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Deconstructing the Cosmological Constant

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Deconstruction provides a novel way of dealing with the notoriously difficult ultraviolet problems of four-dimensional gravity. This approach also naturally leads to a new perspective on the holographic principle, tying it to the fundamental requirements of unitarity and diffeomorphism invariance, as well as to a new viewpoint on the cosmological constant problem. The numerical smallness of the cosmological constant is implied by a unique combination of holography and supersymmetry, opening a new window into the fundamental physics of the vacuum.

KEY WORDS: Cosmological constant; deconstruction; holographic principle.

The validity of general relativity as a classical theory, at least at reasonable length scales is by now beyond any doubt, yet a completely satisfying quantum theory of gravitation remains elusive. The difficulty may be understood on many levels. The most straightforward approach, that of treating general relativity as a local four-dimensional field theory and quantizing it as such, fails unequivocally. The gravitational coupling, $G_N$, is a dimensionful quantity that renders the short-distance...
structure of the theory meaningless. Thus, at best, general relativity should be regarded as a four-dimensional effective field theory that is replaced by something else at short distances, for example, a well-defined perturbative quantum theory of gravity, such as string theory.

Yet, all is not well, even apart from the basic open question of how to formulate a background independent non-perturbative version of quantum gravity. The low-energy effective field theory makes predictions wildly inconsistent with observation. Most notably, when coupled to matter degrees of freedom, the energy density of the vacuum is extremely large, scaling with the largest available energy in the theory. This is the essence of the cosmological constant problem. The insidiousness of the renormalization of the cosmological constant means that it is not even sufficient to find a principle that would set the vacuum energy to some small value at a given ultraviolet (UV) scale; rather it must be canceled all the way into the infrared (IR).

It has recently become clear that quantum gravitational systems display features that cannot be accommodated by local four-dimensional field theories. In particular, the holographic principle [1] asserts that the degrees of freedom of such four-dimensional gravitational systems are better accounted for by three-dimensional data. This principle stems from the well-known non-extensive properties of the Bekenstein-Hawking entropy [2]

\[ S = \frac{A}{4G_N} \]

which scales as the area, not the volume, of a given region of space. Just how holography might be implemented is a matter of some debate, but simple examples, possessing a high degree of symmetry, have been well explored; this is what underlies the duality between gravitating systems on anti-de Sitter (AdS) background geometries and conformal field theories (CFT) in one fewer dimension [3].

If holography is to be taken seriously, we should look to three-dimensional theories for guidance. Recent astrophysical observations of the cosmic microwave background radiation [4] and distant supernovae [5] together suggest that the expansion of the universe is accelerating and that this acceleration is being driven by a “dark energy,” which comprises three quarters of the total energy density of the universe. The leading candidate for dark energy is the energy in the vacuum itself, and the observed value points to a positive small cosmological constant. An extension of the ideas underlying the dualities mentioned above would then seem to suggest looking for a de Sitter/CFT correspondence [6]. It is not clear however, what three-dimensional CFT would be capable of fully describing the present state of our Universe.

However, there is another possibility based on the idea of deconstruction [7]. In this framework, one imagines that the short distance regime of a four-dimensional field theory is described by a three-dimensional theory. The