains elusive. In the absence of such a theory, comparisons between the strength of gravity and that of the other forces cannot be precise. Thus the physical significance of exactly where these various unifications occur--whether it is at precisely the Planck scale rather than, say, the Planck scale times ($1/8\pi^2$)--is correspondingly murky. I'll say more about it in my next column.

The question whether strong, weak, and electromagnetic couplings unite *with each other* at a common scale, by contrast, is ripe. If we take into account the virtual effects of only the particles in the Standard Model, the answer is, "Almost, but not quite." But if we make the further hypothesis, which is quite attractive on other grounds, that the known particles have heavier supersymmetric partners with masses in the neighborhood of 10^3 proton masses, then there is striking quantitative agreement.

Both the strength and the limitation of the running-of-couplings calculation lie in its insensitivity to details. Because the running depends only weakly (logarithmically) on the masses of the virtual particles involved, we can't use the success of our calculation to discriminate finely among detailed models of unified gauge symmetry, or supersymmetry, or the way in which these symmetries are broken.

Were there an abundance of independent evidence for these ideas, we might lament this robustness as a lost opportunity. But at present, independent evidence is extremely thin, especially for low-energy supersymmetry.

Our robust, successful calculation therefore provides a mercifully stable beacon amidst foggy mist. It reveals what appears to be a path with sound footing up Mount Planck, leading us to a dizzyingly high base camp. The indicated path ascends, following the tried and tested physics of quantum field theory, on a gentle logarithmic slope. In calibrated steps, it guides us directly from subnuclear phenomena of the strong and weak interactions to the heights that encode the feebleness of gravity. It is redoubled with unified gauge symmetry and dovetailed with low-energy supersymmetry.

As we approach such ethereal heights, the air grows thin, and even the normally sober can become giddy. Hallucinations are to be expected. How can we demonstrate to skeptics the reality of the places revealed in our visions? The traditional, and ultimately the only convincing, way is to bring back trophies. Unified gauge symmetry powerfully suggests, and almost requires, tiny violations of the laws of lepton and baryon and number conservation. These violations can be observed as small neutrino masses and as proton instability, respectively. Neutrino masses of appropriate magnitude have now been observed through oscillations (though questions remain, even here). Proton decay remains elusive. Low-energy supersymmetry predicts a whole new world of particles, several of which must be accessible to future accelerators including, specifically, the CERN Large Hadron Collider, which is scheduled to begin operation in 2007. In the long view, then, there are genuine, tremendously exciting prospects for bringing this circle of ideas to fruition--or demolition. Unfortunately, the requisite experiments are difficult, slow, and expensive. The main ideas have been in place--ever promising, fundamentally unshaken, but mostly unfulfilled--for 20 years or more. The tempo, unfortunately, is poorly matched to news cycles or even to the timescales for academic promotions. It is tempting to hope that shortcuts will appear or even that the long, hard path, though beautiful, is illusory and that the peak is actually nearby. Personally, I prefer to anticipate that, here, beauty foretells truth, humbly accepting that, as Spinoza wrote, "All things great are as difficult as they are rare."

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Further reading

- For a much more extensive discussion, see my "Future Summary," given at the celebration of the closing of LEP, http://arXiv.org/abs/hep-ph/0101187, and *Int. J. Mod. Phys.* **A16** (10), 1653 (2001).

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