

Can String Theory Be Explained with No Strings Attached?

Using a “bootstrap” approach, researchers show that a small set of assumptions may naturally lead to a string-theory description of certain high-energy processes.

By **Eric Perlmutter**

String theory has been a remarkably influential conceptual framework for modern theoretical physics. While its description of nature in terms of tiny strings captures the imagination, the string framework has had profound impact in a broad range of subfields, going well

beyond its lead role as a viable theory of quantum gravity. For instance, it has led to deeper understanding of black holes and their relation to entanglement and quantum information [1], and it has provided theoretical benchmarks for explaining quark–gluon plasma observations in quantum chromodynamics [2]. As a complement to direct calculations, theoretical physicists would like to understand string theory as emerging from a set of fundamental principles that any theory of nature must respect. Consistency with these bedrock conditions, so goes the idea, could perhaps make string theory inevitable. This concept, known as “string universality,” is the backdrop for a new study by Clifford Cheung from Caltech and colleagues [3]. As the latest in a long line of work, the researchers show that certain string scattering amplitudes—high-energy collisions—are the unique solutions to a set of minimal consistency conditions, playfully referred to by Cheung and colleagues as “almost nothing.” In this sense, string theory is an emergent natural description of our world.

The rational basis of this new work goes beyond strings and is known as the “bootstrap” approach (Fig. 1). This approach goes back decades, but it has experienced a revival within high-energy theory during the past 20 years. The idea is to start with some set of observable quantities, such as the masses and couplings in particle physics or the geometry of spacetime. Rather than trying to directly compute their values as explicit solutions to some theory’s equations, one looks at the “universe” of possible solutions and discards the solutions that are incompatible with certain physical constraints, or axioms. (A simple example would be to impose positivity on the solutions to the equation $x^2 = 1$, which discards $x = -1$.) The goal is to carve out an allowed space in which a limited number of

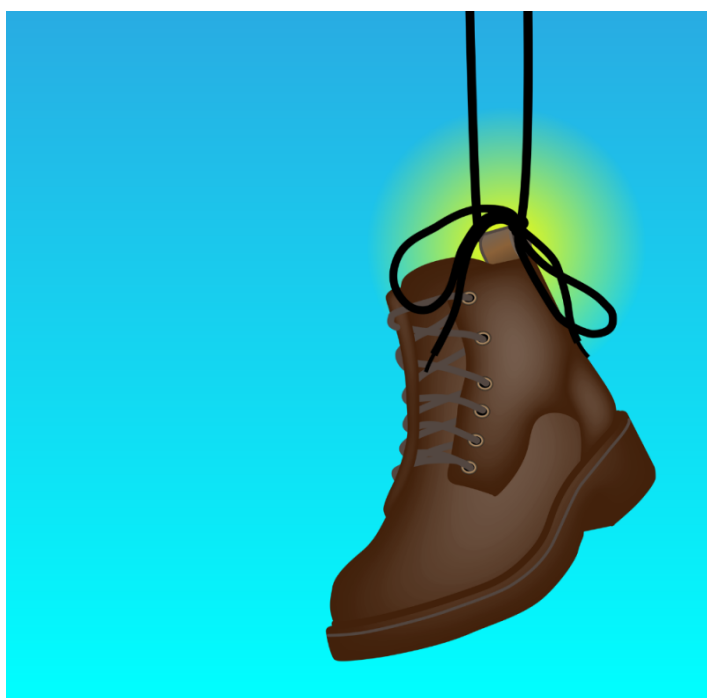


Figure 1: “Pulling oneself up by the bootstraps” takes on a specific meaning in theoretical physics. Bootstrapping a theory, such as string theory, involves showing that it is the unique solution to a set of fundamental constraints.

Credit: APS/Alan Stonebraker

solutions—or, perhaps, just a single solution—exist.

Bootstrap axioms take various forms. The most common class of axioms are symmetry based. For example, Lorentz symmetry and invariance under coordinate transformations are largely sufficient constraints on the description of spacetime geometry to derive the classical gravitational-field equations. In the context of particle physics and so-called conformal field theories [4], it is also common to impose “crossing symmetry,” which says that consistent scattering processes are invariant under swapping the inputs and outputs. A related class of bootstrap constraints are known as positivity, or unitarity, constraints: These encode the absence of states whose energies are negative, which would lead to unphysical consequences. In the language of quantum mechanics such states would violate conservation of probability.

Symmetry and positivity are powerful constraints, but they generally don’t lead to unique solutions for describing physical observables. Fortunately, bootstrappers have more in their axiomatic toolkit. In particular, given a physical observable depending on some set of parameters, one may impose certain functional constraints on the dependence on these parameters, broadly known as analyticity constraints (in the sense of complex analysis). These are often not reducible to any known symmetry principle. For scattering processes, analyticity constraints encode possible particle and bound states, and they can restrict the scattering behavior in various high-energy limits. The latter is directly relevant for processes such as black hole formation, which is directly relevant for questions within quantum gravity.

These high-energy processes provide the context where Cheung and colleagues perform their analysis [3]. Following works by them and many others over the past 15 years [5–10], the researchers consider tree-level scattering amplitudes, such as those involving two incoming particles and two outgoing particles (Fig. 2). String theory predicts a certain functional form and analyticity signature for the scattering amplitudes. The bootstrap approach asks whether general constraints on the amplitudes—constraints that are not overly tailored or implausible—can lead to these stringy signatures.

The strategy of Cheung and colleagues has two steps: First, they derive a new fundamental property of these amplitudes;

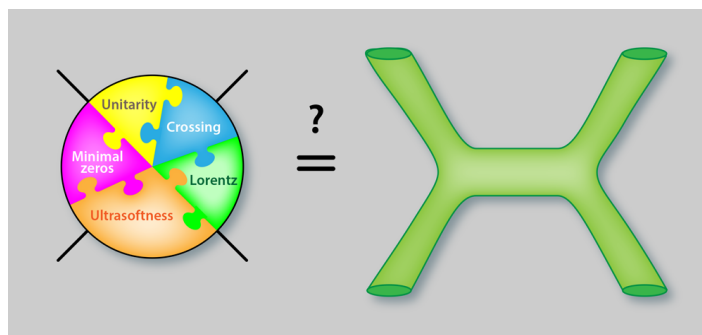


Figure 2: A four-point scattering process, with two incoming and two outgoing particles, can be investigated under certain symmetry and analyticity constraints (left). The results reveal a unique answer for the scattering amplitudes in which the particles behave as closed strings (right).

Credit: APS/Alan Stonebraker

second, they exploit the significant wiggle room in the general analyticity properties of scattering amplitudes to impose two assumptions that they argue are minimal. For the first step, they prove that the relevant scattering amplitudes are always mandated to have a very specific set of zeros—values of momenta where a given amplitude vanishes, known as Regge zeros.

The assumptions are then twofold. The first assumption is what the researchers call “ultrasoftness,” which means that the amplitude decays superpolynomially in a certain high-energy limit. Ultrasoftness is a long-known property of string amplitudes (in contrast to amplitudes in quantum field theory, which are not ultrasoft). Ultrasoft amplitudes are crucial for making string theory a viable theory of quantum gravity. The second assumption is simply that the Regge zeros are the only zeros of the amplitude. There is an appealing simplicity to this assumption: the amplitude does not vanish “for no reason” anywhere.

Cheung and colleagues combine these two assumptions with previously derived constraints [10] and the standard fundamental requirements of Lorentz invariance, crossing symmetry and positivity. This collection of bootstrap ingredients is sufficient to single out the amplitudes of string theory, in particular, the amplitudes for four- and five-point scattering of identical scalars.

What are we to make of this striking conclusion? One may view it as a distillation of a multiyear program to bootstrap tree-level string amplitudes using modern methods. As with any bootstrap approach, the strength of the output depends on the scope of the input. As such, the ultimate legacy of this latest work by Cheung and colleagues may rest on the extent to which its inputs—ultrasoftness and minimality of zeros—can be justified on independent grounds. Indeed, there have been other bootstrap constructions to which string amplitudes are the unique answer. It will be interesting to see the extent to which these string amplitudes may be uniquely derived from wholly distinct assumptions, or whether an approach formulated in terms of properties of black holes, can achieve the same result. In the meantime, this new work elegantly adds to the steadily growing body of evidence that string theory is not only formally consistent but actually stands out as special, possibly unique, in the space of consistent theories of quantum gravity.

Eric Perlmutter: Institute of Theoretical Physics (IPhT), CEA Paris-Saclay, Gif-sur-Yvette, France

REFERENCES

1. S. Ryu and T. Takayanagi, “Holographic derivation of entanglement entropy from the anti-de Sitter space/conformal field theory correspondence,” *Phys. Rev. Lett.* **96**, 181602 (2006).
2. P. K. Kovtun *et al.*, “Viscosity in strongly interacting quantum field theories from black hole physics,” *Phys. Rev. Lett.* **94**, 111601 (2005).
3. C. Cheung *et al.*, “Strings from almost nothing,” *Phys. Rev. Lett.* **136**, 251601 (2026).
4. D. Poland *et al.*, “The conformal bootstrap: Theory, numerical techniques, and applications,” *Rev. Mod. Phys.* **91**, 015002 (2019).
5. S. Caron-Huot *et al.*, “Strings from massive higher spins: the asymptotic uniqueness of the Veneziano amplitude,” *J. High Energy Phys.* **2017**, 26 (2017).
6. M. Correia *et al.*, “An analytical toolkit for the S-matrix bootstrap,” *J. High Energy Phys.* **2021**, 13 (2021).
7. A. Guerrieri *et al.*, “Where is string theory in the space of scattering amplitudes?” *Phys. Rev. Lett.* **127**, 081601 (2021).
8. N. Geiser and L. W. Lindwasser, “Generalized Veneziano and Virasoro amplitudes,” *J. High Energy Phys.* **2023**, 31 (2023).
9. K. Häring and A. Zhiboedov, “The stringy S-matrix bootstrap: maximal spin and superpolynomial softness,” *J. High Energy Phys.* **2024**, 75 (2024).
10. C. Cheung *et al.*, “Bootstrap principle for the spectrum and scattering of strings,” *Phys. Rev. Lett.* **133**, 251601 (2024).