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ORIGINAL RESEARCH

Unification, T-theoreticity, and Testing: The Case of Fitness in Natural Selection

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Abstract

Theoreticity and unification are two main issues discussed in philosophy of science. The first attempts to clarify the different roles of concepts used in a scientific theory. The second concerns the role of unification in scientific explanation and scientific progress. Both discussions have followed separate, independent paths. In this paper, we examine the interrelatedness of these two notions by focusing on classical particle mechanics and the theory of natural selection. We claim that they are interconnected in two distinct ways. On the one hand, a theory's unifying power relies on the presence of some theoretical concepts that apply to heterogeneous phenomena through the assumption of a (sometimes unstated) general principle. On the other hand, a sensible application of the theoreticity criterion to these integrating concepts requires the unification not being spurious. We conclude that a correct determination of the theoreticty status requires analyzing how specific applications of different parts of a theory interact with each other.

1 Introduction

The theoretical status of the concepts of scientific theories and their meaning has been at the center of discussion since the origins of the philosophy of science. The empiricist physics of Newton, which prevailed over the rationalist physics of Descartes, proposed the concept of force that seemed to break with the empiricist

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dictum that there could be nothing in knowledge that was not in experience. This point also became essential in the early twentieth century as part of the Enlightenment program of logical empiricism, which involved understanding the meaning of theoretical concepts and their role in scientific practice, including the communication of science. It was also a key issue for later approaches, for instance in historicist discussions of how the basic concepts of theories change meaning in scientific revolutions. Metatheoretical structuralism is one of the approaches that, in our view, has succeeded in shedding light on how theoretical concepts are determined and applied to the phenomena that a particular theory is supposed to explain. This in turn helps clarify the long-discussed issue of whether theoretical concepts semantically depend on all the theories in which they appear. We will present the structuralist **T**-theoreticity in Sect. 2.

Meanwhile, in the discussions during the second half of the twentieth century that followed the introduction of the covering-law model of scientific explanation, the question of unification acquired certain attention. According to some authors (Friedman, 1974; Kitcher, 1981, 1989), the way in which theories unify the range of phenomena to which they apply is fundamental to understanding important features of scientific practice, especially its explanatory power.

The two discussions, however, have run along different and independent tracks in the philosophical literature. Our aim is to show how they are in fact inextricably linked. The discussion about the semantic dependence of theoretical concepts in the theories that use them and what should count as genuine unification are intertwined, contrary to how things may seem. We introduce this point in Sect. 3, appealing to the example of classical particle mechanics (hereafter **CM**). We also provide some criteria for *genuine unification* in terms of the role played by guiding principles in the extrapolation of values from one part of the theory to another.

In Sect. 4, we present the notion of *unifying concept* (a concept which is specified heterogeneously through different special laws of the theory) and make the relation between the unifying capacity of a theory and the **T**-theoreticity of its concepts more precise, taking as a case study the theory of natural selection (**NS**) and its (unifying) concept of fitness. In Sect. 5, we show that the case of NS involves some peculiarities that reveal intriguing aspects of the relation between theoreticity and genuine, non-spurious unifications, and discuss the significance of these aspects that are not apparent in more simple cases such as **CM**. Then, in the final section, we close with some concluding remarks.

The final moral of our work is twofold. On the one hand, the unifying capacity of a theory seems to rely (at least in the two cases discussed) on the existence of unifying concepts (force and fitness in these cases) that unite heterogeneous phenomena by assuming a (sometimes not explicitly formulated) general principle. On the other hand, the application of the theoreticity criterion to such unifying concepts presupposes that the unification realized by the theory is not spurious. The point is interesting for the structuralist metatheory, since it makes it explicit that the application of the criterion of **T**-theoreticity in unifying theories presupposes assumptions that go beyond what the criterion explicitly formulates. But it is also of general interest beyond the structuralist program, for it reveals the way in which the semantics of theoretical concepts in unifying theories depends on the details of the unification performed.

2 T-theoreticity

The initial observational/theoretical distinction was famously challenged by Putnam (1966), who claimed that there are theories whose theoretical vocabulary refers to observable entities and, in contrast, that there are also many theories whose explained phenomena are hardly directly observable. Thirty years on, Putnam argued, the problem of exactly what characterized theoretical terms remained unanswered. In the 1970s, Hempel, Lewis, and others start replacing this distinction by other, clearer ones. With regard to the concepts used by a given theory, Hempel (1966, 1970, 1973) distinguishes between vocabulary "previously understood", which is borrowed by the theory from previous theories (or even prescientific talk), and "theoretical" vocabulary, which is new and "introduced" by the theory. In a similar manner, Lewis (1970) distinguishes between "old" and "new" vocabulary for a given theory. In a similar vein, Hesse (1967, 1969) claims that the semantics of theoretical terms "is given" by the theoretical model.

To us (and to others, e.g. Frigg, 2023), the clearest approach to this issue is found in Sneed (1971/1979), and the structuralist program that he initiated and that was canonically presented in Balzer et al. (1987). According to that account, behind the observational/theoretical division, there are actually two different distinctions (Bar-Hillel, 1970 makes a similar point). One, observational/non-observational, is epistemological: it has to do with the direct or indirect epistemic access to the entities to which the concepts apply. The other, **T**-non-theoretical/**T**-theoretical, is methodological: it has to do with the way the concepts are introduced or determined. A concept used by **T** in its laws, a **T**-concept, is **T**-non-theoretical when it is possible to determine or measure its extension without assuming that **T** is true, that is, without using any **T**-law. A concept is **T**-theoretical otherwise, that is, when there is no way of measuring or determining it without assuming some **T**-law.

For instance, in the paradigmatic case of Classical Mechanics (**CM**), space/distance is **CM**-non-theoretical. It is true that distance can be measured using mechanical laws, for instance, using Hooke's law $F_h = -k{\cdot}x$, the free fall weight law $F_g = g{\cdot}m$, and the Second Law $\sum f = m{\cdot}a$, one can measure the displacement, x, of a body before equilibrium when we hang it on a spring on Earth's surface (given that one already knows the mass of the body m, the gravitational constant g and the spring's elastic constant k). But it is also true that distance can be measured without using any **CM** dynamical law, for instance, by triangulation in physical geometry. Thus, distance is **CM**-non-theoretical. Likewise for time/duration. In contrast, force is **CM**-theoretical, as every measurement or determination of a force uses some mechanical law. The same holds for mass. One could object that we can measure mass, for instance, as in fundamental measurement, by using a pan balance and without assuming any dynamical law. But this is not true. It is true that we can say that we measure "something" without any such assumption, but in order to say that the something we measure is the property mass, the property mass that **CM** talks about, one needs to assume that the balance satisfies the law of momentum. If the arms of the balance are not homogeneous, or are of a different length, then the something we end up measuring is not the mass **CM** talks about. The same happens, for instance, when we measure mass with a dynamometer: unless the spring satisfies Hooke's law, we cannot say that we are measuring the property mass **CM** talks about.

As Hempel's, Lewis' and others' proposals implicitly show, and structuralism explicitly claims, the distinction of being theoretical is essentially relativized to theories. It simply does not make sense to ask whether a given concept is theoretical *simpliciter*, you have to specify the theory, **T**, relative to which you are asking whether the concept is (**T**-)theoretical. A concept may be **T**-theoretical relative to a theory **T** and **T′**-non-theoretical relative to other theory, **T′**. For instance, pressure is used by both **CM** and thermodynamics, and it is **CM**-theoretical but thermodynamics-non-theoretical.

It should now be obvious that the observational/non-observational and **T**-theoretical/**T**-non-theoretical distinctions do not coincide, either intensionally or extensionally. They do not coincide intensionally since it is one thing to ask whether a concept denotes something that is directly observable and quite another thing to ask whether the determination of a concept can be made without assuming any law of a given theory, **T**. To start with, the former is not **T**-relativized, while the latter is. And they do not coincide extensionally either, for there may be non-observational concepts that are **T**-non-theoretical for some **T**; for instance, pressure is non-observational yet thermodynamics-non-theoretical. Similarly, there may be observational concepts that are **T**-theoretical in some **T**; for instance, enzymes are observable yet biochemistry-theoretical.

The **T**-theoretical/**T**-non-theoretical distinction is crucial to explicate the fallibility of empirical tests, the non-self-justification of a theory's empirical predictions. A theory, **T**, is tested by comparing its "predictions" with "data". The theory makes empirical predictions calculating the values of **T**-non-theoretical properties using **T**-laws (**T**-predictions, e.g. predicted trajectories in **CM**), and these are compared with the values one obtains for these properties when measuring them without assuming any **T**-laws (**T**-data, e.g. measured trajectories). For fallibility to be possible, i.e. for it to be possible that these two values do not coincide, it is necessary that the properties used in **T**-testing are **T**-non-theoretical: it is because **T**-data involve **T**-non-theoretical concepts that **T**-data are determined without assuming the validity of **T**, which in turn implies that such data may not coincide with the theoretical prediction of the same properties using **T**-laws. Thus, if, as is the case in all bona fide empirical theories, data are described in purely **T**-non-theoretical terms, then the theory is fallible. This is "local fallibility": **T**-predictions may fail; **T**-data and **T**-predictions may not coincide. And this fallibility is compatible with theory-ladenness: since a **T**-non-theoretical concept may be **T′**-theoretical (relative to a different theory, **T′**), such a concept may be "theory-laden" in accordance with the theory **T′**; but since it is **T**-non-theoretical, it is not

"**T**-laden". That is, **T**-data may be theory-laden, but never theory-laden according to the very same theory that uses them as data.[1]

For a given theory, **T**, then, its **T**-empirical basis is **T**-non-theoretical. The empirical basis basically serves two roles: it provides the data against which **T** is tested and it also provides the phenomena **T** aims to explain. The latter is why **T**-theoretical concepts are also (part of) **T**- "explanatory machinery". **T**-theoretical concepts are the concepts that **T** introduces in order to explain the phenomena it aims to explain; thus, **T** employs explanatory machinery that is also tested by new predictions and data. The theory explains by introducing new machinery relative to that included in the *explananda*. For instance, in **CM**, *explananda* are kinematic phenomena (spatiotemporal trajectories), which are explained by introducing new, dynamical stuff, i.e. masses and forces, and connecting them with the previous stuff via non-accidental regularities, the **CM**-laws.[2]

These are the basic tenets of the structuralist notion of **T**-theoreticity.[3] In the following sections, we discuss and make explicit some important features that are implicit for a correct application of the theoreticity criterion to highly unifying theories (in a sense that we will develop later). We will show how the criterion of **T**-theoreticity applied to such theories implies additional conditions beyond those explicitly formulated in the criterion itself.

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[1] Whether this is compatible with non-local, holistic self-justification in the case of there being a loop of theories presupposing others that in the long run presuppose the original ones, is a substantive but different issue that we cannot enter into here (see Balzer, Moulines & Sneed, 1987). Hesse (1974) and Longino (1990a, b, 2001) make a distinction similar to the structuralist's local/global theory-ladenness.

[2] See Díez (2014) for an elaboration of this notion of explanation implicit in the structuralist program and Lorenzano and Díez (2022) for the application of this notion to the case of classical genetics, and Díez and Suárez (2023) for the case of the ecology of microbiome. Sometimes part of the new machinery included in the **T**-explanans may come from a different theory, i.e. it may be **T**-non-theoretical (Ginnobili, 2012; Ginnobili & Carman, 2016). This implies that it is not necessary that all **T**-non-theoretical concepts intervene in the description of the **T**-data; what is necessary is that all concepts intervening in the description of **T**-data are **T**-non-theoretical. More on these complexities below.

[3] A terminological clarification. We have presented here the main notion of **T**-theoreticity treated in structuralist literature. Structuralists, however, have also introduced another, different notion of theoreticity which they call "formal" (sometimes also "local"), while the one we have presented is labeled "pragmatic" (sometimes "global"). According to the new, "formal" criterion, a concept is **T**-f-theoretical (we add "f" for "formally" to avoid confusion), when there is at least one method of determination that presupposes **T** and is "**T**-admissible", while it is **T**-f-non-theoretical otherwise, i.e. if it does not have any **T**-method of determination that is **T**-admissible (cf. Balzer, 1985, 1996; Balzer, Moulines & Sneed, 1987 Ch II.3; where not every method of determination that presupposes **T** is **T**-admissible, in a specified sense of **T**-admissibility which we cannot enter into here). While this concept of **T**-f-theoreticity may be useful for some goals (e.g. Balzer 1996), it is important not to mix it with our previous concept which is the only one that is relevant to our present purposes. In what follows, then, we will be using the main structuralist notion of **T**-theoreticity, exclusively in the (global/pragmatic) sense introduced in this section.

3 T-theoreticity: Testing and Unification

The notion of **T**-theoreticity, as we have seen, makes it possible to clearly establish the way in which a theory is tested. We have already mentioned one such way in the example of mass above. When we measure a given property using certain measurement apparatus (mass with a pan balance or with a dynamometer, temperature with a thermometer, time with a clock, length with bars, etc.), we obtain values irrespective of whether the apparatus satisfies theoretical principles; but in order for these values to be values *of the property a given theory talks about*, the apparatus used must satisfy some conditions. For instance, the bar must be rigid, the clock periodical, the liquid in the thermometer must have a constant expansion function, the balance must have equal homogeneous arms, and the dynamometer must have a constant elastic function. All these conditions amount to the satisfaction of certain theoretical principles in the relevant theory: physical geometry, chronometry, thermodynamics, or classical mechanics. Thus, the corresponding measurement or determination procedure counts as **T**-dependent with respect to the theory **T** to which the theoretical principle belongs. This is, as we said, why the measurement of mass with a pan balance does not count as a **CM**-independent method of determination.[4]

However, in unifying theories such as classical mechanics, where there is a theory-net consisting of many special laws that allow different forces to be treated, the analysis of the theory-independent test presupposes the intra-theoretic extrapolation of values. Dealing with this extrapolation involves the use of some new metatheoretical tools. The first element of intra-theoretical extrapolation is captured by what structuralists call "(intermodelic) constraints". Suppose you apply the laws of collision mechanics (a specific part of **CM**) to obtain the mass of a particular ball, say b_1, on a pool table where it hits another ball, b_2, whose mass, change in momentum, etc. you know. Model-theoretically, this situation is represented by a particular single model with particles b_1 and b_2 in the domain, and their masses, initial velocities, resulting trajectories, etc. as the other components of the model. If the model satisfies certain laws of collision mechanics, then given some values of b_2 and the values, but not the mass value, of b_1, you can calculate the mass of b_1. Now suppose that after so determining the mass of b_1, you can use it to determine the mass of another ball, b_3, that hits b_1 and thus obtain the mass of b_3 in the same way you obtained the mass of b_1. The idea of this technical notion of (intermodelic) constraints is that **CM** implicitly includes a constraint for masses that

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[4] The reader may worry that this sits badly with the comments made in the previous section. Length is not **CM**-theoretical but it presumably is physical geometry (**PG**)-theoretical, for this latter theory introduces it and measurements using rigid bars or triangulation presuppose, for really measuring length, the satisfaction of some principles of such a theory. But we said that it can also be measured using dynamical laws; does not this make it false that all methods of determination of length presuppose some principle of **PG**? Actually, it does not; for **PG** is a theory presupposed by **CM** in a specifiable sense (cf. Balzer, Moulines & Sneed, 1987), so that **CM**-methods of determination presuppose **PG**, while **PG** methods of determination do not presuppose **CM**. This makes the formal definition of **T**-theoreticity a little more complicated, but it does not affect the use that we have made, and will make, of the notion.

affects different models together, that is, that constrains sets of models, as opposed to standard laws that apply to individual models independently of each other. This constraint for mass tells you that if two models include the same particle, e.g. b_1, the value of the mass for such a particle must be the same. This is a kind of theoretical constraint of a different nature than standard laws but that is also in place when we do mechanics. It is also the constraint that allows us to "export" the value of a property for an object obtained in one model to another model of the same family (e.g. collision mechanics) in which the same object intervenes.

These (intermodelic) constraints are of course nothing new, they are implicit in scientific practice and the only thing structuralists do is to make them explicit and formally analyze and reconstruct them. The important thing in what follows is that these constraints already apply within a single part of a theory, e.g. collision mechanics within **CM**. But when the theory is sufficiently complex to have parts that are relevantly different, though still parts of the same theory (as in **CM**, which includes collision mechanics, but also harmonic oscillator mechanics, friction mechanics, gravitational mechanics, etc.), we need additional tools to explicate the extrapolation of values between models of *different* parts of the theory. Say we want to export the value of the mass of our billiard ball determined using collision dynamics laws to a model of a different kind, for instance, a gravitational one. In this case, the constraints mentioned above, which are defined for sets of the same kind of models, do not suffice. We need to generalize them to different kinds of models (for instance, within **CM**, collision, gravitational, frictional, oscillating, etc.) in order to combine different kinds of forces (more on this below). To this end, the structuralist notion of a theory-net is brought into play.

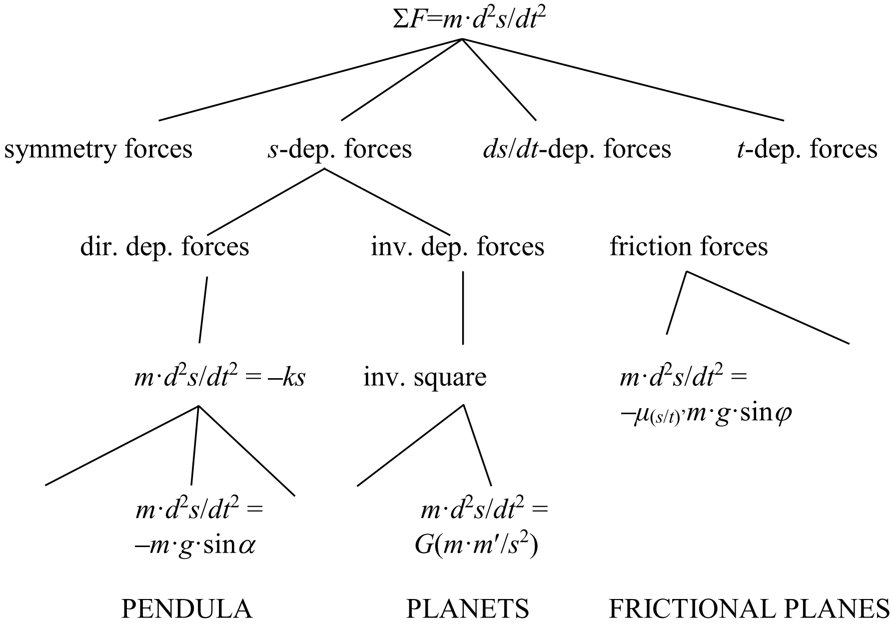
The notion of a theory-net, and the associated distinction between general guiding principles and special laws, is related to the distinction Kuhn draws in the following passage. The basic idea is that highly unified theories explain/account for specific applications/exemplars by developing "specific laws" for specific applications; specific laws that are the specific versions that a general principle takes for the specific phenomenon being addressed. In Kuhn's words:

> […] generalizations [like $f = ma$…] are not so much generalizations as generalization-sketches, schematic forms whose detailed symbolic expression varies from one application to the next. For the problem of free fall, $f = ma$ becomes $mg = md^2s/dt^2$. For the simple pendulum, it becomes $mg\mathrm{Sin}\theta = -md^2s/dt^2$. For coupled harmonic oscillators it becomes two equations, the first of which may be written $m_1d^2s_1/dt^2 + k_1s_1 = k_2(d + s_2 - s_1)$. More interesting mechanical problems, for example the motion of a gyroscope, would display still greater disparity between $f = ma$ and the actual symbolic generalization to which logic and mathematics are applied. (Kuhn, 1974, p. 465)

This Kuhnian idea has been elaborated in detail by structuralists through the notions of *specialization* and *theory-net*, and it has been applied to several sufficiently robust and unified theories (see, among others, Balzer et al., 1987, 2000, Stegmüller, 1986). In unified theories, not all laws have the same strength and scope: such theories are strongly hierarchical systems—forming a kind of net—that include laws with very different degrees of generality, all using the same conceptual setting.

Usually, there is a single fundamental law or guiding principle ‘at the top’ of the hierarchy that is specified by a vast array of special laws which apply to specific situations.

For instance, in the case of **CM** we have at the top a theory-element whose models are constrained only by Newton’s Second Law (and perhaps the Action–Reaction principle). At the second level, different theory-elements impose additional restrictions. One element imposes the constraint for all forces dependent on distance, i.e. it opens the “distance-dependent forces” branch. Another imposes a different restriction for all forces dependent on velocity, opening the “velocity-dependent” branch; and so on. At the third level, the first branch becomes specialized into two additional sub-branches, one for forces that are directly dependent on distance and another for forces inversely dependent on distance; and so on. So, at the ends of the many sub-branches we find the theory-elements with the most restricted sets of actual models, i.e. we find the most specific empirical restrictions: the gravitation law or simple pendulum law, etc. We can represent (part of) the structure of **CM** theory-net as follows:



Now, the idea is that without a connection between, say, collision models and gravitational models, we could not export the mass of a ball measured by a collision to a gravitational problem that involves the same ball. We need to say that the mass we determined on the billiard table and which intervenes in the gravitational problem is the very same property. How can we do so? This is where the notion of theory-net helps. If collision models and gravitational models were defined by satisfying completely independent laws, one could not transfer values from one to the others.

But they are not all that independent. They are partially independent since the laws of collision mechanics are different from the law of gravitation; but at the same time, they are essentially connected since both are different specializations of Newton's Second Law. It is this Second Law which "says" that the property in both cases is one and the same, subjected to the same intermodelic constraint. Since, in a unified theory-net the constraints on the top elements are inherited by their specializations, one way of applying the intermodelic identity-of-mass constraint to all mechanical models, both of the same and of different kinds, is already to introduce such a constraint on the top element defined by the guiding principle. All lower models are also models of the laws of the top elements, thus we can export the value of mass determined in a model of any bottom theory-element to a model of any other theory-element in the net "passing through" the top theory-element. The mass of a single body must be the same on one billiard table when the ball is colliding with certain other balls as when it hits other balls, but also the same as when it is gravitationally attracted.

This net-like structure also sheds considerable light on why it is that we can combine lawful restrictions of different kinds. Some bottom laws tell us the magnitude of a specific kind of force, for instance gravitational attraction on Earth's surface. Some other laws tell us the magnitude of a different kind of force, for instance the elastic recuperation force when hung on a spring. Thanks to the Second Law we know that the same body, with the very same mass, can be affected by different kinds of forces, and it also tells us the final kinematic effect. One easy example is equilibrium problems; for in equilibrium, acceleration is zero. Thus, according to the Second Law, the different forces acting add up to zero. For instance, when hanging a body on a spring on Earth's surface, we have the downward gravitational force, $g \cdot m$, and the upward elastic force, $k \cdot x$, and so we can calculate, for instance, the elastic constant of a specific spring from the displacement, x, at the equilibrium point.

This helps to answer the classical problem (see e.g. Hempel & Oppenheim, 1948, p. 159, n. 28) of distinguishing "true" unification, such as that carried out by Newton, from the spurious kind consisting of "mere conjoining" of different laws, for instance conjoining Kepler's and Galileo's laws. Part of the answer has to do with the point we are making: in Newton's genuine unification, the Second Law allows different forces presented in the different special laws of the theory to be composed, and indeed they need to be in order to account for certain intended applications of the theory, e.g. the equilibrium phenomena mentioned. In the spurious unification proposed by Hempel, this would be impossible.

So, in a unified net-like theory the top guiding principle is always presupposed when we export values of magnitudes from models of some theory-element to models of other theory-elements in the net, and it is thanks to such a top principle that we can combine the effects of different types of the same "acting entity"; forces in the case of **CM**.

This analysis of the role of transferring values between different parts of unifying theories when testing them makes it clear that in this type of theories the discussion of independent testing, the application of the **T**-theoreticity criterion, and the unifying structure are intertwined. Asking about the **T**-theoreticity of a concept like force in **CM** requires an additional endeavor that is not required in non-unified theories. This is because the question assumes that the same concept exists in all the different special laws of **CM**, i.e. that such heterogeneous things as the force of gravity and the force of friction fall under the same concept. And if we want to show that it is the same concept, we need to show that the unifying role of the Second Law is not spurious: that **CM** is more than a mere conjunction of special laws. This, in turn, concerns issues not explicitly included in the criterion of **T**-theoreticity, such as the extrapolation of values from one part of the theory to another.

Note that the suspicion of spurious unification affects the concept of force (a concept that has been metatheoretically controversial since its origin) but not the concept of (inertial) mass. The different special laws of **CM** arise from the specification of this former concept in the different forces that each special law deals with. Let us characterize such concepts as "unifying". The reason why the unification of **CM** is not spurious has to do with the fact that its different parts are integrated, and this integration is essential for the crucial extrapolation of values from one part of the theory to another. This becomes apparent in the logical form of Newton's Second Law, which involves a summation of forces and thus that forces of different types can be combined.

We can now establish certain relations between **T**-theoreticity and unification more clearly. In unifying theories it is not true that every **T**-theoretical concept is unifying in the aforementioned sense. As we have seen, mass is not. But what about the converse: Is it true that every **T**-unifying concept is **T**-theoretical? And more generally: Can there be unifying but phenomenological theories, i.e. lacking **T**-theoretical terms? In order to answer these questions, and to establish the relations between theoreticity and unification in more detail, it will prove useful to turn to a discussion of them in the theory of natural selection.

4 Explanation and Testing in Natural Selection

Although the theory of natural selection is easily understood, there is much discussion in the philosophy of biology about its structure and nature. Since it is not possible to even summarize the different positions on the subject here, we will start directly from previous works that present the theory of natural selection as a theory-net (Díez & Lorenzano, 2013, 2015; Ginnobili, 2012, 2016). Similar concerns apply to the related concept of fitness. Here we will refer to fitness in the sense of "ecological fitness" as the fundamental concept of the theory of natural selection, and not as it is used in population genetics (Rosenberg & Bouchard, 2009; Ginnobili, 2012, 2016) .

Natural selection explains changes in the proportions of (heritable) traits present in a population by appealing to differences in fitness (we will present this idea more carefully later). The reason why a heritable trait increases/decreases its relative presence in a population is that, in the context, the trait facilitates/impedes the performance of a function that is beneficial for differential reproduction. In the paradigmatic case of the giraffe's long neck, the trait has expanded in the giraffe population because, in the savanna context, it facilitates the function of feeding, which is beneficial for differential reproduction by improving survival (in the sense of increasing longevity).

There are different ways in which the function facilitated by the trait could be beneficial for differential reproduction. One is by prolonging survival (during the fertile lifespan). But this is not the only one. In the case of the peacock tail, for example, the trait facilitates, in context, the performance of the function of attracting sexual partners, which is beneficial for differential reproduction by increasing mating opportunities. Other traits affect other functions that are beneficial for differential reproduction by other means. This makes **NS** a characteristic unified theory which explains different phenomena by using different specific *explanantia* but with a similar schematic form. This makes **NS** suitable for analysis in terms analogous to those previously seen in the case of **CM**. There are several such analyses (Díez & Lorenzano, 2013, 2015; Ginnobili, 2012, 2016). These differ in certain details but share the basic idea of reconstructing **NS** as a theory-net with a top theory-element defined by a natural selection guiding principle (**NS-GP**) that specializes downwards, specifying different types of functions and the ways in which they are beneficial for differential reproduction. The schematic fundamental law and the special laws are usually implicit in Darwin's work and in current evolutionary biology; generally, this structure is not made explicit[5] (more on this below). An exception is the work of Endler (1992) which typically presents the theory in a hierarchical manner analogous to that used here.

The **NS-GP** can be spelled out, along the lines set out above, roughly thus:

> Organisms with traits that perform a certain function (in a given context) in a more effective way tend to improve their (ecological) *fitness*, tending consequently to improve, if the trait is inheritable, the success of these organisms in differential reproduction.

This guiding principle specializes into more specific generalizations through the specification of the concept of fitness, in the sense of specifying the different ways in which a functional trait affects differential reproduction. Thus, the possession of different varieties of a trait can affect reproductive success through differences in survival, the ability to attract mates, fecundity, etc. In turn, these generalizations specialize into even more specific situations via further specification. For example, differences in survival may be due to different capabilities for obtaining food, or escaping from predators, and so on.[6]

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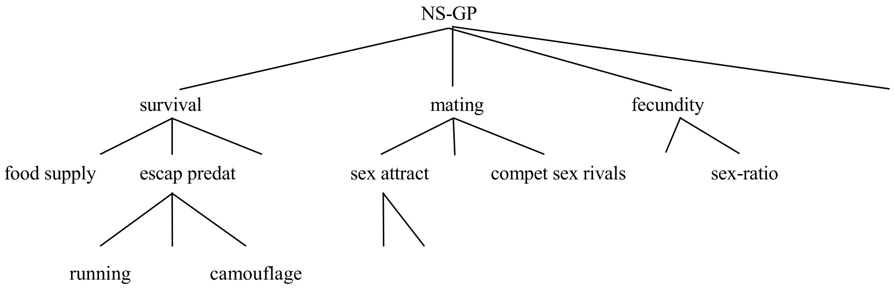
[5] For a general discussion of laws in biology, and pointing out a similar situation in genetics, see Lorenzano (2006).

[6] In the specialized literature and evolutionary biology textbooks, some authors characterize natural selection as a distinct mechanism from sexual selection (e.g. Ridley 2004, p. 688), while others present it more broadly, including sexual selection as one of its specific forms (Endler, 1986, 1992). Even Darwin himself, who typically distinguishes between natural selection and sexual selection, refers to both processes as distinct forms of selection (e.g. Darwin 1872, p. 69). We aim to refer to natural selection in the second, broader sense, which is also the focus of the previous reconstructions of the theory of natural selection we take for reference (Díez & Lorenzano, 2013, 2015; Ginnobili, 2016). The main reason for taking this option is that we are interested here in discussing the most unifying version of the theory, for it possess the strongest challenge to the "T-theoreticity vs T-unification" problem we are dealing with: the broader the unification the less straightforward the application of the T-theoreticity criterion. It is important, though, to note that the core of our account does not depend on this choice. Our thesis could be supported by considering only non-sexual selection, which would still be unifying. As we have just said, choosing the broadest interpretation of NS allows us to face the problem in its greatest generality.



As Kuhn (1974) said, the guiding principle does not apply to the *explanandum* phenomena directly, but through these special laws. The special law in which differences in fitness are specified in survival differences due to improved capabilities for obtaining food applies to the case of the giraffe's neck. The special law in which fitness differences are specified in differences in survival due to improved capabilities for evading predators through camouflage applies to *Biston betularia*.

This is, roughly, the net-like structure of **NS** as a unified explanatory theory. As for the explanatory vocabulary, the *explananda* part is quite clear: every *explanandum* is described **NS**-non-theoretically in terms of heritable traits or phenotypes, e.g. skin color, propulsion system, neck length, tail shape and color, offspring sex ratio, etc. As we have seen, **NS** explains these phenomena by identifying a function that is affected by the trait and that is relevant for differential reproduction in a specific adaptive way (increasing longevity, or capability of escaping predators, or mating opportunities, or fecundity, etc.). The main explanatory concepts used in the *explanans* are, basically, the function (e.g. food supply, attracting sexual partners) and its related fitness (e.g. longevity, mating opportunities, respectively). What makes the case of **NS** particularly interesting is how these explanatory concepts do with respect to **T**-theoreticity, testing and unification. There are two main aspects worth highlighting.

The first point is made by Ginnobili (2012) and is related to the explanatory role played by the notion of function. Of course, the discussion about functional language is extensive and in this context we will simply avoid it, knowing that it may be controversial. As we have said, such a notion is an essential component of the **NS** explanatory machinery; it appears in the **NS** guiding principle, and its different instances are present in all the particular **NS** *explanantia*. Nevertheless, it is arguable that the concept of function is a **NS**-non-theoretical concept: we can determine the function of a trait within functional biology, so it is not necessary to assume any adaptive principle or regularity to determine whether the function of long necks is feeding or that of strong horns is vanquishing sexual competitors (neither is **NS** assumed when determining whether the function is beneficial for reproduction[7]). Thus, although function is **T**-theoretical for a certain theory, that theory is *not* **NS** but rather functional biology (however functional biology is understood and reconstructed). Nevertheless, despite being **NS**-non-theoretical, the concept of function is an essential part of the **NS** explanatory machinery. This is a first sense in which **NS** is peculiar.[8] Although in standard cases, such as **CM**, (i) all **T**-non-theoretical concepts belong to the *explanandum* apparatus, and (ii) all **T**-explanatory concepts used in **T**-explanantia are **T**-theoretical, this is not necessarily so. **NS** provides an example of a bona fide explanatory theory in which not all the **T**-non-theoretical vocabulary belongs to the **T**-empirical basis and not all the **T**-explanatory vocabulary is **T**-theoretical. Yet it is still the case that (iii) all the vocabulary with which we describe the **T**-empirical basis (*explananda* and testing phenomena) is **T**-non-theoretical; and also that (iv) all the **T**-theoretical vocabulary introduced by the theory is part of the **T**-explanatory machinery. Although in many cases the stronger conditions (i) and (ii) are satisfied, conditions (iii) and (iv) are the only ones that are always satisfied, including in **NS**.

The second aspect has to do with the notion of *ecological fitness*. As with *force* in **CM**, it is a unifying concept whose specification, as we saw, allows us to obtain the different special laws of the theory. However, it behaves differently from force in other respects. Ginnobili (2012) points out that there are both analogies and disanalogies between the concept of ecological fitness in **NS** and the concept of force in **CM**. First, while the concepts are introduced by Newton and Darwin in their respective theories, Newton introduces force explicitly but Darwin never explicitly coins a term for the concept that one finds implicit in the specializations of his theory (Ginnobili, 2016). Secondly, although the specifications of the concept of

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[7] This statement presupposes taking a specific position in the long debate about biological function. In particular, it implies rejecting the etiological approach to function, which holds that functional attribution is equivalent to the application of the theory of natural selection (i.e. that claiming that trait *r* has function *f* is equivalent to saying that trait *r* is present in the current population because in the past it improved the reproductive success of its possessors by doing *f*). Again, we cannot discuss this issue here. We will only say that this equivalence is denied by all other approaches to functions, precisely because they do not adequately account for scientific practice (e.g. Caponi, 2020; Cummins 1975; Amundson & Lauder 1994; Boorse 2002; Ginnobili 2022).

[8] In some reconstructions, the principle of natural selection is not presented in the above tripartite form – in which biological function, fitness and reproductive success appear as distinct parts–, but only two components are made explicit–fitness and reproductive success (regardless of the specific terminology used by each author to refer to these concepts, e.g. Brandon, 1990; Sober, 1984; Williams, 1970)- omitting explicit reference to the functional attribution. While we consider our tripartite formulation and reconstruction a better explication, a full defense of this choice exceeds the limits of this paper. It is worth emphasizing that, although necessary for what we think is a correct elucidation of the theory and its peculiarities, our main point does not depend on this choice since our main focus here is the concept of fitness and how it is specified in different applications.

force in specializations of **CM** are as new as the general concept itself, the particular specifications of the fitness concept (i.e. differences in longevity, in capacity for attracting mates, in fecundity, etc.) are not new but already present in the work of pre-Darwinian naturalists.[9] Third, and related to this second point, even though the concept of fitness is explanatory in the theory of natural selection, its specifications (differences in longevity, fecundity, etc.) can be determined without assuming any principle of **NS**; this is contrary to what happens in **CM** where it is impossible to determine/measure the forces specified in its specializations without appealing to some **CM** law or other. This last point is particularly interesting, since it leads to the controversial **T**-theoretical status of the concept of fitness since each of the specifications of the concept can be determined independently of **NS**.

Despite these differences, Ginnobili argues, the explanatory asymmetry in **CM** between forces and accelerations (i.e. forces explain accelerations but not the other way around) is analogous to the explanatory asymmetry in **NS** between fitness and reproductive success (the former explains the latter but not the other way around). Finally, the abstract notion of fitness has the same unifying conceptual value as the notion of force in **CM**: the different fitness specifications (survival, mating, fecundity, etc.) are different ways of improving reproductive success *adaptively*, i.e. *through fitness*, as happens with different specific forces as specifications of the **CM** general notion of force.

These analogies and disanalogies show why **NS** provides an interesting case study for our topic, namely the relationship between **T**-theoreticity, explanation and unification: although the concept of fitness is as unifying as the concept of force in classical mechanics, its status with respect to **T**-theoreticity is far from straightforward. In the next section, we elaborate on this issue and precisely characterize the peculiarities of ecological fitness regarding its theoreticity status.

5 Fitness, T-theoreticity and Unification

The idea that there is a sense in which the concept of ecological fitness depends on the theory of natural selection, despite the fact that in the specializations the notion can be determined independently of the theory, raises some interesting issues with regard to its **NS**-theoretical status.

As the last point in Ginnobili (2012) mentioned above suggests, and other structuralists have pointed out (e.g. Díez, 2002; Díez & Lorenzano, 2013, 2015), **T**-theoreticity and unification within theory-nets are intimately related. If the only thing that the specifications of the concept of fitness (survival, mating, fecundity, etc.) have in common is that they fall under the concept of ecological fitness, one might argue that the notion of ecological fitness is dispensable, together with the

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[9] Of course, the phenomena of free fall, elastic recuperation, friction, celestial orbits, etc. were well known before Newton, but the explanation of them in terms of (specific) forces in general were not (with the possible exception of the impetus theory if one considers it as a partial ancestor of Newtonian inertia, which is controversial).

general and abstract **NS** guiding principle. Why should we not think that what we call "the theory of natural selection" is nothing more than a set of independent phenomenological models that do not form a theory-net? Notice that one could raise the same question about classical mechanics. There seems to be a connection between theoreticity and unified theory-nets. The fact that the specifications of fitness "become non-theoretical in the specializations" of **NS** makes this relation more obvious, but the issue applies to every unified theory, **CM** included. Why should one think that the different specifications of *fitness* or *force* are actually *different specifications* of the *same concept*? The answer is that otherwise, one cannot take the different applications/*explananda* as different applications/*explananda* of the same theory, the theory relative to which we are determining the **T**-theoretical status of the concept.

In the case of **NS**, there are three reasons why the theory could be charged with spurious unification. First, the alleged specifications of fitness can be determined in specific applications independently of the theory. Second, the concept of ecological fitness is not explicit in biological practice, Darwin's work included. Third, the specifications of the concept of fitness are extremely heterogeneous; it seems that the only thing they have in common is that they relate the possession of certain traits with reproductive success (more on this crucial point below). In the case of classical mechanics, the first two features do not apply, but the third, essential one does: the specifications of forces are extremely heterogeneous, and it seems that the only reason they fall under the same concept of force is because they act on particles by accelerating them (to a degree according to their mass). In both cases, the talk of a single theory, and of different applications of the same theory, presupposes that the unification is not spurious. But why can we not simply obviate any such talk?

As we saw, what the theory of natural selection and classical mechanics have in common is that they are unifying theory-nets "driven" by general "guiding principles". What is peculiar about guiding principles is that their key theoretical concepts can be specified in a variety of ways through heterogeneous special laws that apply to different phenomena. We can now strengthen a point that is implicit in the structuralist works but, to the best of our knowledge, has not been made explicit before, namely that the notion of **T**-theoreticity in unifying theories, driven by guiding principles, presupposes that the unification is not spurious. This, in turn, makes the application of the notion of **T**-theoreticity less straightforward than the literal reading of the above criterion of **T**-theoreticity suggests.

The fact that **NS** has specific features that make it more prone to the charge of spurious unification may have triggered some of the criticism that the theory has received. For instance, Jerry Fodor (Fodor 2008a, b; Fodor & Piatelli-Palmarini 2010a, b) directly charges **NS** of spurious unification, claiming that the alleged general principle of natural selection is an empty truism, and that an alleged unified theory of natural selection is not a bona fide empirical theory but methodologically, epistemically and metaphysically unacceptable. Sober (2008, 2011) disagrees with Fodor and defends the notion that **NS** is a perfectly acceptable theory, but qualifies its causal explanations as "a priori", which according to him makes **NS** quite a peculiar theory compared to other standard empirical theories such as **CM**. Barberis (2013) argues that, since what different specifications of ecological fitness have in common is only that they fall under the same concept, the concept of ecological fitness appears to be not just abstract but purely formal; this casts doubt on the criteria for its application, which is something that does not happen in "standard" empirical theories. We think that, despite the dissimilarities we point out above, these claims are ill-founded. Although the dissimilarities mentioned may make certain things more apparent, **NS** is no more spuriously unified than **CM**, nor does it include a priori explanations in any sense in which **CM** does not, and fitness is no more a formal concept than force is (for a detailed criticism of Fodor and Sober along the present lines, see Díez & Lorenzano, 2013, 2015, respectively).

In the light of this, we need to consider the question: Why is neither **NS** *nor* **CM** a case of spurious unification? As is well known, the question of spurious unification has been a recurrent issue in the philosophy of science. Since the problem was pointed out by Hempel and Oppenheim (1948), it has reappeared in several authors (e.g. Blanco et al., 2019; Friedman, 1974; Kitcher, 1981; Lorenzano & Díaz, 2020; Morrison, 2000). Here, we do not intend to give a complete and definitive answer; we just aim to point out some features that may be taken as indicative of the unification being not spurious but "genuine".

First of all, from a sociological point of view, all applications of either theory are considered by the scientific community as applications of one and the same theory. Of course, philosophers may claim that on some occasions scientists are wrong in this regard (as e.g. Fodor does with respect to **NS**), but this sociological feature at least makes it plausible that each theory is a prima facie candidate for genuine unification. Other, more substantive conditions should nevertheless apply if this prima facie reason is to become robust.

A second criterion that, though also pragmatic, has more conceptual import, has to do with the heuristic role of unifying guiding principles. This role, originally noted by Kuhn (1974) and also emphasized by Moulines (1984, see also Diez & Moulines, 2022), is principally to guide the community in the application of the principle to account for specific new cases with new special laws, seeing them as "**T**-relevantly similar" (Kuhn's "resemblances") to previous cases explained by previous special laws. In classical mechanics, for instance, new forces were discovered (i.e. new special laws were proposed) that made it possible to treat novel phenomena that could not be treated under the previously available forces, e.g. the application of gravitation to planets as an extrapolation of parabolic trajectories, or the new electrostatic forces analogous to gravitational force. Likewise, the community of Darwinian evolutionary biologists found new specifications of the concept of fitness that broadened the scope of the theory with new applications (e.g. Díez & Lorenzano, 2013, 2015; Endler, 1986). In this sense, the concept of force, *and* the concept of fitness too, has a surplus of content that goes beyond the disjunction of all its existing specifications at a given time, and an "open scope" that the development of the unifying theory progressively specifies. New applications of the concept to novel cases provide, often, new methods of determination that are accepted as new determination procedures of the same concept.

Finally, as already mentioned in Sect. 2, genuine unifications allow for a crucial practice that is essential to unified theories, namely, the possibility of combining different effects within a single phenomenon. For instance, forces of friction and of harmonic elasticity are quite heterogeneous, but since they belong to the same unified theory, we can combine them in a single case, e.g. the equilibrium point of a body on an inclined frictional plane at the end of a spring pulling it up. This is precisely the combinatorial function of Newton's Second Law, which is as important as its heuristic character. This implies that both forces, though heterogeneous, are *different determinates of the same determinable*. All this would make little sense if **CM** were a spurious unification. Likewise with **NS**. Despite its peculiarities with regard to the implicitness of its guiding principle and the fitness concept, and the pre-disposition of particular fitness properties (Ginnobili, 2012), its key feature is shared with **CM**: thanks to being a non-spurious unification, one can transport adaptive values from one model to another in a different branch of the theory-net and combine different adaptive pressures in a single adaptive *explanandum*, e.g. the preference of females leading to a trait that is more conspicuous and survival favoring camouflage (Díez & Lorenzano, 2013; Ginnobili, 2016).

Of course, this approach comes down clearly on one side in current debates about the theory of natural selection and the notion of fitness. This is true, but we think that the position defended here receives additional plausibility from the demonstration above that the key features of **NS** which, we believe, support its non-spurious unifying character are not exclusive to it but are shared with acknowledged bona fide empirical theories such as classical mechanics. On the one hand, **NS** has the open structure of unifying concepts that goes beyond the mere disjunction of specifications at a given moment. On the other hand, in many applications of the theory, one does not appeal to isolated special laws, but to trade-offs that imply appealing to several adaptive factors at the same time. Both these criteria apply equally to force and fitness, despite the above-mentioned differences between **CM** and **NS**.

This case study also serves to qualify standard approaches to unification. In most common approaches, unification is a trade-off between simplicity and strength, i.e. the number of primitive principles or patterns one has to assume versus the different phenomena accounted for. As our example shows, and Blanco et al. (2019) point out, there is an additional factor that must be taken into consideration, namely, the "heterogeneity" of different *explananda* for different phenomena: given the same simplicity and strength, the more heterogeneous the special phenomena, the more substantially unifying the theory is. Of course, heterogeneity is not a purely formal notion in that it cannot be specified formally, as (in principle) simplicity and strength can; rather, it has an essential pragmatic dimension related to how users of the theory perceive the resemblance between new and previous applications. One might try to encapsulate heterogeneity as a component of strength, but this would not eliminate its pragmatic dimension. However, if one prefers to follow that route (we take it that there is nothing substantive, just terminological in this preference), what we would obtain is simply that strength has a component that is formally specifiable and another that is not. In any event, we defend the notion that heterogeneity, in the sense mentioned here, is an essential aspect of unification that has not been emphasized enough before.

Finally, our case study makes it necessary to reassess the alleged **T**-non-theoreticity of the fitness concept commented above. What conclusion should one draw about the theoretical status of fitness in the theory of natural selection? Is it **NS**-theoretical or **NS**-non-theoretical? In order for the discussion not to be merely terminological, we should draw meaningful conclusions in this regard. What the case of fitness in the theory of natural selection teaches us is that there are different ways in which a concept can depend on a theory, and that, at least in the case of unifying theories, the application of structuralist **T**-theoreticity presupposes the uniqueness of the concept across different applications, and this uniqueness involves appealing to aspects that **T**-theoreticity criteria alone cannot resolve.

If we consider an isolated special **NS** law, e.g. one that appeals to only one form of survival, such as longevity, it seems correct to claim that the concept of longevity can be determined independently of the specialization in question, and thus that it would be non-theoretical in relation to that special application. (It is interesting to note here that Wallace's theory of natural selection lacks the unifying concept of fitness, cf. Ginnobili, 2016; Ginnobili & Blanco, 2019). However, if we ask about the concept of fitness in general, we are forced to give a more complex answer. We have seen that the claim that e.g. longevity and fecundity are both different determinates of the same determinable fitness, makes sense only if one assumes the general **NS** guiding principle. This implies that the determination of specific adaptive properties in specific specializations *taken as combinable* with other adaptive properties presupposes the validity of adaptive principles. And this in turn implies that, a fortiori, the concept, as used within its open/combinable scope, is **NS**-theoretical. In cases such as **CM**, in which the particular specifications of the relevant concept, force, already presuppose the use of theory's laws, the standard structuralist criterion of theoreticity is not affected. But we have seen that in less standard cases, such as **NS**, one has to assess the theoreticity status of a concept more carefully, for the diagnosis may differ if one takes applications in isolation or, given the unifying nature of the theory, as combinable.

This makes it clear that the application of the notion of **T**-theoreticity, at least in unifying theories, presupposes the analysis of aspects that go beyond what is explicitly stated in the criterion of **T**-theoreticity. In fact, it requires discussion of the unifying role of the concept which, as we have seen, in many cases has a strong pragmatic character. This is not a niche question relevant only to those interested in structuralist reconstructions. Although analyzed with the aid of structuralist tools, the conclusion goes beyond that particular analytical apparatus and points to a general, and important, interlink between the meaning of concepts and theoretical unification.

6 Conclusion

In this paper we have shown how theoreticity and unification are conceptually related. By appealing to the theory of natural selection, we have shown more clearly the role that unifying concepts play and how this role is linked in different ways to theory testing. When applied to unifying theories, the criterion of **T**-theoreticity presupposes analysis of the unifying status of the concept to which it is applied, and this may involve appealing to questions that go beyond the literal reading of the criterion itself. We believe this conclusion is of interest beyond the particular reconstructive structuralist program, for it shows the general, relevant fact that the determination of the theoretical status of a unifying concept essentially involves how specific applications of different parts of theories interact with each other.

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