Chapter 2
Unification Principles for Biochemical Kinds

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Abstract Biochemical kinds present an interesting case study in the philosophical literature on natural kinds and functions, as they fall between chemical kinds, defined by their intrinsic microstructural properties, and biological kinds, which involve functional and evolutionary considerations. Here we examine how the distinct chemical and functional properties of biochemical kinds are unified, as well as their identity criteria. We contend that unification principles are crucial for explaining the clustering of properties shared by members of natural kinds and for establishing identity criteria for such kinds. We consider whether there are specific properties that characterize biochemical kinds. This entails investigating the relationship between biochemical functions and structure. We focus on proteins, particularly on vitamin B12, as a representative example of a biochemical kind. We conclude that if there are unification principles for biochemical kinds, these principles exist at the level of biochemistry itself. This supports the naturalness of biochemical kinds as genuine categories and provides identity conditions for such kinds.

Keywords Biochemical kinds · Natural kinds · Functional properties · Microstructural properties · Unification principles · Vitamin B12

2.1 Introduction: The Problem of Biochemical Kinds

Consider a protein, such as haemoglobin. This protein is an object, a chemical macromolecule, and it has specific roles and functions in physiology. However, the more one thinks about such an object and tries to characterise it in terms of properties or similarity to other objects, the more complex the situation gets. On the one hand, a macromolecule such as haemoglobin presents features—chemical properties—that makes it very similar to other chemical objects, such as much

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smaller molecules like water. On the other hand, haemoglobin has features which makes it similar to a biological trait, in that it has functions like carrying oxygen in blood. The complexity of *biochemical objects* such as proteins also presents challenges for their classification: how do we classify objects with contrasting features and under which category should we cluster them? This leads to the more general question about the kindhood of those objects and specifically whether there is a distinct category of objects such as biochemical kinds, and how should these objects be characterised. Either way, biochemical objects appear to be a very special kind of object, worthy of further study.

For these reasons (among others), biochemical kinds, such as proteins, have started to receive increasing attention in the philosophical literature on natural kinds and functions (e.g., Tobin, 2010; Goodwin, 2011; Bartol, 2016; Havstad, 2018; Tahko, 2020; Bellazzi, 2022). They make for an interesting case study because the objects instantiating them fall between the supposedly 'easy' case of chemical kinds (which is not as easy as it seems; see Havstad, 2018) and the more difficult case of biological kinds. Chemical kinds have traditionally been conceived to be definable in terms of their intrinsic microstructural properties—their chemical structure—whereas biological kinds are usually understood to require at least a partially extrinsic account, involving some functional considerations, as in the case of the kind "eye", or the evolutionary history of the kind, as in the case of taxa. Biochemical kinds crosscut this distinction, since they are instantiated in macromolecules and hence can be understood just like any other molecule, but they also have important biochemical functions, which are realised by their chemical structure. This dual nature of biochemical kinds and the special problems introduced by it have received some attention (see especially Tahko, 2020 and Bellazzi, 2022), but there is much more to be said. Specifically, in this paper we will consider the following questions:

(i) How are the distinct chemical and functional properties of biochemical kinds unified?
(ii) Are there any specifically *biochemical* properties?
(iii) What are the identity-criteria of biochemical kinds?

Before we can address these questions, some preliminary considerations are required. In particular, before we address (i), we need to discuss unification principles for natural kinds more generally (Sect. 2.2). The importance of unification principles is two-fold. First, they provide an explanation for the reliable clustering of the various properties that the objects belonging to a specific natural kind share. Second, they serve as a way to provide identity-criteria for natural kinds, helping us to distinguish genuine natural kinds from arbitrary kinds (for background, see Tahko, 2015). Accordingly, to address (iii), we should first put forward a more general theory of unification principles. To address (ii), we need to consider which properties are the target of unification for biochemical kinds, as well as the relationship between biochemical functions and structure (Sect. 2.3). We are then in a position to consider the unification principles for biochemical properties in general (Sect. 2.4), before a case study of one particularly interesting candidate for a

biochemical kind, the vitamin B12 (Sect. 2.5). We conclude by suggesting that if there are unification principles for biochemical kinds, then these principles are "located" at the level of biochemistry, as the properties of biochemical kinds would not be accountable for in purely chemical or biological (evolutionary) terms. This conclusion might support the naturalness of the biochemical kinds category while offering identity conditions for such kinds (Sect. 2.6).

In summary, this paper has the following outcomes. First, and in line with the contributions presented elsewhere in this volume, this paper sheds light on certain "unconventional" objects, namely biochemical objects, which display a series of properties that can inform research on the relationship between chemistry and biology. Second, it puts forward a further case study concerning the debate on the unification of the properties displayed by a kind, following Tahko (2022). Lastly, this contribution has implications for the definition of the domain of biochemistry, a field that has grown in recent years. Specifically, establishing that the objects studied by biochemistry can be seen as members of biochemical kinds would offer further support to the autonomy of the discipline and can improve on how we think about biochemical objects and their properties.

2.2 Unification Principles for Natural Kinds

In the attempt to better understand what biochemical objects are, and whether they constitute a natural kind, our first task is to clarify what natural kinds are taken to be and what it means to unify the properties of a natural kind. We operate in a *realist* framework, whereby natural kinds are considered to reflect some objective, mind-independent distinctions in reality. We remain neutral about the specifics, e.g., whether natural kinds are considered to be substantial universals (Lowe, 2006), complex universals (Hawley & Bird, 2011), nodes in causal networks (Khalidi, 2018) or something else. The question regarding unification may be raised for each of these approaches: what unifies the definitive properties of the kind, which are instantiated in the objects that are members of the kind? This question may be answered by specifying the *unification principle* for the kind in question, as Tahko (2022: 2) puts it:

> *Unification Principle (UP)*: The narrowest common cause for the clustering of properties in members of natural kinds.

On the idea of the 'common cause', see Godman et al. (2020). They regard common causes to be 'super-explanatory' properties, which 'explain the many shared features of things' (2020: 1), and which are metaphysically necessary to those things. However, there is nothing in the idea of a UP that would require the common cause to be a further property which causally explains the clustering. In fact, it would be implausible to think that the common cause could always be a further property: in the case of fundamental kinds, such as, perhaps, *electron*, there does not appear to be any further property or even causal mechanism to appeal to, as Tahko

(2022: 20) notes. Moreover, there is nothing in the idea of a "common cause" that implies it to be the same across every kind of kind: the unification principles for taxa may be different than the ones for molecules. Accordingly, we take it that we should be *pluralists* about UPs and determine the correct unification principle on a case-by-case basis. To this end, the idea of unification principles is best illustrated by discussing some candidate examples.

Let us take a reasonably simple example first, a *methane* molecule. Before putting forward an analysis of the UP for methane, consider how Hawley and Bird (2011: 209ff.) approach the same example. They understand natural kinds as complex universals, and *being a methane molecule* as a structural universal: 'for something to be a methane molecule, it must have four parts which each instantiate *being a hydrogen atom*, and a fifth part which instantiates *being a carbon atom*. Moreover those five parts must stand in the appropriate geometrical and physical relations to one another, i.e. they must instantiate the relevant relational universals in the relevant order' (Hawley & Bird, 2011: 209). This does not yet explain why the properties of methane cluster together though. To explain this, Hawley and Bird appeal to a further, mereological principle:

> As with conjunctive universals, this mereological picture enables us to explain a pattern of coinstantiation. Why is it that, wherever *being a methane molecule* is instantiated, so too is *being a hydrogen atom*? It is because *being a methane molecule* is wholly present in each of its instances, and, quite generally, if an entity is wholly present, then so too are its parts. (Hawley & Bird, 2011: 210)

Now, this is fine as far as it goes, but it is at best a metaphysical explanation of *why* the properties of methane molecules are clustered together, not a causal explanation of *how* they do so. Accordingly, we have not yet discovered the UP for the natural kind methane. Going a bit deeper, Tahko (2022: 19–20) suggests that when a carbon atom and four hydrogen atoms form a methane molecule through covalent bonding, the relevant causal process is partially governed by electrostatic interaction, and hence electrostatic interaction is likely to feature in the UP for methane—we will return to this example in Sect. 2.4.

What are the implications for finding a UP for a given natural kind, and what would it mean if there is no UP for a given candidate kind? If we can find a UP for a candidate natural kind, then this strongly suggests that we are dealing with a genuine natural kind, rather than an arbitrary clustering of properties (say, green and round things). It may not constitute conclusive evidence for the existence of that kind, given that the necessary correlation of properties could sometimes mislead us to postulate a kind in cases where there is some more fundamental cause for such correlation, i.e., the UP might not be at the level of the postulated kind. But in general, finding a UP usually means that we have identified, e.g., some causal mechanism that appears to be responsible for the clustering of the properties. This can be taken to support the existence of the natural kind being considered. In contrast, if we *cannot* find a UP, this is at least a prima facie reason to shed some doubt on the existence of the relevant kind—the explanation for this might be that we are looking for the UP at the wrong level. So, there could be a clustering of properties

at a higher level that suggests the existence of a natural kind, but in fact what we have is a broader clustering of properties of two or more closely related lower-level kinds. The famous case of jadeite and nephrite could be regarded as a toy example of this type of error (see Tahko, 2021: Ch. 2.4).

Kim summarises the case as follows: 'we are told that jade, as it turns out, is not a mineral kind, contrary to what was once believed; rather, jade is comprised of two distinct minerals with dissimilar molecular structures, *jadeite* and *nephrite*' (1992: 11). 'Jade' is supposed to refer to a higher-level natural kind. Kim, who favoured reductionism, argued that it is not a genuine natural kind, partially because there are no genuine special science laws that concern jade rather than one of its realizers. Kim's case in favour of this conclusion is the possibility that we only encounter one or the other of the realizers of jade when dealing with supposed special science laws concerning jade. The upshot, according to Kim, is that jade is a 'true disjunctive kind' (Kim, 1992: 12).

Kim had a famous debate with Fodor on this topic, where Kim argued that special science laws concerning 'wildly disjunctive' higher-level kinds are not genuine laws, because they do not deal with genuine natural kinds; they can be reduced to laws concerning lower-level kinds. Fodor instead insisted that jade is not multiply realisable in the first place, unlike, e.g. mental states like pain and other *functional kinds*—kinds which are defined in terms of what they do.

Fodor (1997: 154) also appealed to the commonly accepted Kripke-Putnam framework of *microstructural essentialism*, stating that jade's being jadeite or nephrite is metaphysically necessary, just like it's metaphysically necessary that water is H_2O. According to this framework, kinds are defined in terms of their microstructural essences. That's how Fodor arrived at the judgement (in agreement with Kim) that jade is not a genuine natural kind. But this nevertheless goes against Kim (1992: 24), who suggested that jade is to be defined in terms of its *macrophysical* properties.

Let's now try to wrap up this case in the context of unification principles. In particular, what could the unification principle be for a kind like jade, considering its different realizers? We know that jadeite and nephrite, the realizers of jade, share many of their chemical properties yet differ in terms of microstructure. But jadeite and nephrite are not exactly identical in terms of their chemical properties. Jadeite ($NaAlSi_2O_6$) is somewhat harder and less prone to scratches due to its dense crystal structure and higher specific gravity—it is a pyroxene mineral. Nephrite ($Ca_2(Mg, Fe)_5Si_8O_{22}(OH)_2$) is a mineral in the actinolite-tremolite series.

All this seems to speak in favour of treating jadeite and nephrite as distinct kinds (if they are to be understood as kinds at all), which, as Kim suggests, have been classified as jade due to some superficial, macrophysical similarities rather than some shared microstructural basis. Hence, if we follow Fodor's microstructuralist criteria, there are good, scientific reasons to think that these minerals are not genuine natural kinds at all; they are mixtures of two elements in close proximity on the periodic table that remain in a stable, homogeneous state, e.g., when combined with silica minerals.

So, why would jade have been treated as a genuine natural kind in the first place? The reason is that its two realizers do come together in terms of some shared aesthetic and cultural properties, such as being valued as materials for crafting intricate artefacts. But if this were enough to count as a unification principle and hence lead to jade being accepted as a genuine natural kind, then, by the same (aesthetic/cultural) criteria, almost anything might count as a natural kind. In contrast, if we had found a more robust unification principle for jade, one that would have provided a reason for the clustering of its properties at the level of the realised rather than the realizers, then this would have corroborated the existence of jade as a genuine kind.

2.3 Biochemical Properties: Functions and Structure

Similar concerns to the ones presented for minerals such as jade can arise for macromolecules such as biochemical objects. As introduced in Sect. 2.1, these objects have properties normally ascribed to chemical and to biological kinds. For instance, a biochemical kind such as vitamin B12 presents a given chemical structure, being a cobalt compound, and a series of biochemical functions, such as contributing to erythropoiesis, the renewal of red-blood cells. The combination of these properties may lead us to classify biochemical kinds either as chemical kinds (favouring the chemical component) or biological kinds (favouring the functional component) arbitrarily or according to pragmatic criteria. Without the identification of precise unification principles, one might think that biochemical kinds do not have UPs at the biochemical level, or that the UPs are given in relation to other kinds or properties. The upshot is that, just like jade, biochemical kinds might not be accepted as genuine natural kinds. In this regard, the inquiry into the unification principles of biochemical kinds seems to be particularly relevant for the discussion of "difficult" kinds. They can be taken to be paradigmatic instances of kinds that present properties that seem to pertain to different kinds of kinds and, thus, we think that the inquiry into the unification principles for biochemical kinds can be relevant not only for the status of biochemical kinds, but also for a general discussion on special or difficult kinds.

Are the properties that biochemical kinds display unified or unifiable? If they are unifiable, at which level is the unification principle? In order to answer these questions, we need to make clear which properties are relevant for biochemical kinds. The growing recent literature on the philosophy of biochemistry identifies two kinds of properties displayed by biochemical kinds: chemical properties and functional ones. The former are identified in terms of molecular structure while the latter concern the function these molecules have in biological processes (Slater, 2009; Goodwin, 2011; Khalidi, 2018; Havstad, 2018; Bartol, 2016; Tahko, 2020; Bellazzi, 2022). For instance, proteins such as haemoglobin or crystallin display a given chemical structure and given functions in biological processes. In the case of proteins, the relevant literature refers to the chemical structure as the protein's primary

structure, in which the amino acid chain is identifiable and brings in specific chemical considerations (Goodwin, 2011; Tahko, 2020). The relevant functions in the cases of haemoglobin and crystallin are the contribution to the transportation of oxygen in blood in the first case and a structural function in sight in the second. The analysis of functional properties—as analysed by Havstad (2018) and Bellazzi (2022)—also brings in evolutionary considerations. In the case of specific biochemical kinds, such as the aforementioned proteins, evolutionary or etiological properties come into play. In order to further explore the unification of biochemical properties in biochemical kinds, a bit more has to be said in this regard. For the sake of clarity, we will explicate these properties by making use of the main case study of this paper, vitamin B12 (as in Bellazzi, 2022), which we will return to in more detail in Sect. 2.5.

Vitamin B12 is a vitamin that acts as a coenzyme in a variety of important biological processes, going from DNA regeneration to erythropoiesis (the production of red blood cells). This vitamin presents at least four vitamers, cyanocobalamin, methylcobalamin, adenosylcobalamin and hydroxocobalamin. These vitamers have a similar chemical structure, in that they all display a corrin ring, a planar tetrapyrrole ring, with the element cobalt (Co) positioned at the centre. This gives a specific chemical structure to the biochemical kind vitamin B12, from which one can infer a series of related chemical properties. However, vitamin B12—like proteins—does not present only a chemical structure, but also a series of biochemical functions, which characterise the kind in relation to the biological processes to which it contributes. For instance, vitamin B12 contributes to the production of red blood cells, and this has an impact on the correct functioning of a variety of biological processes. In order to further understand the functional properties of these kinds, we need to consider an appropriate definition of biochemical functions.

The discussion of functions for biochemical kinds requires us to consider the accounts of functions discussed in philosophy of biology. Broadly, there are two evolutionary-informed accounts of functions: the backward-looking ones and the forward-looking ones, where both make reference to evolutionary considerations, such as contribution to fitness. Backward-looking theories of function state that "what counts as a function of a trait is determined by that trait's history", and that "a function of a trait is the effect for which that trait was selected" (Neander, 1991a, b: 459). A similar definition of function is presented by Mitchell (1993, 2003) and she defines a function as something that enabled the production or the reproduction of the function's bearer in the ancestors of the considered population. As one can notice in both accounts, biological functions are characterised by two main aspects: (i) functions are functions *of a trait*; (ii) they contributed to the fitness of the ancestors of the population in the past.

In contrast, there are forward-looking theories of function or theories of biological advantage. According to this account, the function of a trait is a disposition to maximise the organism's fitness in the future (Bigelow & Pargetter, 1987; Wouters, 2003; for further background on dispositions, see also Friend & Kimpton-Nye, 2023). Again, biological functions are characterised by: (i) functions are functions *of a trait* (ii) being a disposition to maximise fitness in the future of the population.

However, as argued by Bellazzi (2022), these evolutionary accounts seem to fall short of characterising functions within the biochemical domain. The first reason is that they seem to ascribe functions to traits, where traits are often defined as detectable phenotypic properties of organisms, as in Valles (2013). While more complex definitions of traits can be provided, biochemical molecules do not seem to count among phenotypic features of organisms and so cannot count as traits. Secondly, the function they play does not seem to be directly linked to fitness-maximising in the past or in the future. For instance, the vitamers of vitamin B12 are complex compounds that are introduced by nutrition. Accordingly, they do not count as traits, nor can they be seen as produced or reproduced in virtue of the function they have in the production of red blood cells (*contra* the backward-looking theories). And while these molecules are produced in nature by prokaryotes, their production is not directly linked to the function they have, e.g., in human physiology. At the same time, the functions of vitamin B12 do not seem to be directly related to the maximisation of an organism's reproductive fitness in the future. And, in an even stronger sense, it seems that the function of vitamin B12 to contribute to haematopoiesis is indifferent to fitness maximisation in the future (*contra* the forward-looking theories). There are possible scenarios in which there are environmental changes or variations in the quantity of the vitamin. In cases where there is a lack or an excess of B12, the vitamin would still have a function within the production of red blood cells, and this happens independently of fitness considerations. Accordingly, the analysis of the functions of vitamin B12 cannot be conducted in purely etiological terms.

In the same lines, Garson (2018) suggests that there are two main problems with the application of the evolutionary theories to molecular and biochemical cases. The first is what he calls the 'socio-linguistic argument'. This argument points out that in these sciences ascription of function is not done by making reference to selection or evolutionary fitness (see also Wouters, 2003: 658; Griffiths, 2009). For instance, in the case of vitamin B12, scientists seem to make reference to the causal effect of these molecules in the process of the production of red blood cells rather than evolutionary or fitness considerations. This argument comes together with what Garson calls an 'ontological argument', which considers the kinds of entities that can or cannot have an evolutionary function. This is in line with the reasons mentioned before: biochemical molecules can hardly be considered traits, and they might not display the relevant evolutionary history or the relevant contribution to fitness, as in the case of vitamin B12.

The failure of the application of evolutionary theories of functions to the case of biochemical functions can lead to two possible scenarios. First, one can accept the fact that biochemical molecules do not display functions as they lack the relevant criteria for function-ascription. The proponents of the evolutionary theories would instead probably ascribe the function to the processes to which the given biochemical molecules contribute to. Second, if we want to accept that there is a genuine functional ascription to biochemical molecules and compounds, then we should provide a different account. In this latter line, it is possible to define biochemical functions as follows (as in Bellazzi, 2022):

> *Biochemical functions (BF)* = Biochemical functions are associated with a set of chemical dispositional properties to bring out a specific effect within biological processes. These biological processes are a product of evolution and, as such, the relevant chemical dispositional properties are *at least* indirectly evolutionary selected.

Following this definition, we can notice that biochemical kinds have *biochemical* functions. While these functions are not direct evolutionary functions, evolutionary considerations still remain relevant for their identification, and the reference to evolution needs to be at least indirect. Let us unpack this concept a bit further. Biochemical functions are associated with chemical dispositional properties. However, only some of these properties contribute to biological processes, so only some chemical dispositional properties are relevant for biochemical functions. Accordingly, in order to identify such contributions, we need to consider the evolutionary history of the processes to which the biochemical kinds contribute. This makes the reference to evolutionary selection *indirect,* as we are referring to the selection of the relevant dispositional properties not via evolutionary mechanisms that act directly on them, but instead via the selection of relevant biological processes. For instance, the function of vitamin B12 is indirectly selected as it is the relevant hematopoietic process in humans that has been selected (rather than the molecule itself), and this process works thanks to the presence of the vitamin B12 molecule. A similar analysis is presented by Wouters (2003), where the notion of indirect function is defined as a function that takes part or contributes to the process of selection—while not being directly selected. As reported, biochemical functions *per se* are not straightforwardly evolutionary, nevertheless evolutionary history needs to be taken into account to understand the contribution that the molecules make and the context of manifestation of such dispositional properties. The fact that generally biochemical functions are indirectly evolutionary selected does not exclude the possibility of more direct evolutionary selection. In fact, biochemical functions can be played by molecules also when those molecules are biosynthesised directly by the relevant organism. For instance, vitamers of vitamin B12 are directly synthesised by some bacteria and archaea, and these species use them as co-enzymes in various processes that have been selected. This allows the tracing of a more direct evolutionary history of the functions, as the biochemical functions in those species would be associated to chemical powers whose bearers have been retained in the process of biosynthesis. Moreover, the path of such evolutionary selected synthesis seems also possibly identifiable, as we will discuss in more detail in Sect. 2.5. Accordingly, biochemical functions are associated with chemical dispositional properties that need to be at least indirectly evolutionary selected but can also display a more direct form of evolutionary history.

Before discussing unification principles for biochemical kinds, let us clarify one last aspect. The account of biochemical functions used here is not incompatible with the possibility that some biochemical molecules can also display biological evolutionary functions together with biochemical ones. This is the case when there is the possibility of identifying a clear process of selection, as for some sequences of nucleic acids in the genome. Sequences of nucleic acids are ascribed functions in virtue of the causal contribution they make to various evolutionary selected

processes, as in Griffiths (2009). Accordingly, DNA strands can display a biochemical function as in the account presented above. Moreover, genetic sequences can also be ascribed *biological* functions when there is a clearer correspondence between genes and sequences and when such sequences have undergone a clear process of selection. Evolutionary biologists have pointed out that this can be the case for the 3–8% of the genome (Germain et al., 2014; also in Doolittle, 2013). In these instances, the biological function can be identified as that contribution that has been selected due to the benefits it had in the past/previous ancestors. However, not all genes have a biological function, and some might just display a biochemical one, where a dispositional functional property contributes to selected processes. In line with these observations, a more direct evolutionary history, and thus the possibility of ascribing a biological function, can be identified also for proteins encoded by specific parts of the genome that have undergone the relevant processes of selection. This would allow some proteins to display both a biochemical and a biological function.

The consideration of different levels of evolutionary history that the biochemical molecules can display give us a more complex picture of the properties of biochemical kinds, as in addition to the chemical ones, there are also functional and evolutionary ones—potentially three "levels" of properties. The heterogeneity of the properties displayed by these kinds further motivates the need to inquire into the presence of a unification principle for these properties in order to assess the naturalness of these kinds. Answering this need is made even more urgent (and philosophically interesting) by the fact that structural and functional properties of biochemical kinds display multiple realisability and multiple determinability (as noted in Tahko, 2020). This makes the unification and the link between the properties more challenging, as straightforward identity reductionism does not seem to be available. Considering again the example at hand, vitamin B12 is a multiply realisable kind, in that there are at least four different macromolecules that can realise this kind. In the same vein, the various biochemical functions, such as the function to contribute to erythropoiesis, can be realised by the four different vitamers. Similarly, the same vitamin can play different functions, displaying multiple determinability. Accordingly, unifying biochemical properties and finding the relevant unification principles for biochemical kinds can provide further understanding of the nature of biochemical kinds.

2.4 Unifying Biochemical Properties

Biochemical kinds, as reported above, display two broad kinds of properties: chemical and functional—where the latter can be understood either as relating to biological or biochemical functions. How are these properties unified? The answer to this question should address the presumed unification principle (UP) and the "level" at which the unification principle can be located. If the UP is at the biochemical level,

possibly related to the biochemical functions as we have suggested above, then this would support postulating biochemical kinds as genuine natural kinds.

Let us first briefly consider the somewhat simpler example of chemical kinds once more: what is the UP for a chemical kind such as methane (CH_4)? The search for UP starts from the properties of the kind in question, so in this case we are interested in things like the boiling point and reactivity of methane—its chemical and physical properties. Ultimately, these properties are determined by the structure of the molecule, more specifically, the covalently bonded hydrogen and carbon atoms and the resulting electron configuration, where the carbon atom "shares" its outer valence electrons with four hydrogens. If we skip some details, we quickly get to the common cause for the clustering of methane's properties, as required for a UP: electrostatic interaction (and the laws governing this interaction). The same procedure, through somewhat different steps depending on the relevant chemical bonds, always leads to electrostatic interaction as a key ingredient. So, the properties of chemical kinds quite generally can be considered to be unified by electrostatic interaction. While there is much more to be said about the details, the picture seems relatively neat in this case.

How does the case of chemical kinds compare to the case of biochemical kinds? We can obviously give a similar story about the chemical properties of these kinds, albeit the relatively large size of some of these macromolecules introduces additional complications. Specifically, the same primary structure of a macromolecule such as a protein can fold up to produce different three-dimensional structures (tertiary and quaternary structures). In other words, the same chemical formula, and hence the same sequence of amino acids, can result in different three-dimensional structures. This gives rise to what Tobin (2010: 52) calls 'functional promiscuity' and what Tahko calls 'multiple determinations' (Tahko, 2020: 801): the same microstructure can result in distinct biochemical kinds. Moreover, biochemical kinds also display a form of multiple realisability, such as in the case of different vitamers realising the same functional role, and thus, it seems, the same kind. Accordingly, the role of functions (and their complex relation to the underlying chemical structure) in defining and distinguishing biochemical kinds must be taken into account.

As we have seen, biochemical functions (BF) involve at least an indirect evolutionary aspect. Given the possibility of multiple determination, this evolutionary aspect of biochemical functions enables us to distinguish functions at the level of biochemistry even when they are chemically indistinguishable. However, Goodwin (2011) and Tahko (2020) have suggested that the different protein folding structures and hence the biochemical functions could be reduced to dispositions at the chemical level: the primary structure has the potential to fold into different shapes and hence realise the various biochemical functions. Santos et al. (2020) take up this idea, which they label 'potentialist predeterminism':

> [A]ccording to potentialist predeterminism, the causal role of molecular, cellular and organismal contexts and environmental conditions is only to select the potentialities that will actually be instantiated by the developing polypeptide. However, the potentialities are given from the outset by the primary structure. (Santos et al., 2020: 375)

They then argue that this view can be improved upon. The alternative they propose, 'relational-construction based potentialism', suggests that 'new potentialities may come into existence by virtue of certain compositional or structural changes' (Santos et al., 2020: 377). The difference in the accounts is fairly subtle, but crucial from the point of view of accounting for the role of biochemical functions in UPs. The key is that Santos et al propose that *new potentialities* may emerge during protein development. While they do not label this as a form of 'emergence', it is clearly compatible with (strong) emergence understood as bringing about new powers or potentialities (cf., Wilson, 2021). Indeed, in another paper, Santos (2021) explicitly defends the idea of 'integrated-structure emergence', using cells as one of the examples. Specifically, Santos suggests that:

> [S]ome of the properties and causal powers usually ascribed to DNA molecules and particular genic nucleotide sequences are, in fact, relational attributes which they only instantiate by virtue of a cellular network of transformative and structural conditioning relations. (Santos, 2021: 8704–5)

From this, Santos concludes that the biological functions of cells cannot be explained by compositional relations between the intrinsic attributes of a cell's constituents. He takes this to count against what he calls 'proper micro-reductionism', although it should be pointed out that some versions of 'micro-reductionism' can certainly accommodate an extrinsic analysis (see Tahko, 2020), e.g., by also taking into account a reductive analysis of the environment in which a cell or a protein finds itself in.

We see a clear pattern developing here. If we accept that the relevant set of causal powers ascribed to a given biochemical kind cannot be traced to the original potentialities of its chemical constitutions (i.e., the macromolecule or primary structure in the case of proteins), then these would need to be accounted for at the level of biochemistry (if not biology). At this level, the relevant powers have undergone at least an indirect evolutionary selection process. Moreover, the causal efficacy of biochemical kinds appears to be distinctive in that it should bring about specific effects within biological processes, and these effects are difficult if not impossible to explain in terms of the intrinsic causal powers of the macromolecule, at least insofar as it is considered in isolation.

Whether or not the resulting biochemical kind and the set of causal powers associated with it are considered to be 'emergent' in some sense is a question that we can remain neutral about in this connection. This question is complicated by the fact that emergence may be understood in a variety of rather different and incompatible ways. But what is clear is that the biochemical level presents a distinct challenge for unification, given the instances of multiple determination and multiple realisation that have been observed. The relevant UPs for biochemical kinds need to be able to account for the complexity of the various causal powers ascribed to these kinds. Our suggestion is that insofar as biochemical kinds truly are genuine natural kinds, the relevant UP must refer to *both* chemical and distinctly *biochemical powers*, where the latter are at least indirectly selected and cannot be directly accounted for in terms of the intrinsic properties of the macromolecule.

We have so far discussed relatively straightforward cases of prospective biochemical kinds, such as proteins. But if the biochemical level is genuine, there are likely to be many more biochemical kinds, which would all need to involve some proportion of at least indirectly selected dispositional properties or powers. This brings us to our case study, the vitamin B12. The consideration of this case study will allow us also to explore whether the unification principle could be "located" in the evolutionary history that needs to be taken into account when considering biochemical functions. As we will argue, while evolutionary history is relevant and informative for the specificity of such functions, the unification principle does not seem to be located within evolutionary mechanisms, as they vary across instances of such functions.

2.5 Case Study: Vitamin B12

As reported above, vitamin B12 is an interesting case to discuss in order to illustrate unification principles for biochemical kinds. This is so because it displays both multiple determination and multiple realisation and because the evolutionary history relevant for its functions is complex and dependent on various interactions. As defined in Sect. 2.2, the vitamers of B12 are chemical compounds that can act as coenzymes in specific biological processes—specifically, propionate metabolism and methionine biosynthesis. The functions that vitamin B12 displays are varied and relate to different organisms in different ways. This is a case of multiple determination, where the relevant chemical compound can play different (functional) roles. Moreover, the vitamin is multiply realisable, given that a number of vitamers can play the same functions and hence realise the kind. Vitamin B12, and more generally vitamins display a more complex form of evolutionary history compared to proteins. While for the latter, at least the primary structure can be related to genetic sequences and thus show a more direct evolutionary history, vitamins are instead introduced via nutrition. This makes their presence within biological processes not easily accounted for in terms of biosynthesis in the organisms that need them. This brings in interesting considerations in relation to the unification principles for biochemical kinds, which, we will argue, do not lie within the evolutionary history relevant for the function, but lie instead at the biochemical level.

There are three forms of considerations that we can make when exploring unification principles for biochemical kinds, granted the importance that biochemical functions play for the characterisation of these kinds. The first considers whether functions can be reduced somehow to the chemical level, and this would give us a chemical unification principle, instead of a biochemical one. The second considers whether functions can instead be unified in terms of evolutionary history or evolutionary mechanisms, providing a biological unification principle. The third, which seems to be the most plausible given the shortcomings of the previous two, considers biochemical functions as distinctive for biochemical kinds and locates their

unification principles at the biochemical level, providing evidence in favour of genuine biochemical kinds. Let us consider these options with the aid of vitamin B12.

As discussed in the previous sections, biochemical functions do not seem to be easily reducible to chemical properties, as they seem to bring in novel powers. This can be noticed in two ways. First, the powers associated with the biochemical function need to have undergone at least indirect selection. Second, the contribution that the kinds make is specific to the processes in which they take part. In the case of vitamin B12, the biochemical function to contribute to processes such as erythropoiesis is associated with powers that are selected in virtue of the evolutionary history of erythropoiesis and do not correspond to any chemical powers cobalamin has, but rather to distinctly biochemical powers. The causal specificity of the function can be accounted for only within the complex context considered, as specified in Bellazzi (2022). This suggests that we cannot identify a purely chemical unification principle for vitamin B12.

Having noticed the relevance of the evolutionary paths involved with biochemical functions, one might want to explore whether the evolutionary history of the given kind can provide a unification principle for these kinds. As already introduced in Sect. 2.2, evolutionary considerations are needed for the individuation of biochemical functions: these are associated with a specific set of chemical properties that are indirectly evolutionary selected in virtue of the biological processes these molecules contribute to. Let us then explore the possibility that a unification principle could be found in the indirect evolutionary path, with the case vitamin B12 in mind. An interesting feature of vitamin B12 is that in nature it is synthesised by very few organisms directly, and needs to be introduced by nutrition for all the others—despite the fact that its need is shared across many different species. This gives us a varied evolutionary history of the vitamin in relation to its biochemical function. In the case of organisms that synthesise vitamin B12 directly, the set of chemical dispositions relevant for the biochemical function can be identified by looking at the evolutionary history of these organisms. In the case of other organisms, studies in ecology and evolutionary biology have explored the evolutionary history of the auxotrophy (the inability of an organism to synthesise a particular compound required for its growth) of vitamin B12. This offers the chance to track an evolutionary explanation of the need for vitamin B12 in humans (and in other organisms) that considers the relevant connection between the evolution of humans, the relevant procaryotes, and their interaction. The variety in the evolutionary history that characterises the biochemical functions of vitamins can be used as a further reason to not consider such evolutionary history as a source of a possible unification principle: the evolutionary mechanisms that are involved and relevant for the function are much too varied. This can be further supported by the fact that biochemical kinds do not seem to display a direct form of evolutionary history, as summarised in Sect. 2.2. Let us consider this more in detail, by looking at the case of vitamin B12 synthesis and auxotrophy, as studied by Lawrence and Roth (1996) and Helliwell et al. (2011).

Vitamin B12 biosynthesis is confined to few prokaryotic species and this might support the possibility that the evolutionary paths that lead to such biosynthesis could be the same or that the species inherited the genes responsible for such biosynthesis from a common ancestor. This may offer the chance of finding some form of evolutionary unification principle. For instance, both *Salmonella typhimurium* and *Klebsiella pneumonia* are known to synthesise vitamin B12 *de novo* under specific anaerobic conditions (Lawrence & Roth, 1996). However, phenotypic data gained in studies regarding the evolution of the genes responsible for such synthesis strongly suggest that 'cobalamin synthetic genes in Salmonella taxa differ substantially from those present in other enteric bacteria', such as the ones of *Klebsiella pneumonia* (Lawrence & Roth, 1996: 19). This can be taken as evidence against the possibility of finding a common unification principle thanks to evolutionary history, as the genomes directly synthesising the vitamin display a varied and different evolutionary history across the species.

The situation is similar also when considering the case of vitamin B12 auxotrophy, as studied by Helliwell et al. (2011). As noted above, vitamin B12 is essential for a series of biological processes in humans and a similar need is found among algae, where half of the species require vitamin B12 for their growth. However, as for humans, the algae species considered do not synthesise vitamin B12 and, thus, display auxotrophy. Again, a unification principle for the properties of the biochemical kind vitamin B12 could be found in the evolutionary history of these algae. If the auxotrophy could be explained in terms of phylogenetic relations, then the indirect evolutionary selection of the biochemical functions could be provided for in these terms. This would support the presence of a unification principle at the biological level. However, these species do not share a phylogenetic relationship, as there is no common evolutionary history between the species (Helliwell et al., 2011). This suggests firstly that auxotrophy arose in different moments during the evolutionary history of these species. Secondly, and more relevantly for the purposes of the paper, this shows that the indirect evolutionary histories of the processes that require vitamin B12 are indeed different. Accordingly, evolutionary considerations on their own are not sufficient for establishing unification principles for biochemical kinds.

Biochemical kinds, such as vitamin B12, are instantiated in those chemical compounds that present a biochemical function. We have seen that this calls for a novel unification principle for such kinds. An appropriate characterisation of biochemical functions brings in two aspects that can be explored in the search for this unification principle. The first regards the chemical powers associated with the biochemical function. The second regards the evolutionary considerations that are needed in order to identify such functions, as the relevant chemical powers are at least indirectly evolutionary selected. As explored, these two aspects do not seem to provide the relevant unification principle on their own.

Accordingly, the most plausible option is that the relevant UP refers to the *biochemical functions* of these kinds. The biochemical functions unify the various aspects of biochemical kinds, allowing the multiple realisability and the multiple determinability of these kinds. Moreover, biochemical functions enable us to

combine both chemical and evolutionary considerations. More specifically, the biochemical functions are associated with powers that, on the one hand, are at least indirectly selected and cannot be directly accounted for in terms of the intrinsic properties of the macromolecule, and on the other, cannot be accounted for purely in terms of their evolutionary history. This seems to indicate that the UP lies specifically at the biochemical level, supporting the conclusion that biochemical kinds are genuine natural kinds and biochemical objects can be characterised as such.

2.6 Conclusion

In this paper, we have considered the question of whether biochemical objects constitute a distinct natural kind, and how their properties can be unified. As we have demonstrated, biochemical objects are interesting for questions regarding natural kinds more generally because they present biological and chemical features and accordingly biochemical kinds crosscut the distinction between the chemical and the biological. On the one hand, they can be understood just as any other molecule; on the other, they also have important physiological and biochemical functions. In this paper we aimed to answer three questions, concerning the unification of the chemical and functional properties of biochemical kinds, the distinctness of biochemical properties, and the identity-criteria of biochemical kinds. We focused especially on the first question, as this could represent a key part in any answer to the other two questions. Biochemical kinds seem to be characterised by a specific type of property, biochemical functions. These properties do not seem to be reducible to intrinsic chemical properties, as there are indirect evolutionary and contextual considerations that are needed in their identification. Moreover, given the difficulty of identifying a UP at the chemical level or at the biological level (the evolutionary history), the most plausible alternative may be that the UP for biochemical kinds is located at the biochemical level. Accordingly, the identity-criteria for biochemical kinds are closely associated with biochemical functions, which themselves involve two aspects. First, chemical considerations are needed, as biochemical functions are associated with given chemical powers of the molecule. Second, biochemical functions bring in complex evolutionary considerations, which often appear to be indirect.

The identification of a unification principle for biochemical kinds within the biochemical level has a series of benefits for how we think about “unconventional” objects. The first is that these objects do not have to be characterised as “dual” or disunified if they present apparently contrasting properties, such as biological and chemical properties. Thanks to a unified picture of biochemical kinds, it is possible to see that biochemical objects display unified properties. Moreover, this discussion has an impact on the identification of biochemistry as the discipline studying biochemical objects and kinds, and a philosophical account that supports the unification of such kinds can offer a theoretical framework for the discipline. The existence of genuine biochemical kinds offers further support to the autonomy of

the discipline. Lastly, these conclusions can shed further light on the relationship of the different domains involved in the study of these kinds, namely, biology and chemistry.

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