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Duality and ‘particle’ democracy

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ABSTRACT

Weak/strong duality is usually accompanied by what seems a puzzling ontological feature: the fact that under this kind of duality what is viewed as ‘elementary’ in one description gets mapped to what is viewed as ‘composite’ in the dual description. This paper investigates the meaning of this apparent ‘particle democracy’, as it has been called, by adopting an historical approach. The aim is to clarify the nature of the correspondence between ‘dual particles’ in the light of a historical analysis of the developments of the idea of weak/strong duality, starting with Dirac's electric-magnetic duality and its successive generalizations in the context of (Abelian and non-Abelian) field theory, to arrive at its first extension to string theory. This analysis is then used as evidential basis for discussing the ‘elementary/composite’ divide and, after taking another historical detour by analyzing an instructive analogy case (DHS duality and related nuclear democracy), drawing some conclusions on the particle-democracy issue.

1. Introduction

Among the significant philosophical issues raised by the central role of physical dualities in recent fundamental research, one has a specific ontological flavor, as it concerns ‘dual entities’, i.e. entities exchanged by a duality mapping between theories. In particular, the type of duality that is known as *weak/strong duality*,[1] or *S-duality* according to current terminology,[2] seems to imply new surprising features from an ontological point of view.

Weak/strong duality has become a basic ingredient in field and string theories, especially since the 1990s (see Polchinski, 2017). In general terms, it is described as an equivalence map between two different theories of the same physics, such that the weak coupling regime of one theory is mapped to the strong coupling regime of the other theory. Hence the special interest in this form of duality, seen as a new tool for getting information on physical quantities in the case of large values of the coupling constant (where the usual perturbative methods fail) by exploiting the results obtained in the weak coupling regime of the dual description.

This duality is usually accompanied by a novel, puzzling feature: the fact that under this kind of duality it often happens that what is viewed as ‘elementary’ in one description gets mapped to what is viewed as ‘composite’ in the dual description. To use the words of Ashoke Sen – one of the physicists who significantly contributed in the 1990s to extend dualities to the string setting – “the classification of particles into elementary and composite loses significance as it depends on which particular theory we use to describe the system” (Sen, 2001, p. 3). What does this mean? At first sight, this interchanging role of elementary and composite seems to have strong implications for reductionism and fundamentality issues. According to Sen, for example, it implies a radical change in our understanding of the ultimate constituents of matter “by bringing in a sort of democracy between all particles, elementary and composite” (Sen, 1999, p. 1642). Another leading string theorist, Leonard Susskind, goes further: in the section significantly entitled “The End of Reductionism” of his contribution to a *Foundations of Physics*'s 2013 special issue on “Forty Years of String Theory”, he gives a clearly anti-reductionist reading of

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[1] Or, indifferently, strong/weak duality.

[2] The term “*S*-duality” started to be used in connection with the first proposals for extending the weak/strong duality conjecture from the case of supersymmetric four dimensional Yang–Mills theories to the context of superstring theory (first of all, Font, Ibanez, Lüst, & Quevedo, 1990). The name was “a historical accident”, to quote Harvey (1996, p. 30): it was introduced, for reasons of practicality, to indicate the discrete symmetry group $SL(2, \mathbf{Z})$ of the 10-dimensional heterotic string theory compactified to four dimensions. More details can be found, for example, in Schwarz (1996, p. 3).

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the apparent ontological ambiguity connected with weak/strong duality (Susskind, 2013, pp. 177–178).[3]

Philosophers, on their side, cannot draw such quick conclusions. If they want to go this route and discuss weak/strong dualities in relation to fundamentality and reductionism, it is their task to address some basic issues before: first of all, how to understand fundamentality, whether to ascribe it to objects or just to structures, and how to substantiate the link between elementary and fundamental.[4] This is not the route followed in this paper. The stance adopted is rather to avoid a literal reading of the elementary/composite interchange and, on this basis, to avoid mixing the question of its meaning with the question of physical fundamentality. The attitude is analogous to the one shared in this volume about how to understand apparently puzzling features such as the interchange of tiny and huge dimensions connected with *T*-duality in string theory,[5] or the duality of dimension under the AdS/CFT (gauge/gravity) correspondence.[6] The underlying idea is that, what the dual descriptions do not agree upon, should not be attributed a real physical significance.[7] In fact, this means nothing else than saying that the physics (including its ontology) remains the same under the duality. What changes, is just the way of looking at it.

This paper elaborates a bit on this shared view on dualities, in the specific case of weak/strong duality and related elementary/composite correspondence. In order to have a better informed view on the meaning of this correspondence, Section 2 is devoted to examining the history of weak/strong duality by following the main developments of the idea of electric-magnetic duality (EM duality) from which it originates – from the origin of EM duality with Dirac's theory of magnetic monopoles and its successive generalizations in the context of (Abelian and non-Abelian) field theory, to arrive at its first extension to string theory. The aim is to clarify, in the light of this history, the nature of the correspondence between dual particles. This analysis is then used as evidential basis for discussing, in Section 3, the philosophical implications of weak/strong duality.

2. Electric-magnetic duality and its generalizations

"Electromagnetic duality is an idea with a long pedigree that addresses a number of old questions in theoretical physics, for example: Why does space–time possess four dimensions? Why is electric charge quantized? What is the origin of mass? What is the internal structure of the elementary particles? How are quarks confined?". These are the introductory remarks on EM duality by David Olive, in his contribution to the collective volume on *Duality and Supersymmetric Theories* (Olive & West, 1999). He then continues by pointing out how the "old idea of electromagnetic duality" could be considerably enhanced in the light of crucial and apparently unrelated developments in the quantum field theory of the last 40 years, such as "unified gauge theories with Higgs, supersymmetry, instanton theory, the theory of solitons, the idea of integrable quantum field theories as deformations of conformally invariant QFTs", with the bonus of obtaining "a compelling framework of ideas within which these apparently disparate developments become much more unified" (Olive, 1999, p. 62).

This section will try to highlight some of the key moments and notions of the fascinating history of the electric-magnetic duality idea in field theory, setting the basis for its successive extension to supergravity and string theory.

2.1. First steps

As is well known, the idea of a close similarity between electricity and magnetism, going back to Ampère and Faraday, was first made more precise with Maxwell's formulation of his famous equations for a unified theory of electric and magnetic fields.

Maxwell's equations display an evident similarity in the role of electric and magnetic fields. In the absence of source terms, the similarity is complete and the equations are invariant under the duality transformation D exchanging the role of the electric field $\vec{E}$ and the magnetic field $\vec{B}$ as follows:

$$D: \ \vec{E} \to \vec{B}, \quad \vec{B} \to -\vec{E}. \tag{1}$$

Generalizing D to duality rotations parameterized by an arbitrary angle θ and reformulating in terms of the complex vector field $\vec{E}+i\vec{B}$, Maxwell's equations then display the following duality rotation symmetry:

$$\vec{E}+i\vec{B} \to e^{i\theta}(\vec{E}+i\vec{B}). \tag{2}$$

The first natural extension of this duality was to include the presence of charges. For the duality to still obtain, the existence of magnetic charges had to be assumed beside the presence of electric charges. The accordingly modified Maxwell's equations were then invariant under the duality rotation exchanging, at the same time, the role of electric and magnetic fields, and electric and magnetic sources: that is, the duality rotation (2) augmented by the charge transformation

$$q+ig \to e^{i\,\theta}(q+ig) \tag{3}$$

The following natural step was the extension of this EM duality to the quantum context. This was achieved by Dirac (1931, 1948). His theory of magnetic monopoles represented the first attempt to obtain a consistent quantum generalization of EM duality.[8] In particular, Dirac proved that it was possible for a magnetic charge g to occur in the presence of an electric charge q, without disturbing the consistency of the coupling of electromagnetism to quantum mechanics, if the following quantization condition was satisfied:

$$qg = 2\pi n \quad n = 0, \pm 1, \pm 2, \ldots \tag{4}$$

(using the unit system $\hbar = c = 1$).

This is the famous *Dirac quantization condition*, establishing an inverse relation between electric and magnetic charge

[3] He concludes the section in the following way: "I could go on and on, taking you on a tour of the space of string theories, and show you how everything is mutable, nothing being more elementary than anything else. Personally, I would bet that this kind of anti-reductionist behavior is true in any consistent synthesis of quantum mechanics and gravity" (Susskind, 2013, p. 178).

[4] A discussion of the metaphysical implications of weak/strong duality, especially in regard to the fundamentality question, is provided in McKenzie, 2017. Concerning the ontological significance of dualities, a common attitude in previous philosophical literature has been to envisage some form of ontological structural realism (in short, the thesis that "all that there is, is structure") as the only viable option for escaping the antirealist conclusions apparently implied by the elementary/composite ambiguity. This has been usually discussed in connection with the issue of theoretical equivalence and, in particular, the question as to whether the equivalence between dual theories should be read as an instance of underdetermination of scientific theory by empirical evidence. See Rickles, 2017, for an updated discussion of this point. Previous references are Dawid (2007), Rickles (2011) and Matsubara (2013).

[5] See Huggett (2017).

[6] See de Haro (2017).

[7] In this sense some authors propose to view duality as a 'gauge'. This is discussed by Rickles, 2017, and in the contribution of de Haro, Teh, & Butterfield (2017).

[8] Dirac (1931) treated the case of an electrically charged particle moving in a fixed magnetic monopole field. Dirac (1948) is a more general analysis of the relativistic classical and quantum dynamics of a system of moving magnetic monopoles and electric charges in interaction.