

Deconstruction and Holography

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Abstract

It was recently pointed out that the physics of a single discrete gravitational extra dimension exhibits a peculiar UV/IR connection relating the UV scale to the radius of the effective extra dimension. Here we note that this non-locality is a manifestation of holography, encoding the correct scaling of the number of fundamental degrees of freedom of the UV theory. This in turn relates the Wilsonian RG flow in the UV theory to the effective gravitational dynamics in the extra dimension. The relevant holographic c-function is determined by the expression for the holographic bound. Holography in this context is a result of the requirements of unitarity and diffeomorphism invariance. We comment on the relevance of this observation for the cosmological constant problem.

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1 Introduction and relation to previous work

Recently, we have argued that the vanishing of the vacuum energy of $(2+1)$ -dimensional gravity [1, 2, 3, 4] may be deconstructed [5] to $3+1$ dimensions under certain conditions [6]. Our discussion pointed towards a possibility that there exists a well-defined UV completion of $(3+1)$ -dimensional gravity. (For related discussions, see Refs. [7] and [8].)

More recently it was pointed out by Arkani-Hamed and Schwartz [9] that the physics of gravitational deconstruction exhibits a fascinating relation between the characteristic UV and IR scales. This UV/IR relation was argued [9] to indicate the presence of non-local interactions in the defining UV theory.

Here, we point out that the UV/IR relation found in Ref. [9] is nothing but a manifestation of the holographic principle [10, 11, 12]. In particular the specific form of the UV/IR correspondence found in the problem of deconstruction of gravity is very analogous to a similar relation found [13] in a seemingly completely unrelated topic - the AdS/CFT correspondence [14] (see also [15])!

As reviewed in Ref. [6], in $(2+1)$ -dimensional theories it is possible [1] to have vanishing vacuum energy in the absence of a mass degenerate spectrum of bosonic and fermionic states. The basic point is that the vacuum state is supersymmetric, but the excited states are not mass degenerate because unbroken global supercharges do not exist in $2+1$ dimensions [2]. Any excited state gives a conical geometry whose deficit angle prohibits spinor fields with covariantly constant asymptotics. Thus, there are no global supercharges and no mass degeneracy between Bose and Fermi excitations. The size of the non-degeneracy of the spectrum of low-energy excitations scales as the inverse power of the three-dimensional Newton constant under the assumption of weak gravitational coupling [3].

The idea behind deconstruction [5] is that the UV region of a theory might be described in terms of a co-dimension one theory. Motivated by this idea in Ref. [6] we argued that the $(2+1)$ -dimensional phenomenon described above can be deconstructed as follows:

- (1) Assume a local spatial foliation of 4d spacetime.
- (2) Deconstruct the vacuum part of pure 4d gravity from (N copies of) 3d general relativity [16] coupled to certain 3d matter fields represented in terms of currents. Assume that the 4d sources can be defined in terms of a deconstructed 3d theory. For sources represented by gauge fields this should be possible given the discussion in Ref. [6].
- (3) In the deep UV we have (N copies of) 3d gravity coupled to some 3d sources. Whatever the matter content of this 3d theory is, the resulting geometry has to be conical. Thus, provided we have 3d (but not 4d!) supersymmetry, Witten's argument applies: the vacuum is supersymmetric, yet the excited states are not.

- (4) In the range of intermediate scales, we have N linked copies of 3d gravity coupled to 3d currents. Once again, the resulting 3d geometry is conical. Thus Witten's argument holds in the region between the UV and IR.

Note that on dimensional grounds, the mass splitting should be inversely proportional to the three-dimensional Newton constant and should vanish at zero deficit angle. Thus as long as the three-dimensional Newton constant is of order one as the continuum limit is taken, and the deficit angle (on each local three-dimensional slice) is taken to scale as the inverse of the lattice spacing, the Bose-Fermi splitting will be finite in the infrared.

According to the outlined argument the vacuum energy is zero in the UV, and also some place in between UV and IR. But does it remain zero in the IR? In the concluding part of this note, we remark that the UV/IR relation found in Ref. [9], which as we argue is just the statement of the saturation of the holographic bound, can be utilized to put an upper bound on the maximum value of the deconstructed cosmological constant.

2 Holography and Deconstruction

Before we proceed to establish a relation between the UV/IR correspondence found in Ref. [9] and the holographic bound it is useful to remember how holography arises in the framework of our previous paper [6].

The Bekenstein-Hawking bound on entropy [12] arises as follows. Let us first suppose that the $(2 + 1)$ -dimensional matter fields are local. The coupling of $(2 + 1)$ -dimensional gravity to matter is of the general form

$$S_{EH} = \frac{1}{G_3} \int d^3x \sqrt{-g^{(3)}} (R^{(3)} + \mathcal{L}_{\text{matter}}). \quad (1)$$

The entropy of local matter degrees of freedom scales as the two-dimensional area. As there are N copies, we have

$$\mathcal{S} \propto \frac{NA}{G_3}. \quad (2)$$

Obviously this expression does not have the correct mass dimension. The crucial step at this point is to remember that the usual prescription for dimensional reduction determines the pre-factor to be $1/G_3L$, where $L = Na$ is the size of the fourth (lattice) dimension. Thus, on dimensional grounds,

$$\mathcal{S} \simeq \frac{NA}{G_3L} = \frac{A}{G_3a} = \frac{A}{G_4}, \quad (3)$$

which reproduces the Bekenstein-Hawking scaling in $3 + 1$ dimensions.

Note that this reasoning applies only in the case of 3d to 4d, where there are no local gravitational degrees of freedom. We wish now to relate this scaling to the UV/IR relation found in Ref. [9]. The latter result is stronger, applying in any dimension.

3 Deconstruction and UV/IR mixing

As argued by Arkani-Hamed and Schwartz in a recent paper [9], there exists a subtlety in the implementation of deconstruction in the gravitational context. Namely, the cutoff of the theory cannot be taken to be M_4 , the four-dimensional Planck scale, as one would expect. A simple tree-level calculation indicates that instead, there are amplitudes involving longitudinal components of gravitons which de-unitarize around a scale

$$\Lambda \sim \left(\frac{M_4^2}{L^5 a^2} \right)^{1/9}, \quad (4)$$

where $L = Na$, a being the lattice spacing, and $G_4 = G_3 a$, as in Ref. [6]. This result seems to be indicative of a UV/IR mixing phenomenon. Indeed, when one looks more closely at the details of the effective action for the interactions, one finds that one may indeed interpret it as non-local.

In fact, if we require that the cutoff be above the most massive Kaluza-Klein states but below the unitary threshold, one finds that the highest cutoff that the theory may possess is of order

$$\Lambda_m \sim \left(\frac{M_4^2}{L} \right)^{1/3}. \quad (5)$$

This scale has an important implication in terms of holography. To demonstrate this, consider a calculation of entropy. In the four-dimensional theory, we would estimate

$$\mathcal{S} \sim AL\Lambda^3, \quad (6)$$

which would give the standard wrong result if $\Lambda \sim M_4$. With the cutoff of eq. (5), we find instead¹

$$\mathcal{S} \sim AL\Lambda_m^3 \sim \frac{NA}{G_3 L} \sim \frac{A}{G_4}, \quad (7)$$

which is nothing but the holographic bound on the number of degrees of freedom in the UV theory, *as it should be if the theory is really expected to describe a UV definition of gravitational 4d dynamics*. The deconstructed theory resists the temptation to lift its cutoff too high. It appears that unitarity plus diffeomorphism invariance are sufficient to imply holography! As indicated above, this argument generalizes to any number of dimensions.

As an aside, it is interesting to observe that the above expression for the holographic bound is reminiscent of the one obtained from the heuristic argument based on the properties of gravitational focusing [11]. Given a boundary region of area A , the number of UV degrees of freedom is estimated from the effective volume determined by the area and the Planck length AL_P and the UV cut-off given by $1/L_P^3$ which combines into the holographic (Bekenstein-Hawking) bound A/L_P^2 .²

¹Here we used the thermodynamic relation $\mathcal{S} \sim VT^3$ where the volume $V \sim AL$ and $T \sim \Lambda_m$, by construction.

²We thank Nemanja Kaloper for an enjoyable discussion concerning these heuristics.

Notice that this kind of relation between a UV/IR correspondence and holography is in complete analogy to what happens in the context of the AdS/CFT correspondence, even though the two topics seem unrelated. Taking clues from the AdS/CFT correspondence, we also see that the UV/IR mixing found in the context of gravitational deconstruction can be interpreted locally. That is, the local rescaling in the UV theory corresponds to the rescaling of the size of the extra dimension: the UV Wilsonian evolution corresponds to the gravitational evolution in the extra dimension.

More explicitly, a local form of the UV/IR correspondence can be recast in the form of a holographic RG formalism even in the present discussion of the deconstruction of gravity.

This formalism runs as follows [17, 18]. First we fix the gauge so that the bulk metric can be written as

$$ds^2 = dr^2 + g_{ij} dx^i dx^j. \quad (8)$$

This is just the ADM gauge discussed both in Ref. [6, 9]: the shift vector is set to zero and the lapse to one. As noticed above, the UV rescaling corresponds to the rescaling in the size of the extra dimension, which in the chosen gauge is nothing but the natural evolution parameter. Given the fact that the (3+1)-dimensional gravity theory is reparametrization invariant, the local UV rescaling is encapsulated in the IR by the four-dimensional Hamiltonian constraint

$$\mathcal{H} = 0. \quad (9)$$

More explicitly

$$\mathcal{H} = (\pi^{ij} \pi_{ij} - \frac{1}{2} \pi_i^i \pi_j^j) + \frac{1}{2} \pi_I G^{IJ} \pi_J + \mathcal{L}. \quad (10)$$

Here π_{ij} and π_I are the canonical momenta conjugate to g^{ij} and ϕ^I

$$\pi_{ij} = \frac{1}{\sqrt{-g}} \frac{\delta S}{\delta g^{ij}}, \quad \pi_I = \frac{1}{\sqrt{-g}} \frac{\delta S}{\delta \phi^I}. \quad (11)$$

Here ϕ^I denotes some background matter fields coupled to (3+1)-dimensional gravity — for example, the Standard model fields; \mathcal{L} is a local Lagrangian density, and G^{IJ} denotes the metric on the space of background matter fields.

As in the context of the AdS/CFT duality [17, 18], the Hamiltonian constraint can be formally rewritten as a renormalization group equation for the dual RG flow.³ In the Hamiltonian constraint

$$\frac{1}{\sqrt{-g}} \left(\frac{1}{2} \left(g^{ij} \frac{\delta S}{\delta g^{ij}} \right)^2 - \frac{\delta S}{\delta g^{ij}} \frac{\delta S}{\delta g_{ij}} - \frac{1}{2} G^{IJ} \frac{\delta S}{\delta \phi^I} \frac{\delta S}{\delta \phi^J} \right) = \sqrt{-g} \mathcal{L}, \quad (12)$$

assume that the local four-dimensional action S can be separated into a local and a non-local piece

$$S(g, \phi) = S_{loc}(g, \phi) + \Gamma(g, \phi). \quad (13)$$

³Here we follow the formalism of Ref. [17].

Given this rewriting of the four-dimensional action, the Hamiltonian constraint can be formally rewritten as a Callan-Symanzik renormalization group equation for the effective action [17] Γ of the UV theory at the scale Λ

$$\frac{1}{\sqrt{-g}} \left(g^{ij} \frac{\delta}{\delta g^{ij}} - \beta^I \frac{\delta}{\delta \phi^I} \right) \Gamma = HO, \quad (14)$$

where HO denotes higher derivative terms of the expression for the four-dimensional conformal anomaly. Here the “beta-function” is defined (in analogy with the AdS situation) to be $\beta^I = \partial_\Lambda \phi^I$, where Λ denotes the cut-off of the defining UV theory.

In the context of the holographic RG formalism developed in the AdS/CFT correspondence, it is also possible to introduce a holographic “c-function” which measures the number of accessible degrees of freedom and which decreases during RG flow. When the spacetime is four-dimensional, one has [17, 18]

$$c \sim \frac{1}{G\theta^2}, \quad (15)$$

where θ is the trace of the extrinsic curvature of the boundary surface.⁴ In the context of the AdS/CFT correspondence the Raychauduri equation, that is, gravitational focusing, implies monotonicity of the holographic “c-function”

$$\frac{d\theta}{dt} \leq 0, \quad (16)$$

as long as a form of the weak positive energy condition is satisfied by the background test matter fields.

The important point here is that the holographic “c-function” is determined by the holographic bound, that is the Bekenstein-Hawking entropy. In our context the Bekenstein-Hawking entropy is determined by ALA_m^3 . Thus at a scale Λ below the maximal scale, the natural expression for the holographic “c-function” in the present context is precisely the quantity

$$c \sim AL\Lambda^3 \quad (17)$$

which measures the number of degrees of freedom in the UV theory.

4 Conclusion: UV/IR, cosmological constant, non-local interactions and all that

The argument for the vanishing of the cosmological constant in $(3+1)$ -dimensional gravity as presented in Ref. [6] is obscured by the region of strong coupling in the infrared. The question is whether the cosmological constant remains zero all the way at long distances even in the presence of strongly coupled physics. In the conclusion

⁴The trace of the quasi-local Brown-York stress [19] tensor turns out to be $\langle T_i^i \rangle \sim \theta$, up to some terms constructed from local intrinsic curvature invariants of the boundary. Therefore the RG equation of the defining UV theory is given by $\langle T_i^i \rangle = \beta^I \frac{\partial \Gamma}{\partial \phi^I}$.

of this note, we argue that one can actually derive the upper bound on the value of the induced four-dimensional vacuum energy based on the above discussion regarding the relation deconstruction and holography.

The essential point is that the picture of vacuum energy based on deconstruction [6] naturally presents us with two different energy scales in the IR. One scale is the mass splitting between fermion and bosonic degrees of freedom M_s , indicating the crucial importance of supersymmetry in our argument [6], and the other is the four-dimensional Planck scale M_P . These two scales come from the two dimensional parameters provided by the UV definition of the infrared physics via deconstruction: the lattice spacing a and the three-dimensional Newton's constant G_3 [6].

Now, given these two mass scales and the requirement that in the limit when the mass splitting of the bosonic and fermionic degrees of freedom goes to zero, the four-dimensional vacuum energy should go to zero as well, we can associate one four-dimensional scale m with M_s and M_P . This scale will provide the natural cut-off in the computation of the four-dimensional vacuum energy.

Dimensional analysis and the requirement that $m \rightarrow 0$ when $M_s \rightarrow 0$ dictates that

$$m \sim \frac{M_s^2}{M_P}. \quad (18)$$

This, we claim, is the only effective UV scale left in the problem in four dimensions. Notice that this relation is also a manifestation of a UV/IR correspondence. The M_P is already an IR scale from the point of view of the defining UV theory. That follows from the relation $G_4 = G_3 a$. As we approach the continuum, the three-dimensional scale is much higher than the effective four-dimensional gravitational scale. Now, given the fact that the effective action contains fields coupled to four-dimensional gravity, one expects that the natural cut-off scale m goes as an inverse power of the IR scale, which is set by the Planck scale M_P , and the scale M_s that governs the Bose-Fermion mass splitting. The quadratic scaling of m with M_s is determined by the gravitational coupling of the matter fields at the scale M_s . (By the deconstruction of Witten's argument [6], the vacuum energy is still zero at this scale.) Then the above formula indeed follows by dimensional analysis.

When evaluating the vacuum diagrams in order to estimate the upper bound on the vacuum energy in the infrared we should therefore use m as the only effective cut-off scale. The naive expression for the vacuum energy is bounded by m^4 or

$$\lambda \sim M_P^4 \left(\frac{M_s}{M_P} \right)^8, \quad (19)$$

which is a formula previously discussed in the literature [20]. Therefore, provided the large ratio of the mass splitting to the Planck scale we get the observed bound on the vacuum energy density!

Note that this argument is based on dimensional analysis, the UV/IR relation discussed above, and the fact that the deconstruction of Witten's argument for the vanishing of the cosmological constant in three dimensions implies zero vacuum energy

at a very low scale, set by the value of M_s . The violation of the usual effective field theory reasoning comes from the UV/IR relation and the vanishing of the cosmological constant at the scale determined by M_s , as implied by the deconstruction of Witten's argument.

Of course, we have not presented a detailed calculation, and it is not completely clear if m^4 really determines the cosmological constant. Also, one should carefully consider radiative corrections. Given the fact that the cosmological constant vanishes at the scale determined by M_s by deconstruction, the radiative corrections determined by usual effective field theory, cannot be expected to be very large. It is desirable therefore to provide an explicit calculation to show this.

In concluding, we raise the question of whether the non-local interaction expected in the UV theory [9] should be of the type discussed in the “wormhole” program [21]. The idea here is that a guiding principle for the construction of a defining UV theory should be the recovery of the full path integral over four-dimensional metrics in the IR. This, at least at the level of Euclidean gravity, can be implemented by an insertion of bilocal operators which create “wormholes”. It was shown in the late 80's [21] that such topology changing processes make all couplings in the Wilsonian effective action describing the interaction of gravity and matter into true dynamical random variables. It would be interesting to see whether there is a natural implementation of this idea in the present context.

Acknowledgments

We thank Vijay Balasubramanian and Nemanja Kaloper for conversations and comments. VJ thanks the High Energy Group at the University of Pennsylvania for their kind hospitality. RGL thanks the Instituto de Física Teórica de la Universidad Autónoma de Madrid for their kind hospitality. DM thanks the Cosmology Group of the University of California at Davis for their kind hospitality. This work is supported in part by the U.S. Department of Energy under contracts DE-FG02-91ER40677 and DE-FG05-92ER40709.

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