

The Case for Multiple Realization in Biology

Abstract: Polger and Shapiro argue that their *official recipe*, a criterion for judging when the phenomenon of multiple realization (MR) exists, renders MR less widespread than its proponents have assumed. I argue that, although Polger and Shapiro's criterion is a useful contribution, they arrive at their conclusion too hastily. Contrary to Polger and Shapiro, I claim that the phenomenon of multiple realization in the biological world, judged by their criterion, is not as scarce as they suggest. To show this, an *updated official recipe*, namely a multiple mechanistic realization thesis (MMRT), integrating Polger and Shapiro's criterion with a compositional conception of realization, is developed. Then, three examples of varied kinds are examined, showing that cases of MR are not so hard to find in the biological world.

1. Introduction

Very recently, the longstanding debate surrounding multiple realization (MR) has been substantially invigorated. Though many detailed scientific examples have been introduced and extensively discussed (Aizawa 2007, 2009, 2013; Gillett 2007, 2010), agreement has not been achieved. On the one hand, the existence of MR is still in dispute, because many authors either believe that multiple realization is metaphysically impossible (Kim 1992, 1999; Bickle 2003, 2010, 2013; Bechtel and Mundale 1999; Couch 2004; Klein 2013; Polger 2008, 2009), or is at most only epistemologically plausible (Clapp 2001). On the other hand, even if many authors grant the existence of MR, they disagree on how widespread cases of MR are. For example, some authors believe that it occurs in only a few cases (Shapiro 2000, 2004, 2008; Shapiro and Polger 2012; Polger and Shapiro 2016). Others think there might be more cases of MR than opponents have envisioned (Sullivan 2008). Still others believe that MR not only exists, but is

widespread (Sterelny 1996; Rosenberg 2001, 2006; Gillett 2002, 2003, 2007, 2010; Aizawa 2007, 2009, 2013; Aizawa and Gillett 2009a, 2009b, 2011; Richardson 2008; Piccinini and Maley 2014; Balari and Lorenzo 2015).

Among those who suspect the scope of MR, Polger and Shapiro's (2016) recent work deserves special attention. They have proposed a criterion for assessing supposed cases of MR, which they call the *official recipe*. Under the aegis of their official recipe, Polger and Shapiro's attitude towards MR can be described as twofold. On the one hand, they do not deny that there might be cases of MR in the biological world. On the other, they argue that, even if there exist cases of MR in the biological world, the phenomenon of MR might happen less commonly than many philosophers envision. However, though I appreciate the value of their recipe for clarifying thorny issues surrounding MR, I disagree with their verdict that their recipe implies that MR is probably quite rare. Instead, I think that their recipe renders MR less rare than they suggest, and that cases of varied kinds in the biological world are not hard to find. Thus, my disagreement with Polger and Shapiro comes down to their assessment of the scope of MR implied by their criterion, rather than their criterion itself.

Therefore, the goal of this essay is to show that, *pace* Polger and Shapiro, MR is not so hard to find in the biological world. To achieve this, the essay proceeds in two steps. First, it clarifies the concept of multiple realization by integrating Polger and Shapiro's official recipe with a compositional conception of realization, leading to an updated official recipe. Second, various biological examples are then examined to see if they count as cases of MR according to the updated official recipe. Specifically, the essay goes as follows. Section 2 discusses Polger and Shapiro's criterion for MR, namely their official recipe. Section 3 clarifies several issues surrounding the conception of realization and suggests a compositional alternative. Then, an *updated official recipe*, i.e., a mechanistic multiple realization thesis (MMRT) is developed in Section 4. Finally, three kinds of biological phenomena are examined to show if they could potentially constitute cases of MR.

2. Polger and Shapiro's Official Recipe

Shapiro's (2000) example of corkscrews is a good starting point for the discussion of MR. Suppose there are two corkscrews, one composed of steel and the other of aluminum. On the higher level,¹ one might say that, because a corkscrew is typically used for removing corks no matter what microstructures are involved, these two corkscrews have the same *property of being able to remove corks*. When moving to the level of microstructure, however, controversy arises. The pro-MRT side would say that since they have different microstructures, they have different micro-properties. Hence in this case, given that the two corkscrews have the same property of removing corks at the higher level, multiple realization ensues. However, the anti-MRT side would reply that, admittedly, there are indeed different micro-properties in these cases, but these are *irrelevant* to realizing the higher-level property of removing corks. Hence, a case of multiple realization is challenged.

Shapiro points out that, though the fact that one corkscrew is steel and the other is aluminum is irrelevant with respect to removing corks, other properties such as mechanical principles—i.e., the way corkscrews create friction on corks—are relevant. That is, Shapiro admits that if two corkscrews differ in mechanical principles, say one is a waiter's corkscrew and another is a winged corkscrew, then they realize the property of removing corks in different ways—thus this is a case of MR (2000, 644; also see Polger and Shapiro 2016, 61-67).

This brings us to the crux of the debate: on what grounds can we legitimately say that some properties P_1 and P_2 (instantiated in two individuals) are distinct realizations of property Q while others P_3 and P_4 are not? As the corkscrew case shows, this question cannot be straightforwardly answered. Instead, we need a

¹ Some philosophers may be skeptical of the talk of "levels", e.g., Potochnik and McGill (2012). However, since the talk of levels has a well-defined meaning through the essay (i.e., compositional organization), and this essay's argument does not hinge on the talk of levels, I will not address this dispute in the essay. I thank Jay Odenbaugh for letting me notice this dispute.

principled way to determine when a case of multiple realization is present. In this spirit, Shapiro offers a *causally relevant differences* criterion,² stating that

Multiple realizations count truly as *multiple* realizations when they differ in causally relevant properties—in properties that make a difference to how they contribute to the capacity under investigation. (Shapiro 2000, 644; author’s emphasis)

That is, without making causally relevant differences to the realized kind’s property, two property instances P_1 and P_2 cannot genuinely count as different realizers. Much clarification and refinement has occurred since this somewhat abstract criterion was first proposed (e.g., Shapiro 2008; Polger 2009; Shapiro and Polger 2012). Recently, the criterion has been refined by Polger and Shapiro (2016), using what they call the *official recipe* for MR. The recipe says that for a case to be MR it must satisfy the following four conditions:

- (a) P_1 and P_2 are of the same kind in model or taxonomic system S_1 ;
- (b) P_1 and P_2 are of different kinds in model or taxonomic system S_2 ;
- (c) The factors that lead the P_1 and P_2 to be differently classified by S_2 must be among those that lead them to be commonly classified by S_1 ;
- (d) The relevant S_2 -variation between P_1 and P_2 must be distinct from the S_1 intra-kind variation between P_1 and P_2 (adapted from Polger and Shapiro 2016, 68).

Conditions (a) and (b) jointly capture the requirement that, for MR to arise, two different realizers must realize the same property. Note that *sameness* and

² Shapiro is not the first to have proposed a “causally relevant differences” criterion. Shoemaker makes a similar point in his causal theory of properties, stating that two properties are different when they contribute different powers to the individuals in which they are instantiated when under the same conditions (Shoemaker 1980; Cf. Gillett 2010, 169). Kim’s principle of causal individuation of kinds also asserts that “kinds in science are individuated on the basis of causal powers; that is, objects and events fall under a kind, or share a property, insofar as they have similar causal powers” (Kim 1992, 17).

differentness are defined by different sciences; that is, the realizing properties are classified as the same or not using a taxonomic system S_2 in science B , and the realized properties are classified as the same or not using a taxonomic system S_1 in science A (Ibid., 26-32). Condition (c) captures the idea that MR requires P_1 and P_2 “to be not merely different, but to be ‘relevantly different’—to be different in ways that are relevant to their performing the same function” (Ibid., 68). The case of corkscrews illustrates this idea: the waiter’s and winged corkscrews are different in ways that are relevant to how they remove corks, while the steel and aluminum corkscrews are not different in these ways (Ibid., 68). Finally, condition (d) captures the idea that for MR to arise, the differences among realizers must be more than only individual variations (e.g., different colors in the corkscrew case); in other words, the differences must be big enough to classify two realizers as different kinds in terms of the taxonomic system S_2 in science B (Ibid., 69).

Notice that, since Polger and Shapiro regard the realization relationship as different from both compositional and constitutional relationships, they use P_1 and P_2 to refer to both the realizing and realized properties. In particular, they suggest that for a property P to realize another property Q , P must have the function *constitutive* of Q ’s, i.e., the Q -function (Ibid., 23).³ This view seems to assume a *flat* view of realization in contrast with a *dimensioned* view—I will return to this point in the next section. However, they add immediately that their theory of multiple realization does not depend on the correctness of their view of realization, since some other view of realization may better capture core characteristics of realization (Ibid., 23). In one footnote (Footnote 4 in Chapter 6), they add that their approach to MR does not make any assumptions about the right account of realization (Ibid., 122). Given this, I will suggest in the next section an alternative to their conception of realization, which I believe better captures the core of the realization relationship in the biological world.

³ With respect to the conception of function, they say that “for some entities—properties, states, kinds, objects—being that entity is a matter of *having* a certain function” (Polger and Shapiro 2016, 23; original emphasis).

With the official recipe in hand, we are now in a good position to evaluate when there is a case of MR and when there is no such case. However, before evaluating would-be cases of MR, we need to clarify several points concerning the concept of realization.

3. The Conception of Realization

This section attempts to clarify the following points regarding realization: (a) realization as a compositional relationship in the biological world; (b) realization involves different taxonomic systems defined by different sciences; and (c) the abstract way of talking about realization calls for flesh and blood.

3.1 Realization as a compositional relationship in the biological world

As Umut Baysan summarizes, the term “realization” refers to a number of different relationships in different cases, e.g., functional realization, determinable realization, subset realization, mereological realization, etc. (Baysan 2015). Of importance to the context of biology is the mereological realization, because a biological system (e.g., an organism, a tissue, a cell, a molecule, etc.) is typically characterized as a whole composed of parts located at the next, lower-level (Wimsatt 1976a, 1976b, 1994; Bechtel 2007). Other authors make slightly different distinctions about realization, with the biological system characteristically described by compositional or constitutional realization relationships which also concern the part-whole relationship (e.g., Fodor 1974; Boyd 1980; Kitcher 1984; Heil 1992, 1999; Sober 1999; Wilson 2001; Gillett 2002, 2003, 2007; Pereboom 2002; Craver 2004; Craver and Bechtel 2007; Aizawa 2007, 2009, 2013).

However, as mentioned in the last section, Polger and Shapiro disagree with the recognition that realization can be characterized as compositional. More specifically, they claim that realization is a kind of *ontological dependence* relationship, meaning that “the dependent thing would not exist (or would not

exist as the kind of thing it is) without the existence of that on which it depends” (Polger and Shapiro 2016, 19-20). For example, “a desk would not exist if the desktop and legs did not exist—the existence of the desk depends on the existence of its parts, the desktop and legs” (Ibid., 20). Moreover, the realization relationship is *synchronic* (in contrast with the causal relationship which is diachronic) and *constant* (for instance, “current psychological states ontologically depend on current brain states and do so continually for as long as they persist” (Ibid., 20)).

Nevertheless, it seems unclear how a compositional relationship cannot constitute one type of ontological dependence relationship. To begin with, it is commonly agreed that the compositional relationship is one kind of ontological dependence relationship (Sober 1999; Aizawa and Gillett 2009a; Baysan 2015). More importantly, even leaving the agreement aside, it is not difficult to find that the compositional relationship shares key characteristics with the realization relationship, e.g., ontological dependence, synchronic and constant. For example, it is legitimate to say that a desk is composed of its desktop and legs (such that the desk would not exist without the existence of the desktop and legs), and that this compositional relationship is clearly synchronic and constant. In addition, since we restrict our focus to the biological world, which is typically characterized as a hierarchy of organizational levels within which a system at a higher-level is composed of its parts at a lower-level, I think it is appropriate to view the realization relationship in the biological world through the compositional (mechanistic) lens.⁴

⁴ Note that this is by no means denying that there might be other kind of realization in the biological world, e.g., functional realization. Functional realization may have different forms depending on what one means by function. For example, it might refer to the evolutionary history of the function through which that function was selected, or the causal process in which one thing is caused or causing other things, etc. For a discussion of functional realization see Polger (2004). However, given that concentrating on compositional realization is sufficient to show that the biological world is abundant in the phenomenon of multiple realization, this essay will not consider other potential kinds of realization.

Within the category of compositional realization, mechanistic realization constitutes a special kind pertaining to the context of biology (Craver 2004; Aizawa and Gillett 2009b; Haug 2010): a biological system capable of manifesting a certain function (or property) is typically described as having an underlying mechanism for explaining that function (Machamer et al. 2000). Hence, throughout this essay when referring to compositional realization I denote mechanistic realization.

3.2 A consensus: Realization involves different taxonomic systems

As has been made very clear by Polger and Shapiro, evaluating cases of MR involves comparing different taxonomic systems defined by different sciences. That is, as discussed in Section 2, to count as a genuine case of MR, the realizing properties must be classified as different kinds by a taxonomic system S_2 in science B , and the realized properties must be classified within the same kind by a taxonomic system S_1 in science A (Polger and Shapiro 2016, 26-32). Other authors from the anti-MRT side seem to agree with Polger and Shapiro (e.g., Couch 2004; Polger 2008). Note that these disputants also seem to agree that the realized properties can be broadly construed as functions or functional kinds, where a function denotes what a property, state, kind, or object can do (Polger and Shapiro 2016, 22).

Interestingly, this construal suits the pro-MRT side's taste. Charitably read, Fodor's central idea concerning MR can be understood that lower-level properties *defined by lower-level sciences* are of disparate kinds while higher-level properties *defined by higher-level sciences* are of supposedly homogenous kinds (Richardson 2008, 530). Robert Richardson, another proponent of the MRT, says that

In the end, lower-level properties are not the same *kinds*, construed in terms of theories pitched toward the lower level. However, assuming there is an articulated and defensible higher-level theory, the corresponding higher-level properties are of a unified—perhaps homogeneous—kind, in terms articulated by the appropriate higher-level theory. [...] Much

depends here on talk of levels of organization and on talk of levels of theory. (2008, 530; author's emphasis)

In sum, there seems to be a consensus between both sides: there is a case of multiple realization when and only when a (functionally defined) property/kind Q classified by a taxonomic system in a higher-level science/theory Y can be multiply realized by distinct properties/kinds P_1, P_2, \dots, P_n classified by a taxonomic system in a lower-level science/theory X . For simplicity, in what follows I will only claim that for there to be a case of MR, a property Q in a higher-level science Y can be multiply realized by distinct properties P_1, P_2, \dots, P_n in a lower-level science X . However, as we shall see in the next sub-section, this way of putting the consensus is still too abstract.

3.3 *The full-fledged form of realization*

The third point crucial for understanding realization concerns the *flesh-and-blood* form of realization. It is characteristically claimed that a property P realizes a property Q (Putnam 1967; Fodor 1974; Kim 1992; Shapiro 2000). However, this is actually a shorthand way of talking about realization. As Shoemaker says, “to speak of one property as realizing another is shorthand for saying that instances of one are among the possible realizers of the instances of the other” (2007, 3). Hence, there seems to be two ways of talking about realization: (a) a property P realizes a property Q , and (b) an instance of a property P instantiated in an individual S_i realizes an instance of a property Q instantiated in an individual S_j (Baysan 2015, 249). In the context of biology, an individual usually stands for a biological system, which is typically composed of individuals at a lower-level.

Integrating these considerations together and assuming Shoemaker's casual theory of properties,⁵ we obtain a more detailed way of talking about compositional realization in the biological world:

⁵ According to this theory, a property is individuated by the causal powers it contributes to the individual in which it is instantiated (Shoemaker 1980, 109-135).

Property instance(s) p_1-p_n realize a property instance Q in an individual S , if and only if S has the causal powers of Q in virtue of the causal powers that are contributed by p_1-p_n to S or S 's component(s), but not vice versa (adapted from Gillett 2003, 594).

Note that property instance(s) p_1-p_n are instantiated in individuals e_1-e_n that are components of the individual S . This way of talking about realization can be expressed in Figure 1 below:

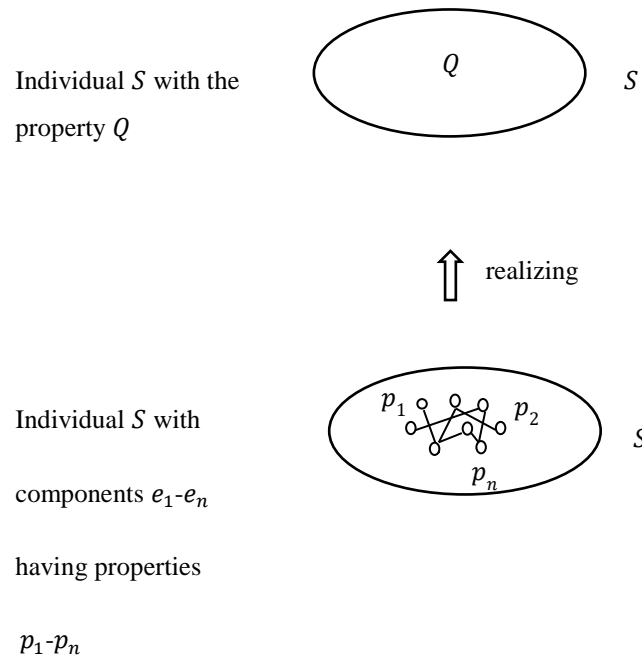


Figure 1. An individual S made up of components e_1-e_n has the property Q .

Figure 1 uses two big ellipses to describe *component properties* and realized properties p_i and Q respectively, to highlight the idea that p_i and Q are not necessarily instantiated in the same individual S . For example, p_1 may be instantiated in individual e_1 but not in individual S , while Q may be only instantiated in S but not in e_1 . Furthermore, the lower ellipse in Figure 1 contains

a number of small ellipses standing for the components of the individual, indicating that these elements may have their distinctive properties p_1 - p_n that cannot be found in individual S .

This conception of realization draws on the *dimensioned view* suggested by Carl Gillett (2002, 2003, 2010), which is contrasted with the *flat view* accepted as a default position among major disputants (e.g., Kim 1998; Shoemaker 2001). The dimensioned view differs from the flat view in two substantial ways: (a) it holds that the realized and realizer properties are not necessarily instantiated in the same individual, e.g., a diamond has the property of hardness, while components of the diamond, i.e., carbon atoms, have the properties/relations of being bonded and aligned with one another; (b) it holds that the causal powers of the realized property do not necessarily match the causal powers of the realizer properties, e.g., the diamond has the causal power of scratching glass, while the carbon atoms have the power of causing a contiguous carbon atom to remain in a certain position and in a certain direction.

So far, we have filled in the details for the shorthand way of talking about realization. Nonetheless, we may notice that the realizing property P seems to be missing in the detailed way of talking about realization—i.e., instead of P , we only have a set of properties p_1 - p_n associated with the components of the individual. So, where can we obtain the realizing property P ? My answer is that it comes from the particular way an individual is composed of. More specifically, a realizing property concerns two aspects of an individual: (a) components of the individual, and (b) organization of these components. Therefore, a realizing property is determined by two sets of properties: (a) properties of the components of the individual, and (b) organizational properties of these components.

Understood in this way, the implication is threefold. First, we now know that the realizing property is also a shorthand way of talking about the *collective property* arising from the way an individual is made up of. Second, given the first point, it follows that the differences in the realizing property may be tracked back to the differences in the properties of the components of the individual and/or differences in the organizational properties of these components. Third, given the

second point, this understanding informs us of how to judge cases of multiple realization: to judge whether a property is multiply realized by two (or more) different properties, we first must decide if the components involved in the two individuals are classified as different or not, and then decide if the organizations of the components of the two individuals are classified as different or not. However, in light of Polger and Shapiro's recipe, to judge cases of MR we must also be careful if the differences in the realized properties are only intra-kind variations or inter-kind disparities, and if the differences in components and/or differences in organizations matter to how the realized properties are realized, i.e., if they are relevant differences.

In sum, in filling in the details for the shorthand way of talking about realization, and especially in filling in the details for the talk of the realizing property, we obtain a full-fledged way of talking about realization: realization consists in how a realizing property arising from the way an individual is made up of realizes a property of the individual itself.

4. Multiple Mechanistic Realization and Case Studies

Recall the core of Polger and Shapiro's recipe: for there to be a case of MR, two realizers must be classified as different kinds by a taxonomic system S_2 in science B , and the realized properties must be classified within the same kind by a taxonomic system S_1 in science A . Integrating this recipe with the full-fledged way of talking about realization, we obtain an updated official recipe, namely a multiple mechanistic realization thesis (MMRT):⁶

(MMRT): a case is an example of multiple mechanistic realization, *iff*:

⁶ This definition draws heavily on Aizawa and Gillett's account (2009a, 2009b), though this account differs in two substantial ways: (1) it makes clear that realization in the biological world is mechanistic realization (i.e., a type of compositional realization); and (2) it attempts to integrate Polger and Shapiro's criterion for MR.

- (1) there are at least two individuals S_1 and S_2 that are classified into different kinds by a lower-level science X ,⁷
- (2) S_1 is composed of entities e_1, e_2, \dots, e_n , organized in a certain way M , S_2 is composed of entities f_1, f_2, \dots, f_n , organized in a certain way N , and $e_1, e_2, \dots, e_n \neq f_1, f_2, \dots, f_n$ (meaning that the set $\{e_1, e_2, \dots, e_n\}$ is distinct from the set $\{f_1, f_2, \dots, f_n\}$), and/or $M \neq N$,
- (3) S_1 and S_2 manifest the same property Q or *similar* properties Q_1 and Q_2 respectively,⁸
- (4) there is a higher-level science Y ($Y \neq X$) that classifies Q_1 and Q_2 as being of the same kind Q , and classifies S_1 and S_2 as members of the same kind S in virtue of property Q (or similar properties Q_1 and Q_2) they manifest, and
- (5) the differences between e_1, e_2, \dots, e_n and f_1, f_2, \dots, f_n , and/or between M and N are *relevant* to how S_1 and S_2 realize Q (or Q_1 and Q_2).

Obviously, the MMRT satisfies all conditions of Polger and Shapiro's criterion: (I) S_1 and S_2 are of the same kind in a higher-level science Y ; (II) S_1 and S_2 are of different kinds in a lower-level science X ; (III) the factors that lead S_1 and S_2 to be differently classified by X are those that lead them to be commonly classified by Y , because it is the *relevant differences* between e_1, e_2, \dots, e_n and f_1, f_2, \dots, f_n , and/or between M and N that lead S_1 and S_2 to be differently classified by X (since these differences lead to inter-kind disparities in X) and to be commonly classified by Y (since these differences merely lead to intra-kind variations in Y);

⁷ Note that properties and kinds are two different concepts. However, I sometimes use kinds to mean that something has a property P such that, due to having this property, it is classified into the kind X . I thank Patrick McGivern for alerting me to the difference between them. Also notice that we here do not use the shorthand way of talking about realization (i.e., property P realizes property Q), but rather use the full-fledged way introduced in Section 3.3 (i.e., individual S_i as a realizer realizes property Q).

⁸ "Have the similar property" should be understood as having the same property with different property-values, e.g., being crimson and being scarlet are different property-values of being red. I thank Jay Odenbaugh for helping me clarify this point.

(IV) as implied by (III), the relevant X -variations between S_1 and S_2 are inter-kind disparities, whereas the Y -variations between S_1 and S_2 are intra-kind variations, so these are two distinct types of variations.

Looking closely, it may be seen that the MMRT allows three different ways of obtaining multiple mechanistic realization: (MMR1) if S_1 and S_2 are composed of two different kinds of entities and these different kinds of entities are organized in the same way, and the different kinds of entities matter to how S_1 and S_2 *differently* realize a *common* property Q ; (MMR2) if S_1 and S_2 are composed of the same kind of entities and these entities are organized in different ways, and the different organizations matter to how S_1 and S_2 *differently* realize a *common* property Q ; and (MMR3) if S_1 and S_2 are composed of different kinds of entities and these different kinds of entities are organized in different ways, and both the different kinds of entities and different organizations matter to how S_1 and S_2 *differently* realize a *common* property Q .⁹

Due to limitations of space, examining the second and third types (i.e., MMR2 and MMR3) might be sufficient for our current purposes, namely establishing that MMR is not difficult to find in the biological world. The way to do this is to see whether MMR2 and MMR3 can be readily found in the biological world. Three different kinds of cases involved in different areas of investigation will be scrutinized, one concerning neural plasticity in neuroscience, one concerning enzymes in biochemistry, and one concerning respiration in physiology. The first two examples are proposed as cases of MMR2, while the last is proposed as a case of MMR3.

4.1 Neural plasticity

This example comes from Polger and Shapiro (2016, 90-98). The reason for re-examining this example is simply that I think Polger and Shapiro's analysis of the

⁹ Piccinini and Maley also make this distinction (2014, 137-141).

example is problematic.¹⁰ Let us turn to their example. There is one form of neural plasticity called cortical functional plasticity, referring to the phenomenon in which “whole areas of the cortex seem to perform different tasks at different times or in different subjects” (Ibid., 90). One case in point is that of “rewired” ferrets:

The standard pathway from the ferret’s eye to its visual cortex travels through the lateral geniculate nucleus and the lateral posterior nucleus. Von Melchner et al. (2000) redirected retinal axons from the right visual field that usually project to these areas, connecting them instead to the medial geniculate nucleus, which innervates the audio cortex. Thus, the ‘rewired’ ferret’s auditory cortex received visual information from the ferret’s right visual field. (Polger and Shapiro 2016, 92)

One important difference between the normal visual cortex (NVC) and normal auditory cortex (NAC) is that they show substantially different forms of organization:

Within visual cortex, groups of cells are arranged into orientation columns, with each column of cells especially tuned to specific orientations of stimulus (Sharma et al. 2000). Moreover, the visual cortex contains a 2D map of the retina, with each point on the retina corresponding to a point on this map. In contrast, the auditory cortex contains no columns of orientation-sensitive cells. Nor does it contain a 2D map of auditory space. Rather, the cochlea maps onto a 1D map in auditory cortex and neurons in auditory cortex are grouped in clusters that receive excitation from both ears, or excitation from one ear and inhibition from the other (Roe et al. 1990). (Polger and Shapiro 2016, 92)

One surprising thing happened after scientists performed the operation on the visual and auditory cortices: the “rewired” ferrets regained vision in their right visual fields:

¹⁰ There is another reason for re-examining Polger and Shapiro’s example: it is meant to show that the examination of various examples in this essay does not proceed in a cherry-picking way, only selecting cases in favor of my position while ignoring cases speaking against my position.

The ferrets that had been trained to respond in one way to an auditory stimulus and another to a visual stimulus displayed the visual response to stimuli presented to their right visual fields (von Melchner et al. 2000). Rewired ferrets were also tested for their visual acuity, and they were able to discern gratings of various frequencies and at various contrasts. In short, the rewired ferrets appear able to see with their auditory cortex. (Polger and Shapiro 2016, 92-93)

So far, the case being discussed suggests that this is a case of MMR, for it satisfies all conditions of MMR2. That is: (1) the normal visual cortex (NVC) and rewired auditory cortex (RAC) are classified as being of two different kinds in a lower-level science (e.g., neuroscience); (2) the NVC and RAC have substantially different organizations; (3) the NVC and RAC manifest the same or similar visual capacities; (4) going one level higher, i.e., the eye level, the NVC and RAC are classified as being of the same kind (suppose, e.g., there is such an “eyelike”-kind defined by visual capacities) in terms of their common visual capacities; and (5) the differences between the organization of the two cortices are relevant to how they realize their respective visual capacities.

Assessing whether our case meets condition (5), however, requires further analysis. The rewired ferrets were able to see with their RAC, but did not do so as perfectly as the normal ferrets. For example, when placed under test conditions, “the rewired ferrets show significant degradation in their discriminatory ability, being unable to detect gratings at lower contrasts or higher spatial frequency than the normal ferrets” (Polger and Shapiro 2016, 95). This difference in discriminatory ability is due to that the RAC is an imperfect machinery with respect to *seeing things*, and it is the internal organization of the RAC that makes the machinery less perfect than the NVC.

Nevertheless, Polger and Shapiro do not think this is a case of MR. Their argument has two main parts. To begin with, due to the difference in discriminatory ability of the RAC and NVC, Polger and Shapiro think it is illegitimate to classify their visual capacities as being of the same kind. Rather, the visual capacities of the rewired and normal ferrets belong to two different kinds, so that the case in question is not a case of MR. They claim that “If visual processing in the visual and auditory cortices were indeed the same, we should

expect the normal and rewired ferrets to perform *identically* in discrimination tasks” (Ibid., 95; my emphasis).

I disagree, however. First, recall Polger and Shapiro’s recipe, according to which the realized property or kind should tolerate intra-kind variations. As a consequence, it is not to be expected that all members of a kind manifest exactly the same or *identical* property. The intra-kind variation is a matter of degree, while being identical or not is an all-or-nothing issue. Therefore, insofar as the rewired ferrets had visual capacities, though not as perfect as the normal ferrets, it remains unclear why we should not classify them as being of the same kind as the normal ferrets. Second, aside from the type of intra-kind variations in the rewired ferret case, other types of intra-kind variations are numerous. For example, a doddering ferret’s visual capacities might not function as perfectly as that of a younger ferret (e.g., the doddering ferret, when performing the test, is unable to detect gratings at a lower contrast or higher spatial frequency). Also, a shortsighted ferret’s visual capacities may well be remarkably worse than that of a normal-sighted ferret, with the shortsighted ferret performing very poorly in detecting gratings at lower contrasts or higher spatial frequencies than the normal-sighted ferret, and so on. Hence, if we classify the visual capacities of the rewired and normal ferrets as being of different kinds, nothing can prevent us from classifying the visual capacities of the doddering and younger ferrets as being of different kinds, much less prevent us from classifying the visual capacities of the shortsighted and normal-sighted ferrets as being of different kinds.

In addition, there is another reason for holding that the visual capacities of the rewired and normal ferrets are of the same kind. In Section 3.2 we noted that disputants in the debate seem to agree that the realized properties can be broadly construed as functions or functional kinds, where a function denotes what a property, state, kind, or object can do (Polger and Shapiro 2016, 22). Also recall Shapiro’s example of the waiter’s and winged corkscrews where they are classified as being of the same kind at the higher-level because they both *can remove* corks, though they may do so with different efficiency. Conforming to this agreement and illuminated by Shapiro’s example, we have no good reasons to

classify the visual capacities of the rewired and normal ferrets as being of different kinds given that they can do the same thing, i.e., seeing, though with different degrees of perfection.

In short, the differences between the normal ferrets (i.e., doddering, younger, shortsighted and normal-sighted ferrets) and the differences between the rewired and normal ferrets are of the same kind with respect to the function of seeing: intra-kind variations. Nonetheless, one may point out that underneath the intra-kind variations among the various normal ferrets, there might also exist inter-kind variations, as do in the case of the rewired and normal ferrets (I will discuss this latter point in the following). That is, the underlying neural details of the various normal ferrets differ in kind. This might be true, and much more empirical work is required to confirm this. However, even if this turns out to be true, this line of reasoning goes in favor of my position because it entails cases of MR. But for my current purposes, we only need to consider Polger and Shapiro's second major argument concerning whether the rewired and normal ferrets count as two different kinds with respect to realizing the function of seeing.¹¹

Polger and Shapiro's second major argument is that, since there is a tendency that the "the auditory cortex in the rewired ferrets appears to be trying its best to turn itself into a visual cortex for purposes of processing the information it receives from the retina" (Ibid., 97-98), the differences in the RAC and NVC may be not large enough to classify them as being of different kinds. In particular,

What one notices when examining the auditory cortex of a rewired ferret is a cortex structured something like a normal auditory cortex, but also something like a normal visual cortex (Sharma et al. 2000). Thus, the rewired auditory cortex displays columns of orientation-sensitive cells, just as normal visual cortex does. It also contains regions that bear horizontal connections to each other, as do regions in visual cortex. (Polger and Shapiro 2016, 96)

¹¹ I thank an anonymous referee for suggesting me comparing the similarities and dissimilarities between the various normal ferrets and the similarities and dissimilarities between the rewired and normal ferrets.

Nonetheless, the RAC is not exactly the same as the NVC, for

[...] whereas one finds a great number of orientation maps in visual cortex that resemble something like a pinwheel, in rewired auditory cortex the density of these maps is far lower. Moreover, the volume of the regions of orientation-sensitive cells in rewired auditory cortex is much larger than the volume of these regions in visual cortex. (Ibid., 96)

Given these similarities and dissimilarities, Polger and Shapiro claim that “To the extent that they do realize visual processing, they also resemble the structure of visual cortex. Correlatively, to the extent that their physical organization diverges from visual cortex, they fail to process visual information as successfully as visual cortex does” (Ibid., 98). In other words, it is the lower-level similarities that result in the higher-level similarities, and it is the lower-level dissimilarities that result in the higher-level dissimilarities. Therefore, this is not a case of MR.

In response to Polger and Shapiro’s argument, I have two rebuttals: in terms of our updated official recipe, (a) the RAC and NVC do constitute two different kinds, and (b) it is not the case that similarities result in similarities while dissimilarities result in dissimilarities. For the first, let me examine Polger and Shapiro’s example more closely. Polger and Shapiro claim that there are organizational similarities between the RAC and NVC, because the RAC also displays columns of orientation-sensitive cells, and contains regions that bear horizontal connections to each other. There are two features that influence the organization of the cortex: orientation preference and horizontal connections. For the first feature, Sharma et al. state that the two cortices contain a pinwheel organization, though the density of pinwheel centers in the RAC is one-quarter of that present in the NVC (2000, 842). For the second feature, however, the situation becomes more complex. It is true that the RAC also contains regions that bear horizontal connections to each other, but key features of horizontal connections such as cell aggregation and sizes of cell patches differ in these regions between the RAC and NVC.

Cell aggregation is an important index in scientific practice, used to measure the extent to which cells are clumped into patches or are randomly distributed

(Ibid., 845; see also Ruthazer and Stryker 1996). Sharma et al. show that cell aggregation in the RAC is larger than in the NAC but smaller than in the NVC (Ibid., 845). That is, the RAC stands somewhere in between the NAC and NVC with respect to the property of cell aggregation. Moreover, the size of cell patches in the RAC is larger on average than that of the NVC but smaller than that of the NAC (Ibid., 845). Thus, given the differences in the two sub-features of horizontal connections, it seems that the RAC stands somewhere in the middle of the NVC and NAC. This conclusion is in concert with Polger and Shapiro's claim that "What one notices when examining the auditory cortex of a rewired ferret is a cortex structured something like a normal auditory cortex, but also something like a normal visual cortex" (2016, 96).

Let us dwell on the critical sub-feature, i.e., cell aggregation, a little bit longer. Since neurons are connected with one another (directly or indirectly) and it is basic practice in science to represent linked neurons as neural networks (Martindale 1991; Wu and McLarty 2000; Heaton 2015), an alternative way to stress the importance of cell aggregation is to look at how scientists approach neurons through tools provided by network biology. In network biology, the clustering coefficient C_l , as an important topological characteristic (Mostafavi et al. 2011, 399; also see Gursoy et al. 2008), is a tool used to measure cell aggregation (Barabási and Oltvai 2004). Moreover, differences in topological characteristics matter for functioning, connecting or collaborating with other networks, and even matters for the evolution of the networks in question (Barabási and Oltvai 2004).

From the perspective of network biology, we might say that, because cell aggregation in the RAC is smaller than in the NVC and larger than in the NAC, the RAC shows a topology differing from both of the other two cortices, enabling it to constitute a distinct network. However, one may point out that the topological characteristic constitutes a continuum, entailing that there is no nonarbitrary reason to classify one topology as belonging to one category but not the other. I think this is true, and, confronted with this problem, we only have three options. First, we classify all three cortices into one kind. However, this is

clearly inappropriate, for we all agree that the NAC and NVC are two different kinds. Second, we classify the RAC and NVC into one kind. Yet, this move is also inappropriate, for, given that the RAC stands in the middle of the other two cortices, the reason to classify the RAC and NVC as being of the same kind is also a reason to classify the RAC and NAC as being of the same kind. Hence, all three cortices collapse into one kind again. Our final option, which I think is the most plausible option, therefore, is to classify the RAC as being of a distinct kind, i.e., an intermediate kind differing from both of the other two.

Now let us turn to my second rebuttal: it is not the case that similarities result in similarities whereas dissimilarities result in dissimilarities. *Prima facie*, a proponent of MR must face the challenge that the RAC and NVC do have some lower-level similarities, and that it seems that these similarities result in the higher-level similarities. However, first, we must not conflate two different types of similarities. Recall that we both agree that whether the degree of similarities or dissimilarities at one level constitutes intra- or inter-kind variations must be judged by the relevant taxonomic system at that level. As discussed in the first rebuttal, from the perspective of neuroscience the neural-level dissimilarities (i.e., their topological disparities) between the three cortices outweigh their similarities at this level such that we classify them as different kinds. By contrast, from the perspective of the 'eyes-science' the similarities at the 'eyes-level' outstrip the dissimilarities at that level so that we classify the three cortices as the same kind. Therefore, considering the relationship between the two taxonomic systems employing different criteria of similarity or dissimilarity, it is inaccurate to say that it is the similarities at the neural-level that result in the similarities at the 'eyes-level'.

Second, and more importantly, the view that it is the similarities at the lower-level that result in the similarities at the higher-level whereas it is the dissimilarities at the lower-level that result in the dissimilarities at the higher-level reflects an oversimplified image of the biological world. Though it might be conceptually possible to draw such a similarity-dissimilarity mapping relationship across levels, that is, similarities at the lower-level map to (e.g., result in)

similarities at the higher-level while dissimilarities at the lower-level map to (e.g., result in) dissimilarities at the higher-level, it is impossible to do so in reality. This is simply because a biological system is not composed of a set of storage boxes in which this item is put here and that one is put there and among which there are clear-cut boundaries. Rather, the biological system is a causally connected network in which the similarities and dissimilarities at the lower-level may interact with one another in a way that contributes to the realization of a function. As a result, the function that arises cannot simply be traced back to the shared parts of the two systems since the unshared parts of the systems are not causally insulated from the shared parts—they may also be involved in realizing the function in question.¹² Therefore, in our case of visual cortices, insofar as there are causally relevant dissimilarities at the neural level that are involved in realizing the function of seeing at the higher-level, the case accords with Shapiro’s criterion for MR that the differences should be causally relevant to the realization of the function and thus counts as a case of MR. The next section will return to this point when discussing MR in enzymes.

In sum, we have seen that Polger and Shapiro’s denial of the example of rewired ferrets classifying as a case of MR fails. For one, since the variations of visual ability in the RAC and NVC are merely intra-kind variations in a science of ‘eyes’, it is better to consider the two cortices as being of the same kind. For two, because the RAC and NVC constitute two distinct neural networks in terms of their respective topological characteristics, it is better to classify them as being of different kinds through the lens of neuroscience. Moreover, the differences in the neural networks are causally relevant to the realization of the same function. Therefore, the example is a case of MR.

¹² Note that the inter-level realization scenario described here differs from the intra-level causation scenario, because in the latter case a difference in effect can in principle be tracked back to a difference in cause and thus there does exist such a similarity-dissimilarity mapping. Exploring how the similarity-dissimilarity mapping does not arise in the non-causal, inter-level realization case, however, must wait for another occasion.

4.2 Enzymes: transformational analogues

We now consider a case concerning enzymes from biochemistry, one that also instantiates MMR2. There is one mode of convergent evolution called *transformational analogues*,¹³ which refer to non-homologous enzymes that catalyze exactly the same or similar reaction but may use different mechanisms (Gherardini et al. 2007). One case in point is about two non-homologous enzymes, pyruvate formate lyase (PFL) and biosynthetic thiolase (BT):

The crucial active-site residues in both enzymes are two cysteine residues which can be superimposed with a RMSD of 1.3 Å. In both reactions the first step comprises a nucleophilic attack by a cysteine, which leads to the formation of an acyl-thioester intermediate. The intermediate is subsequently cleaved by another nucleophilic attack performed by a compound activated by the other active-site cysteine. *While the overall strategy is similar the details of the reactions are quite different: biosynthetic thiolase uses standard acid/base chemistry, while pyruvate formate lyase uses radical chemistry.* (Gherardini et al. 2007, 825; my emphasis)

Prior to going further, some conceptual clarification must be in place. To describe an enzyme's function, one needs to consider the transformation it performs (Ibid., 818). The transformation is typically described via the Enzyme Commission (EC) classification, in which each enzyme is assigned a four-digit EC number with the first number describing the overall chemical reaction the enzyme catalyzes and the rest embodying different meanings (Ibid., 818).¹⁴ Thus, if some non-homologous enzymes perform exactly the same or similar transformation, then

¹³ Note that here convergent evolution constitutes an important source for MR to emerge. However, there might be other ways for MR to arise, e.g., parallel evolution, evolution by chance, divergent evolution, etc. For a discussion of how divergent evolution could modify the active sites of certain enzymes but the enzymes modified can still perform the same or similar function, see Gerlt et al. (2001), Todd et al. (2001) and Bartlett et al. (2002). I thank an anonymous referee for letting me notice this point.

¹⁴ For a discussion of the EC number, see Webb (1992).

they are transformational analogues and their transformation is expressed by the same four-digit EC number.

It is discovered that PFL and BT perform exactly the same chemical transformation, i.e., the transformation has the same four-digit EC number, and for this reason they are grouped into the same enzyme superfamily (Ibid.). Now we say that PFL and BT perform the same function, i.e., the same chemical transformation. However, the mechanisms involved in PFL and BT when performing the function differ. First, the structures (or organizations) of PFL and BT are not the same: although the active sites of the two enzymes both contain two cysteine residues crucial for the functioning of the enzymes, their locations in each enzyme are different (Figure 2). As can be seen in the figure below, the active site of PFL contains Cys89 and Cys378, and BT contains Cys418 and Cys419, where the number denotes the location of an amino acid residue in a protein. In other words, the active sites of the two enzymes are organized in different ways. More importantly, when performing the same transformational function, PFL and BT employ two entirely different strategies causally responsible for the transformation, the former involving standard acid-base reaction while the latter involving radical reaction.

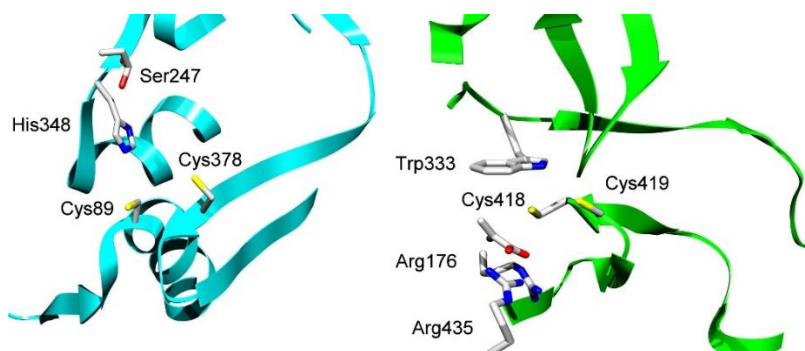


Figure 2. The active sites of PFL and BT. This figure comes from Gherardini et al. (2007, 826).

Therefore, this seems to be a case of multiple realization according to the MMRT. More specifically, (1) PFL and BT are classified as being of two different kinds in a lower-level taxonomic system due to their differences in chemical mechanisms when performing the chemical transformation; (2) PFL and BT have different

organizations (i.e., active sites); (3) PFL and BT manifest exactly the same transformational function (recall the same four-digit EC number); (4) going a level higher, PFL and BT are classified as being of the same kind/family in terms of their common transformational function; and (5) the differences in the organizations of PFL and BT, and in the chemical mechanisms involved are relevant to how they perform the transformational function.

Before proceeding to the next section, consider what an opponent of MR would say. She might say that, to support a genuine case of MR, one must show that with respect to the biological function these enzymes perform, the structures and/or mechanisms of these enzymes do not share *any* property that is in some sense essential to the function in question. So, our case fails to satisfy this requirement for PFL and BT have one thing in common: they both have two cysteines at their active sites, and therefore it is not a case of MR. Nevertheless, I find this requirement too demanding and flies in the face of Shapiro's *causally relevant differences* criterion discussed in Section 2. The spirit of the criterion is that for two things to be different realizers of a property or function, they should contribute causally relevant differences to the realization of the property or function. The criterion implies that there should *exist* some causally relevant differences with respect to realizing the function in question, rather than that the two things should not share *any* property essential to the function in question. In other words, the criterion implies that, even if two things share some property essential to the function, they can still count as two different realizers as long as they possess some different properties respectively that are also essential to realizing the function in question.

The too-demanding requirement also assumes an oversimplified picture of the biological world discussed in the previous section, where things either share no property at all yet surprisingly realize the same function or share all important properties and thus unsurprisingly realize the same function. Within these two extremes, we find that, in consonance with Shapiro's criterion, there exists a more dappled sphere where things both share some essential properties and do not share some also essential properties, and they do so in such an orchestrated way that

these similarities and dissimilarities collectively causally contribute to the realization of the same or similar function.¹⁵ The case of PFL and BT is just such a middle ground example, in which PFL and BT both share some essential properties, e.g., their active sites involve two cysteines, and do not share some essential properties, e.g., the organizations of their active sites and their chemical mechanisms are different. How exactly nature could orchestrate these similarities and dissimilarities in a meaningful way, however, is an empirical question for which much work has been done (e.g., Wright 1972; Galperin et al. 1998; Hegyi and Gerstein 1999; George et al. 2004; Gherardini et al. 2007).

To conclude, we have here another case of MMR associated with transformational analogues. Furthermore, given that transformational analogues constitute a common phenomenon in the biological world, it should not be surprising to generalize that we have found a large category of MMR cases, rather than a single case of MMR (see Gherardini et al. (2007) for a discussion of the scope of transformational analogues).¹⁶

4.3 Respiration

The Antarctic hemoglobinless icefish, also called Channichthyidae, is regarded as a unique model for adaption because they do not have the essential-life oxygen-binding protein: hemoglobin (Hb), and some also lack another essential-life protein: cardiac myoglobin (Mb)—these proteins are essential for animal respiration (Feller and Gerday 1997; Tota et al. 1997; Garofalo et al. 2009). However, given their lack of Hb and Mb, they have been surviving very well in

¹⁵ This is not denying that there might exist the extreme case of MR where things sharing no essential property at all could realize the same function. However, though this might be the case, this paper only needs to meet the more moderate goal that there exist middle ground cases where things that both share some essential properties and do not share some essential properties can realize the same function.

¹⁶ Note that the concern here is not with the amount of transformational analogues but with the frequent occurrences of their associated functions. I think one anonymous referee for helping me clarify this.

the deep Antarctic oceans with the low temperature ranging from -2.2 to 8 °C (Feller and Gerday 1997, 981). Hence, a scientific question arises: how can the icefish carry out the function of respiration if they do not have the oxygen-binding protein Hb (and Mb)? The answer is that the lack of both kinds of proteins has been compensated by other complex mechanisms ranging over multi-levels (from biochemical and ultrastructural to tissue and organismal) during evolution, which involve at least the following five aspects:

(1) Blood volume is two to four times higher than in most teleosts; (2) a high cardiac output due to a very large stroke volume (6-15 times greater than in other teleosts) at low heart rate and at relatively low ventral aortic pressure; (3) low oxygen demands; (4) high vascularity of the skin and fins; (5) impressive cardiac enlargement, resulting in relative heart weights similar to that of small mammals, and characterized at the ultrastructural level by a massive proliferation of mitochondria in the cardiomyocytes. (Tota et al. 1997, 409-410)

Putting technical details aside, the most important point to be drawn is that, despite the lack of key elements for respiration, the icefish has fulfilled the function of respiration in virtue of an alternative physiological design described above. Therefore, first, according to some “taxonomic system” the icefish and other red-blooded oceanic fishes having Hb and Mb would be classified into the same kind in terms of their function of respiration (or the property of *being able to perform the function of respiration*). Second, because of their different underlying mechanisms associated with respiration, i.e., one employing mechanisms associated with Hb and Mb while one employing mechanisms associated with elements other than Hb and Mb, the icefish and the other red-blooded oceanic fishes would be classified into different kinds by a lower-level taxonomic system (e.g., physiology). Hence, this case satisfies the conditions (1), (3) and (4) for the MMRT.

Furthermore, it is obvious that this case also satisfies the condition (2), for the respiratory systems of the icefish and the other red-blooded oceanic fishes are (a) composed of different elements, with one having Hb and Mb whereas one lacking, and (b) made up of in different ways, with one having high vascularity of the skin

and fins and having a massive proliferation of mitochondria in the cardiomyocytes, etc. Last but not the least, these differences in components and organizations matter to how they realize the function of respiration. Take the oxygen-carrying capacity of the icefish for an example:

In the hemoglobinless blood, oxygen is carried strictly in physical solution. Being oxygen solubility higher at low temperature, the arterial oxygen-carrying capacity in the icefish is < 9 to 10% of that seen in closely related red-blooded species (Garofalo et al. 2009, 14).

This difference in oxygen-carrying capacity between the icefish and its closely related red-blooded species is due to its lack of Hb and Mb, and this reduced oxygen-carrying capacity of the icefish has been compensated by “an impressive increase of mass-specific blood volume which is 2-4 times greater than in red-blooded teleosts” (Ibid., 14). Therefore, though varying in the oxygen-carrying capacity, the icefish performs the function of respiration equally well as its closely related red-blooded species. As a consequence, this case also satisfies the condition (5) for MMRT, for the differences in the components and organizations between the icefish and the other red-blooded fishes are relevant to how they differently realize the function of respiration. (Before concluding, it is worth mentioning other possible cases of MMR also associated with respiration: instead of using hemoglobins, many animals use hemerythrins (in sipunculids, priapulids and brachiopods) and hemocyanins (in arthropods and mollusks), two different kinds of respiratory proteins, to bind and transport oxygen (Magnus et al. 1994). This indicates that there might be far more strategies to realize the function of respiration than expected in the biological kingdom, resulting in the further claim that, with respect to respiration, a large class of cases of MMR might be found.)

Before concluding this section, let us consider one potential objection. Some may ask whether Hb and Mb are essential for respiration. Given our icefish example, it seems they are not because they can be replaced by each other for respiration. Then one may further ask whether there are other things that may be essential for respiration. If the answer is yes, then my claim that the icefish example is a case of MR does not work because it is some other things, i.e., the

shared essential things that realize the function of respiration in different animals. If the answer is no, then it seems unclear why all the processes that go under the name of respiration should be classified as the same kind in the higher level.¹⁷

My response to the objection is twofold. First, it seems that we have changed the topic, for what is under discussion is not whether there are different *essential* things that realize the same function, but whether there are different things that contribute causally relevant differences to the realization of the same function. So, the focus is not on whether two different things are essential with respect to realizing the same function, but on whether they can contribute causally relevant differences to the realization of the same function. These are two different topics. Thus, requiring the two different things contributing causally relevant differences to the realization of the same function to be essential amounts to setting an extra condition for MR, a condition that cannot be found in Polger and Shapiro's work.

Second, the objection implies that the thing contributing to the realization of a function must be essential to that function. However, this requirement for *essentialness* seems to beg the question, for if what we mean by essential is indispensable or irreplaceable or absolutely necessary—that is, the specific way of realizing a function cannot be replaced by any other agent(s) or cannot be lacking in any case—then the possibility of MR is ruled out *a priori*. This is because what MR seeks to find is if the biological world may have alternative—or dispensable—ways of achieving the same goal, and this is an empirical question open to scientific investigation. There might exist the situation in which one problem can only find one solution, a situation that we may say the solution is essential, or exist the situation in which one problem finds two or more solutions, a situation that we may say the solutions are inessential. In either case, the problem worth pursuing is if there are well-defined (different) systems that have causally relevant differences with respect to realizing the same function, regardless of whether these causally relevant differences are essential or not.

In sum, we have presented three different kinds of examples in the biological world that constitute cases of MMR. The list of examples may be further

¹⁷ I thank an anonymous referee for alerting me to this possible line of objection.

extended—though the purpose of this essay is not to create a comprehensive inventory of MR cases. Nonetheless, the examples discussed so far are sufficient to demonstrate that it is not so much empirically-grounded to say that “multiple realization is much less common in naturally occurring systems than is usually recognized” (Polger and Shapiro 2016, 73).

5. Conclusion

This essay has showed that, contrary to Polger and Shapiro’s claim, multiple realization is not so difficult to find in the biological world. Polger and Shapiro motivate a criterion, i.e., their official recipe, for MR, in the hope of setting a clear standard for judging cases of MR on the one hand, and of assessing the scope of MR in the naturally occurring systems on the other. Their conclusion is that “multiple realization is much less common in naturally occurring systems than is usually recognized” (Ibid., 73). However, when integrating their criterion with a compositional conception of realization, whence developing a multiple mechanistic realization thesis, we have found that cases of multiple realization are abundant in the biological world. The cases might be of numerous kinds, though this essay concentrated on just three among many. Maybe the case of neural plasticity can be more broadly generalized to developmental plasticity, the case of enzymes can be further extrapolated to proteins, and the case of respiration can be more widely applied to other functions of living organisms. At the end of the day, we may find that the phenomenon of multiple realization is a norm, as opposed to an exception, in the iridescent and ever-changing biological world.

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