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Dualities and emergent gravity: Gauge/gravity duality

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ABSTRACT

In this paper I develop a framework for relating dualities and emergence: two notions that are close to each other but also *exclude* one another. I adopt the conception of duality as 'isomorphism', from the physics literature, cashing it out in terms of three conditions. These three conditions prompt two conceptually different ways in which a duality can be modified to make room for emergence; and I argue that this exhausts the possibilities for combining dualities and emergence (via coarse-graining).

I apply this framework to gauge/gravity dualities, considering in detail three examples: AdS/CFT, Verlinde's scheme, and black holes. My main point about gauge/gravity dualities is that the theories involved, *qua* theories of gravity, must be background-independent. I distinguish two senses of background-independence: (i) minimalistic and (ii) extended. I argue that the former is sufficiently strong to allow for a consistent theory of quantum gravity; and that AdS/CFT is background-independent on this account; while Verlinde's scheme best fits the extended sense of background-independence. I argue that this extended sense should be applied with some caution: on pain of throwing the baby (general relativity) out with the bath-water (extended background-independence). Nevertheless, it is an interesting and potentially fruitful heuristic principle for quantum gravity theory construction. It suggests some directions for possible generalisations of gauge/gravity dualities.

The interpretation of dualities is discussed; and the so-called 'internal' vs. 'external' viewpoints are articulated in terms of: (i) epistemic and metaphysical commitments; (ii) parts vs. wholes.

I then analyse the emergence of gravity in gauge/gravity dualities in terms of the two available conceptualisations of emergence; and I show how emergence in AdS/CFT and in Verlinde's scenario differ from each other. Finally, I give a novel derivation of the Bekenstein–Hawking black hole entropy formula based on Verlinde's scheme; the derivation sheds light on several aspects of Verlinde's scheme and how it compares to Bekenstein's original calculation.

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1. Introduction

1.1. Two views on the emergence of gravity

Recent developments in string theory are deeply transforming the way we think about gravity. In the traditional unification programme, gravity was a force which was to be treated on a par with the other forces: the aim was for a unified description of the four forces; and strings seemed to be of help because different vibration modes of the string give rise to different particles. But with the advent of holographic ideas,[1] a slightly different view is emerging that seems to be both more concrete and more modest in its approach. The new view starts from the realisation that gravity may be special after all, admitting a holographic reformulation that is generally not available in the absence of gravity: a gauge-theoretic reformulation in one fewer dimension; hence the name 'gauge/gravity duality'. Thus the general goal of understanding gravity at high energies is now,in the context of string theory,best conceptualised as consisting of two steps: (1) reformulate gravity (holographically) in terms of other forces, specifically: quantum field theories; (2) extract from this reformulation how gravity can be quantised. Progress on the first step over the past seventeen years has been impressive; whether the second step is actually needed is still a matter of debate.

It is the latter question, on the necessity to quantise gravity, that prompts the main topic of this paper: the relation between

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[1] See 't Hooft (1993) and Maldacena (1998).

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dualities and emergence; and whether gauge/gravity dualities satisfy the usual standards for theories of 'quantum gravity'. Broadly speaking, when there is a holographic duality—when gravity is dual to a quantum field theory—it makes sense to ask how to 'reconstruct' the bulk,[2] including the quantum manifestations of the gravitational force.

And on this question, there are two main views: first, if the bulk and the boundary are exactly dual to one another, then the duality map can be used to find out what string theory or quantum gravity look like in the bulk. Gravity may be emergent or not; but the presence of duality up to arbitrarily high energy scales guarantees that it makes sense to speak of a theory of 'quantum gravity'.

The second, contrasting, view claims that gravity 'emerges' from the boundary, without being exactly dual to it. In this case, gravity and the bulk are the product of an *approximate* reconstruction procedure.[3] On this view, gravity does not exist at the fine-grained level, but exists only by grace of its emergence from the fine-grained degrees of freedom. Hence the guiding idea here is not duality but coarse-graining. On this view, step (2) above is superfluous; indeed, nonsensical: all there is to gravity is its reformulation in terms of some deeper (non-gravitational) theory; but asking how to quantise gravity is as futile (or as useful) as asking how to quantise water waves. Of course, the claim does come with a prediction: namely, that fundamental gravitons (or fundamental closed strings, for that matter) will never be found.

It is not the purpose of this paper to assess the relative merits of these contrasting viewpoints on the quantum gravity programme.[4] Instead, the aim is to analyse them separately, thereby contrasting the different roles and conceptualisations that these approaches assign to 'duality' and 'emergence' of gravity and space–time. Regarding duality, I will concentrate on gauge/gravity duality (the duality between a gauge theory and a gravity theory) and its best-studied realisation, the so-called AdS/CFT correspondence (Section 2). Some salient philosophical consequences of duality for AdS/CFT were already explicated in a previous paper, herein after referred to as Dieks and Dongen (2015). In that paper it was pointed out how, borrowing ideas from the 'emergence' camp, gravity can be seen to emerge in AdS/CFT as well; this requires an additional ingredient, which was identified as coarse graining.

Accordingly, in the current paper, I will investigate in more detail the relation between dualities and emergence; for a priori, the presence of a duality *precludes* the phenomenon of emergence (the argument is presented in Section 3.1). From my articulation of the notion of duality into three conditions (in Section 2) it will follow that emergence, realised when there is *duality broken by coarse-graining*, can only take place in two ways. I will use this simple framework for dualities and emergence to exhibit the mechanism for emergence in three important examples: AdS/CFT, Verlinde's scenario, and black holes.

The application of dualities to AdS/CFT in Section 2 will lead to the study of one of the requirements that are usually imposed on theories of quantum gravity: background-independence (Sections 2.3.2–2.3.4); and which here is required for AdS/CFT to qualify as a 'gravity/gauge duality'. There will be two accounts of background-independence: (i) a minimalist one and (ii) an extended one. I will argue that only the first is strictly necessary for a theory of gravity (modelled after general relativity). AdS/CFT will be seen to be background-independent on this account. Verlinde's scheme, on the other hand, seems to suggest a background-independence more akin to the extended notion (Section 3.6).

I will discuss the interpretation of dualities (Section 2.4) and articulate a choice of 'internal' vs. 'external' viewpoints, (Dieks et al., 2015) in terms of two relevant factors: (i) epistemic and metaphysical commitments; (ii) parts vs. wholes. I will identify a case in which *only* the internal viewpoint is available.

I will develop the framework of emergence for approximate dualities in Sections 3.1 and 3.2 and apply it in three examples of gauge/gravity relations: AdS/CFT, black holes, and Verlinde's scheme. I will make some of the underlying assumptions of Verlinde's scheme explicit (Section 3.3) and provide a new derivation (Section 3.4) of the Bekenstein–Hawking black hole entropy formula based on Verlinde's scheme. I will discuss its significance, compare it to Bekenstein's original calculation, and discuss the extent to which this is a clear case of emergence (Section 3.5).

Before these two main jobs, I turn in the rest of this introduction to the philosophical motivation (Section 1.2), and a summary of basic facts about AdS/CFT (Section 1.3).

1.2. Should philosophers care?

Why should philosophers care about these specialised branches of theoretical physics in which the dust has not yet settled on several central theoretical questions? I think there are two main reasons.

First, my comments above clearly reflect different attitudes that physicists take in their approaches to the problem of quantum gravity: there are those who believe that gravity needs to be quantised; and those who believe gravity is an effective description of what in essence is a gravitation-free microscopic world. In the absence of any experiments, these assumptions are necessarily theoretical and ontological; they involve a stance about whether gravity exists at the fine-grained level or whether gravity only emerges as a coarse-grained phenomenon. Thus philosophical analysis is of help here.

The second reason I believe philosophers should care about gauge/gravity duality is because there are interesting philosophical questions here: about duality; and about emergence of space, time, and gravity. Whatever the answers to the main questions about AdS/CFT—whether the duality breaks down due to some non-perturbative effect or not; or whatever answers about the ultimate nature of the objects that populate the bulk we may one day get—the result that the two sides of the duality are related by a map such as the one presented in [AdSCFT] (Section 1.3 below) is robust, i.e. well established theoretically. And this result also significantly impacts upon concepts, such as 'duality' and 'emergence' of gravity, that philosophers of physics have thought about. So it is worth taking examples such as AdS/CFT and Verlinde's scheme as case studies; so that general philosophical concepts can be analysed and set to work in concrete physical applications.

The paper is aimed at philosophers of physics but it is not meant as a self-contained introduction to gauge/gravity duality: although in Section 1.3, I summarize the main facts that I will use later. For an introduction to this topic, as well as other background on which this paper is based, I refer the reader to Dieks et al. (2015); other interesting philosophical work on AdS/CFT is Rickles (2011, 2012). There are also many excellent reviews of AdS/CFT: see for instance Ammon and Erdmenger (2015).

1.3. Brief introduction of the gauge/gravity dictionary

To fix ideas, and for future reference, I will now summarize some facts about gauge/gravity relations:

- The AdS/CFT correspondence is a duality (a one-to-one mapping between states and quantities of two theories: see Section 2.1)

[2] de Haro, Skenderis, & Solodukhin (2001).

[3] This is also the guiding idea in other approaches to quantum gravity, such as analogue models of gravity and group field theory, which do not attempt to quantize the gravitational field itself; but rather regard it as emergent from some underlying non-gravitational fine-grained structure.

[4] One reason I will not do this is because a final answer to this question depends on the answer to physical questions that are not yet settled.