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Relativities of fundamentality

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ABSTRACT

S-dualities have been held to have radical implications for our metaphysics of fundamentality. In particular, it has been claimed that they make the fundamentality status of a physical object theory-relative in an important new way. But what physicists have had to say on the issue has not been clear or consistent, and in particular seems to be ambiguous between whether S-dualities demand an anti-realist interpretation of fundamentality talk or merely a revised realism. This paper is an attempt to bring some clarity to the matter. After showing that even antecedently familiar fundamentality claims are true only relative to a raft of metaphysical, physical, and mathematical assumptions, I argue that the relativity of fundamentality inherent in S-duality nevertheless represents something new, and that part of the reason for this is that it has both realist and anti-realist implications for fundamentality talk. I close by discussing the broader significance that S-dualities have for structuralist metaphysics and for fundamentality metaphysics more generally.

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1. Introduction

Over the last 30 or 40 years, dualities have moved centre-stage in fundamental physics. They have been claimed to be a sort of 'Rosetta stone' for physical theories, enabling us to translate between descriptions that might otherwise have seemed incommensurable. They have facilitated the investigation of strongly-coupled regimes through perturbative methods, in spite of their seeming inapplicability by definition in such regimes. Dualities have also been lauded for furnishing us with a new conception of unification, raising hopes that the many candidate string theories may be shown to be ultimately one and the same. Indeed, it was the postulation of a duality that ushered in the framework of string theory in the first place, showing that they can be of great heuristic value too.[1]

Having led to new computational technologies, new conceptions of unification, and whole new physical frameworks, duality principles have established themselves as richly fertile tools in physics. However, dualities have also been claimed to subvert certain metaphysical doctrines long embedded within the discipline. In particular, the conjectured existence of S-dualities—those dualities which relate strong- and weak-coupled regimes—has prompted the claim that the *fundamentality* of the objects of physics must now be regarded as only theory-relative in some significant new way. This phenomenon has provoked physicists to suggest, among other things, that the concept of fundamentality now has more pragmatic than ontological significance, and even that reductionism is over; among philosophers, it has tentatively been taken to signal the triumph of ontic structural realism.[2]

All of these are big metaphysical claims, and prompting each of them is a *relativity of fundamentality* perceived to be implicit in S-duality. It is identifying the nature of this relativity, and its metaphysical implications, that is the principal purpose of this paper. My first point will be that many of the fundamentality claims with which we are already acquainted in the philosophy of physics are themselves made relative to host of defeasible background assumptions, so that a mere relativity of fundamentality in itself is nothing new. Nevertheless, as I shall go on to argue, the type of relativity involved in S-duality is unlike that in any of these more familiar cases, and as such it presents a new set of issues to naturalistic fundamentality metaphysics. In more detail, in Section 2 I will give a brief description of S-duality and enumerate some of the claims that have been made on behalf of it by the physicists Sen

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[1] In particular, the DHS duality in S-matrix theory provided the foundation for string theory. See Cushing (1990).

[2] On the first point, see Susskind (2013, p. 177); regarding reductionism, see Sen (1999, Section 1); Susskind (2013, Section 3); on the connection with ontic structural realism, see Rickles (2011, Section 5.3).

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and Susskind—both of whom have been vocal on the issue—and underline that they form a confusing thicket: in particular, I will argue that they fail to discriminate between whether the relativism implicit in S-duality prompts *antirealism* about our fundamentality talk or merely a revised *realism*. Since a great deal of metaphysical interest clearly hangs on this distinction, the rest of the paper is an attempt to clarify the situation enough to permit adjudication on this matter. To this end, I will place S-duality in context in Section 3 by explaining that many of the fundamentality claims already familiar in the philosophy of physics are also made relative to non-trivial theoretical assumptions—in particular, certain physical, mathematical, and metaphysical assumptions—and that these relativities each carry determinate implications for whether a realist or antirealist attitude towards the corresponding fundamentality talk is warranted. However, in Section 4 I will argue that the relativity of fundamentality involved in S-duality is unlike that in any of these more familiar cases, and that this relativity has *both* realist *and* antirealist implications.[3] I will close in Section 5 by considering how S-duality impacts upon broader issues in fundamentality metaphysics, arguing in particular that it is a genuine threat to ontological fundamentalism, and that, despite claims to the contrary, there is no obvious route from S-duality to ontic structural realism.

Before I start any of that, however, I should make a few clarifications. Firstly, while S-dualities are present in string theory, and can also relate string theories to quantum field theories (QFTs), the focus here will be on dualities involving only QFTs; I am not qualified to speculate how my conclusions will carry over to the string-theoretic case. Secondly, my discussion of S-duality will be based around 'Montonen–Olive duality' (sometimes known as 'electric–magnetic' duality)—the duality relating theories of electric charges and magnetic monopoles in four spacetime dimensions and described in Polchinski, 2017, Section 2.5. While this is the paradigm example of S-duality, the extent to which the positive claims I make regarding the metaphysical interpretation of Montonen–Olive duality in Sections 4 and 5 generalize to every S-duality that can be defined in QFT is something I am not qualified to speculate upon. Finally, note that in what follows I will talk about realist and anti-realist interpretations of 'fundamentality claims'. With this term, I intend to denote claims asserting either the fundamentality or the non-fundamentality of some particular entity (be it object, category, level or anything else), as well as generic claims either asserting or denying that fundamental entities exist. Thus really a better term than 'fundamentality claim' would be 'fundamentality-related claim', but I hope that the context will make it sufficiently clear for me to not have to use this clunkier term.

2. Introducing S-duality

The technical details required for what follows Polchinski's contribution to this volume will be confined to a sketch, for much of the relevant material is already covered in Polchinski's contribution to this volume.[4] Duality in its most general form is a statement of equivalence—although an equivalence, as we shall see, of a difficult to articulate sort—between two physical theories that on the surface appear to be different. As already noted, my focus throughout this paper will be on QFTs, and a crucial condition of calling theories 'dual' is that they match in their particle spectra and in the correlation functions determining the probabilities for interactions between those particles, but that nevertheless have classical limits that are genuinely different. While this might initially strike one as impossible, the situation can arise naturally if more than one coupling is required to characterize the interactions between the entities under study. As already noted, to keep things concrete in what follows we will focus on Montonen–Olive duality—that relevant to the quantum theory of electric charges and magnetic monopoles. As Dirac showed, the dynamical laws of any quantum description featuring both types of objects will contain a charge coupling g and a magnetic coupling g', related through a function of the form $g \propto 1/g'$ (the 'Dirac quantization condition'). As noted in the Introduction, Section 1, the $h \to 0$ limit of any such description taken with g' held fixed reproduces the limit in which $g \to 0$.[5] It follows that a QFT featuring both types of particle but that is *defined* by a classical Lagrangian L_e describing the electrically charged fields will be amenable to perturbative treatment.[6] Such a perturbative treatment will present the charged particles as the fundamental quanta of the theory—that is, as that ultimately used to model all processes and emergent structures that can be derived in the theory. And since we are usually helpless in QFT outside of perturbative regimes, it therefore makes good practical sense to treat the charged particles as the fundamental particles in this limit. Grinding through the mathematics, one can then show that the magnetic monopoles arise as solitons in this theory.

However, by parity of reasoning, had we taken the limit with g held fixed, then it would make sense to use a Lagrangian L_m describing the interactions of the magnetic monopoles to define our quantum theory; for now it is *this* theory that can be investigated perturbatively. In doing so, we now present the monopoles as the fundamental quanta and the charged particles as arising as solitons. The question thus arises of what the relation between the QFTs, each defined in different ways by means of distinct Lagrangians, should be taken to be. The essence of the Montonen–Olive conjecture is that the QFTs defined by L_e and L_m are related by a *duality symmetry*. This means that the theories in which the elementary particles and solitons are interchanged are unitarily equivalent; following the standard criterion of theory identification in the quantum context, the theories defined by the two Lagrangians are to be regarded as *one and the same theory.* And while I will not review it here, there is a battery of evidence pointing in the direction of this duality conjecture being true.[7]

Let us then take it that the two theories just defined are not two different QFTs but rather only, as Harvey puts it, 'two complementary perspectives, formulations, or constructions' of one and the same QFT.[8] Let this theory be denoted T_{em}. Such complementary perspectives on a single theory is the essence of duality, and the appellation 'S-duality' is there to mark out that that the duality transformation involves the interchange of strong and weak coupling regimes. The main upshot of S-duality for our purposes is that there seem to exist two different ways of defining

[3] As I will emphasize in Section 5, not all of my conclusions regarding this paradigm instance will necessarily generalize to all instances (Polchinski, 2017).

[4] For further discussion of this material in addition to Polchinski, 2017, see e.g., Harvey, 1996; Figueroa-O'Farrill, 1998.

[5] As usual, since h is a constant, to talk about the '$h \to 0$ limit' is to talk about a limit in which a quantity formed by the ratio of Planck's constant to another with the same dimensions disappears. What this quantity is will depend on the system of interest (cf. Bokulich, 2008; Polchinski, 2017).

[6] As noted in Polchinski, 2017, quantum amplitudes are obtained from classical Lagrangians through the Feynman path integral (cf. Eq. (1.8)). Thus, as Landau and Lifshitz note, 'quantum mechanics occupies a very unusual place among physical theories: it contains classical mechanics as a limiting case, yet it requires this limiting case for its own formulation' (Landau & Lifshitz, 1977, p. 3). This fact arguably has profound implications for approaches to ontological priority based on definitional priority, though I shall not comment further on these here. However, the fact that the classical theory is (as I shall argue) a limiting case of the corresponding quantum theory will play a role below.

[7] For the justification of this conjecture, see Figueroa-O'Farrill (1998, p. 30), Sen (1999, Section 3); and Polchinski (2017), Section 2.5. See also Castellani (2009) for critical discussion.

[8] Harvey (1996, p. 5).