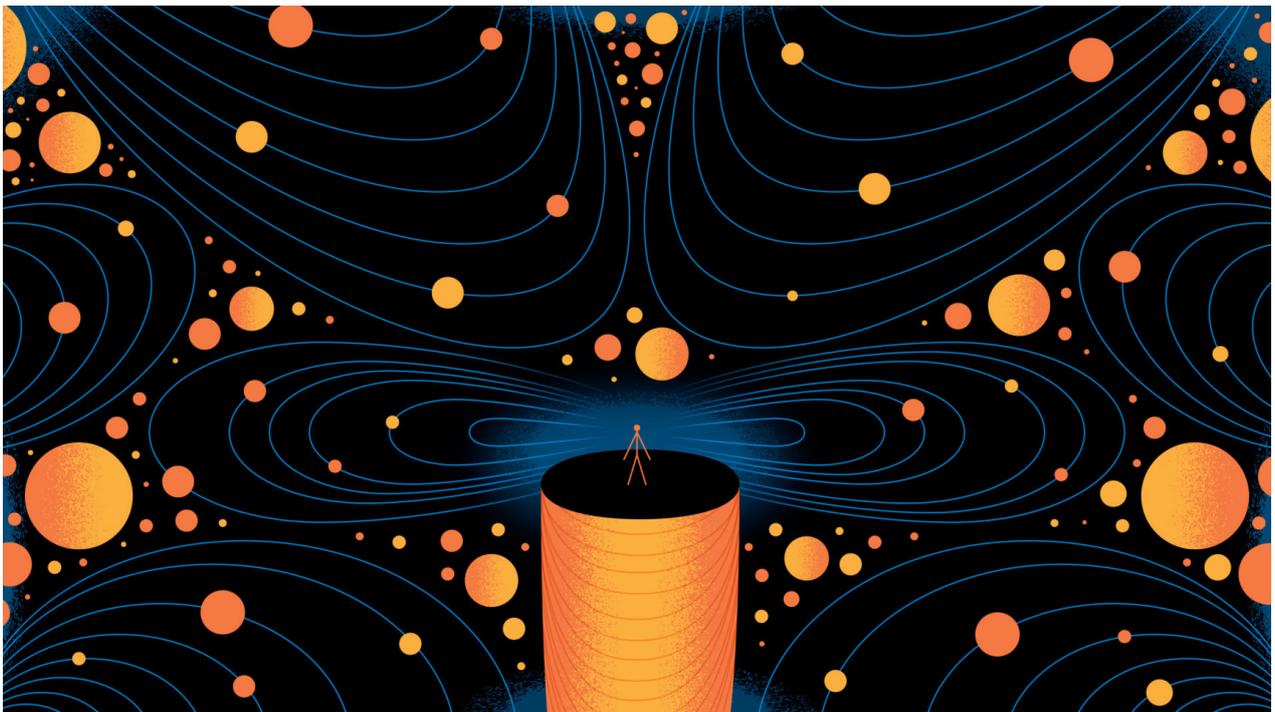




# Why an Old Theory of Everything Is Gaining New Life

For decades, physicists have struggled to create a quantum theory of gravity. Now an approach that dates to the 1970s is attracting newfound attention.

*By Sabine Hossenfelder*



[James O'Brien](#) for Quanta Magazine

Twenty-five particles and four forces. That description — the [Standard Model of particle physics](#) — constitutes physicists' best current explanation for everything. It's neat and it's simple, but no one is entirely happy with it. What irritates physicists most is that one of the forces — [gravity](#) — sticks out like a sore thumb on a four-fingered hand. Gravity is different.

Unlike the electromagnetic force and the strong and weak nuclear forces, gravity is not a quantum theory. This isn't only aesthetically displeasing, it's also a mathematical headache. We know that

particles have both quantum properties and gravitational fields, so the gravitational field should have quantum properties like the particles that cause it. But a theory of quantum gravity has been hard to come by.

In the 1960s, Richard Feynman and Bryce DeWitt set out to quantize gravity using the same techniques that had successfully transformed electromagnetism into the quantum theory called quantum electrodynamics. Unfortunately, when applied to gravity, the known techniques resulted in a theory that, when extrapolated to high energies, was plagued by an infinite number of infinities. This [quantization of gravity](#) was thought incurably sick, an approximation useful only when gravity is weak.

Since then, physicists have made [several other attempts at quantizing gravity](#) in the hope of finding a theory that would also work when gravity is strong. [String theory](#), [loop quantum gravity](#), causal dynamical triangulation and a few others have been aimed toward that goal. So far, none of these theories has experimental evidence speaking for it. Each has mathematical pros and cons, and no convergence seems in sight. But while these approaches were competing for attention, an old rival has caught up.

The theory called asymptotically (as-em-TOT-ick-lee) safe gravity was proposed in 1978 by [Steven Weinberg](#). Weinberg, who would only a year later [share the Nobel Prize](#) with Sheldon Lee Glashow and Abdus Salam for unifying the electromagnetic and weak nuclear force, realized that the troubles with the naive quantization of gravity are not a death knell for the theory. Even though it looks like the theory breaks down when extrapolated to high energies, this breakdown might never come to pass. But to be able to tell just what happens, researchers had to wait for new mathematical methods that have only recently become available.

In quantum theories, all interactions depend on the energy at which they take place, which means the theory changes as some interactions become more relevant, others less so. This change can be quantified by calculating how the numbers that enter the theory — collectively called “parameters” — depend on energy. The strong nuclear force, for example, becomes weak at high energies as a parameter known as the coupling constant approaches zero. This property is known as “asymptotic freedom,” and it was worth [another Nobel Prize](#), in 2004, to [Frank Wilczek](#), [David Gross](#) and [David Politzer](#).

A theory that is asymptotically free is well behaved at high energies; it makes no trouble. The quantization of gravity is not of this type, but, as Weinberg observed, a weaker criterion would do: For quantum gravity to work, researchers must be able to describe the theory at high energies using only a finite number of parameters. This is opposed to the situation they face in the naive extrapolation, which requires an infinite number of unspecifiable parameters. Furthermore, none of the parameters should themselves become infinite. These two requirements — that the number of parameters be finite and the parameters themselves be finite — make a theory “asymptotically safe.”

In other words, gravity would be asymptotically safe if the theory at high energies remains equally well behaved as the theory at low energies. In and of itself, this is not much of an insight. The insight comes from realizing that this good behavior does not necessarily contradict what we already know about the theory at low energies (from the early works of DeWitt and Feynman).

While the idea that gravity may be asymptotically safe has been around for four decades, it was only in the late 1990s, through research by [Christof Wetterich](#), a physicist at the University of Heidelberg, and [Martin Reuter](#), a physicist at the University of Mainz, that asymptotically safe gravity caught on. The works of Wetterich and Reuter provided the mathematical formalism necessary to calculate what happens with the quantum theory of gravity at higher energies. The

strategy of the asymptotic safety program, then, is to start with the theory at low energies and use the new mathematical methods to explore how to reach asymptotic safety.

So, is gravity asymptotically safe? No one has proven it, but researchers use several independent arguments to support the idea. First, studies of gravitational theories in lower-dimensional space-times, which are much simpler to do, find that in these cases, gravity is asymptotically safe. Second, approximate calculations support the possibility. Third, researchers have applied the general method to studies of simpler, nongravitational theories and found it to be reliable.

The major problem with the approach is that calculations in the full (infinite dimensional!) theory space are not possible. To make the calculations feasible, researchers study a small part of the space, but the results obtained then yield only a limited level of knowledge. Therefore, even though the existing calculations are consistent with asymptotic safety, the situation has remained inconclusive. And there is another question that has remained open. Even if the theory is asymptotically safe, it might become physically meaningless at high energies because it might break some essential elements of quantum theory.

Even still, physicists can already put the ideas behind asymptotic safety to the test. If gravity is asymptotically safe — that is, if the theory is well behaved at high energies — then that restricts the number of fundamental particles that can exist. This constraint puts asymptotically safe gravity [at odds with some of the pursued approaches to grand unification](#). For example, the simplest version of [supersymmetry](#) — a long-popular theory that predicts a sister particle for each known particle — is not asymptotically safe. The simplest version of supersymmetry has meanwhile been [ruled out by experiments at the LHC](#), as have a few other proposed extensions of the Standard Model. But had physicists studied the asymptotic behavior in advance, they could have concluded that these ideas were not promising.

Another study recently [showed](#) that asymptotic safety also constrains the masses of particles. It implies that the difference in mass between the top and bottom quark must not be larger than a certain value. If we had not already measured the mass of the top quark, this could have been used as a prediction.

These calculations rely on approximations that might turn out to be not entirely justified, but the results demonstrate the power of the method. The most important implication is that the physics at energies where the forces may be unified — usually thought to be hopelessly out of reach — is intricately related to the physics at low energies; the requirement of asymptotic safety connects them.

Whenever I speak to colleagues who do not themselves work on asymptotically safe gravity, they refer to the approach as “disappointing.” This comment, I believe, is born out of the thought that asymptotic safety means there isn’t anything new to learn from quantum gravity, that it’s the same story all the way down, just more quantum field theory, business as usual.

But not only does asymptotic safety provide a link between testable low energies and inaccessible high energies — as the above examples demonstrate — the approach is also not necessarily in conflict with other ways of quantizing gravity. That’s because the extrapolation central to asymptotic safety does not rule out that a more fundamental description of space-time — for example, with [strings](#) or [networks](#) — emerges at high energies. Far from being disappointing, asymptotic safety might allow us to finally connect the known universe to the quantum behavior of space-time.

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