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Dual theories: 'Same but different' or 'different but same'?

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ABSTRACT

I argue that, underneath the glitz, dual theories are simply examples of theoretically equivalent descriptions of the same underlying physical content: I distinguish them from cases of genuine underdetermination on the grounds that there is no real incompatibility involved between the descriptions. The incompatibility is at the level of purely unphysical structure. I argue that dual pairs are in fact very strongly analogous to gauge-related solutions even for dual pairs that look the most radically distinct, such as AdS/CFT. However, again by analogy with gauge freedom, I conjecture that dualities always point to a more fundamental (intrinsic) description, namely that in which the representational redundancy is eliminated.

1. Same but different

A duality is an equivalence relation between a pair of theories: a pair of theories is said to be *dual* when they generate the *same physics*.[1] The existence of a duality signals some freedom in the representation of the relevant physics of the dual pair. However, according to the standard story, unlike ordinary symmetries (including gauge symmetries), the representations connected by dualities are often radically *different* in terms of their formulations and, if we are literal in our reading of these formulations, also in terms of the ontological pictures they paint. It is this marked formal/ontological difference combined with qualitatively indistinguishable physics that make dualities special from the point of view of philosophy of physics, also linking them to ongoing debates in general philosophy of science.[2]

As Yeminima Ben-Menahem has pointed out, whenever one has incompatible descriptions of the world that are equally capable of describing, predicting, and explaining phenomena one has a possibility that "constitutes a challenge to the realist and comforts his opponent" (Ben-Menahem, 1990, p. 261). Structural realism is often viewed as an adequate response to this challenge: be realist about the structure that is (inevitably) shared by the descriptions at a level deeper than where the incompatibilities lie. However, it might well be possible that this same 'incompatible descriptions+observational equivalence' problem reemerges at the deeper 'structural' level in which case a primary motivation for the structuralist programme is undermined. Steven French makes no bones about it: "if the anti-realist can come up with examples of UTE where there are no common (structural) parts beyond the empirical level, then the structural realist will be scuppered" (French, 2007, p. 118).[3]

Dualities at first sight appear to fit the bill: fully empirically equivalent but underdetermined descriptions of the world that appear to diverge in their deeper structural aspects.[4] After all, one has dualities holding between descriptions with gravity (curved space) and without gravity (flat space); in four dimensions and in ten dimensions (and so topologically inequivalent); at large coupling strength and small coupling strength (a highly non-trivial difference for all cases but $g=1$); with spacetime of large radius

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[1] Where "same physics" is understood in terms of a matching of observables and global symmetries (but not gauge-dependent variables and gauge symmetries).

[2] For example, according to Kevin Coffey's recent 'interpretation based' (non-formal) account of theoretical equivalence, dual theories would be clearly inequivalent (Coffey, 2014). I will briefly return to this account below.

[3] Structuralism is not one of my central concerns here: I'm concerned with how the dual pairs are to be treated: as physically the same or physically different. However, structuralist themes are never far from the surface given the nature of the subject matter.

[4] "[A]lternative hypothetical substructures that would surface in the same observable ways" in Quine's words (Quine, 1975, p. 313). To the best of my knowledge, all authors that have considered dualities in the philosophical literature follow this line: see, e.g. Gryb & Thébault (2015).

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and spacetime of small radius (and so non-isometric as Riemannian manifolds); for electric (elementary states) and magnetic (solitonic states); with order (low temperature) and with disorder (high temperature), and so on. Surely these are sufficiently structurally orthogonal to scupper the structuralist ship? What is shared but the observable content in these cases?

But this is too quick:

- Dualities are not quite cases of underdetermination, at least not in the sense of the thesis of underdetermination of theory by data (*logically incompatible* yet empirically equivalent theories). There is no *competition* between dual descriptions, and the incompatibility can be transformed away in a certain sense (not available in standard underdetermination scenarios) by application of the duality group, as we shall see.
- Nor are dual descriptions along the lines of Glymour's indistinguishable (yet incompatible) spacetimes (Glymour, 1977), in which observational equivalence is guaranteed by the fact that differences show up only behind causal horizons inaccessible to observers so that nobody of experimental or observational evidence could decide between competing hypotheses about certain global features of such universes.[5] There are no structures hidden from our gaze by the world's causal structure in the case of dualities: the equivalence applies to *complete sets* ('totalities') of observables (whether or not they are measurable in practice).[6]

In this paper I argue that dualities are examples of equivalent descriptions *simpliciter* (when supplemented with the duality mapping) and therefore we should not be at all surprised when they generate equivalent physical content. The apparent differences emerge from the freedom in assigning physical meanings to the formulations. We should withhold literalistic readings when a duality exists since they are examples of 'unphysical structure' functioning more or less in the same way that arbitrary coordinates and other gauges do.

Whenever a duality exists, I argue (by analogy with gauge freedom) that a formulation's natural interpretation should be taken as a mere representation of a deeper underlying (intrinsic) structure rather than a 'fundamental' representation of the world. I claim that this procedure of finding a deeper structure eliminating the representational freedom found in any dual pair is a general feature of dualities.[7] As with gauge freedom, one can look upon dualities as vital clues in uncovering (invariant) physical content without which one would have great difficulty in understanding the underlying structure of whatever aspect of the world one is trying to represent. Indeed, I think this is the proper way to understand the existence of gauge symmetries and dualities: having expanded mathematical ('surplus') structure leads to improvements in one's knowledge of the physics by providing different perspectives. Without the multiplication in perspectives surplus structure brings, one is in a situation not unlike the proverbial blind men and the elephant.

2. Different but same

As Quine put it, "Scientists invent hypotheses that talk of things beyond the reach of observation" (Quine, 1975, p. 313). That much is obvious. The thesis of underdetermination of theory by data, so beloved of structural realists (since it provides a key motivation through its natural resolution), builds on this feature of science: since most working theories (certainly in physics) go beyond actual (and indeed possible) observations, for any theory T we can 'always' find some competing theory T^* that matches T with respect to the observable or observed content but differs elsewhere. More precisely, given some body of observed empirical evidence E_{obs} we have it that $\forall E_{obs}$ both $T \vdash E_{obs}$ and $T^* \vdash E_{obs}$ despite the fact that, by assumption (or construction), $T \neq T^*$. Structural realists are able to slyly evade this problem since E_{obs} involves (empirical) relational structure so that T and T^* will always wind up being structural isomorphs and so can be identified.

So goes the story. But the general thesis[9] has recently come under fire from various directions. For example, Earman (1993) complains about the missing 'genuine' examples in science. Norton complains that all such cases show is that $T = T^*$, in the sense of being descriptive counterparts, for all genuine cases we do have, and so should not trouble even standard realists. More recently Lyre (2009) has argued that there are in fact *no* interesting puzzling cases of UTD in the mature sciences. He dismisses the cases discussed by Glymour (1977) and Malament (1977), mentioned above, in which, as Lyre nicely expresses it, "even idealized observers, observers who live forever, are unable to determine the global topology of space" (Lyre, 2009, p. 238) on the grounds that they are based on the empirical limitations (inaccessibility) mentioned above.

These claims are interesting and relevant, but my focus in this paper is on whatever special features dualities might bring to the table. My view is that in cases of dualities at least, Norton's view is vindicated: we have $T = T^*$ whenever T and T^* are dual. But then again, I don't think T and T^* are properly underdetermined whenever they are dual—T and T^* are dual but not *duelling* descriptions! So this might be somewhat distinct from Norton's view.

There are some distinctions to be made concerning underdetermination, depending on what content is underdetermined and by what. There are three broad classes (not necessarily mutually exclusive):

- *Interpretive*[10] *underdetermination* occurs when there is a multiplicity of interpretations of one and the same formulation of a theory.

[5] Holger Lyre has called these cases of "empirical limitations" (Lyre, 2009, p. 237).

[6] In fact, inasmuch as there is anything 'hidden' in one side of a dual description (say because of the breakdown of a perturbative description at higher coupling), the weakly coupled dual description *uncovers* it. However, even independently of this specific utility, dualities have a more general significance in expanding the information we have about some system (see footnote 8).

[7] They are indeed, as Michael Atiyah has claimed, "two different points of view of looking at the same object" (Atiyah, 2007, p. 69)—in this case the same *physical content*. In general, the more perspectives one has, the more information one has. But, again, this is quite unlike standard cases of underdetermination where knowing two incompatible descriptions does *not* provide more information about some 'underlying structure.' For example, having Poincaré's 'discworld' theory (with its distorting forces) *and* an infinite curved space theory (without such forces) does not provide us with more information than either would alone.[8] The fact that the descriptions are incompatible (rather than, say, complementary) means that discoveries in one do not apply to the other. Hence, it is the absence of *incompatibility* that separates dualities from underdetermination (and, as seen here, conventionalist moves) and, I will argue, means that dualities are in fact fully theoretically equivalent.

[8] As Magnus (2005) pointed out, there is genuine discord between Poincaré's pair, as a result of non-mappable properties (e.g. a space with a distinguished origin in one but not in the other). I have argued that dualities are of a kind with gauge redundancies. They point to the fact that neither of a dual pair of descriptions is 'physical' (in the sense of invariant). For any description one can apply the duality transformation, sending it to another equivalent description with a distinct naive interpretation.

[9] In fact, I have in mind the weaker thesis in this paper, so that we needn't assume that such competing theories are *always* available, but only that some examples exist.

[10] Oliver Pooley (2006, p. 97) calls this "metaphysical underdetermination," which occurs when one formulation of a theory has many interpretations differing with respect to their ontologies (say, an interpretation with and without spacetime points). Coffey's approach to theoretical equivalence appears to simply line up with this kind of underdetermination: metaphysical underdetermination (when real)