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ORIGINAL RESEARCH

Kinds of modalities and modeling practices

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Abstract
Several recent accounts of modeling have focused on the modal dimension of scientific inquiry. More precisely, it has been suggested that there are specific models and modeling practices that are best understood as being geared towards possibilities, a view recently dubbed modal modeling. But modalities encompass much more than mere possibility claims. Besides possibilities, modal modeling can also be used to investigate contingencies, necessities or impossibilities. Although these modal concepts are logically connected to the notion of possibility, not all models are equal in their affordances for these richer modal inferences. This paper investigates the modal extent of selected models and argues that analyzing singular model-target pairings by themselves is typically not enough to explain their modal aptness or to identify the kinds of modalities they can be used to reason about. Furthermore, it is argued that some important concepts that are not explicitly modal - like biological robustness - can be understood modally through their relational nature to a background space of possibilities. In conclusion, it is suggested that the strategy of modal modeling is contrastive, situating particular possibilities in larger modal spaces and studying the structural relations within them.

Keywords Modalities · Modeling · Possibility · Necessity · Contingency · Biological robustness

1 Introduction

Several recent accounts of modeling have focused on the modal dimension of scientific inquiry. More precisely, it has been suggested that there are specific models and modeling practices that are best understood as being geared towards *possibilities*.

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Examples include accounts of so-called how-possibly models (e.g., Koskinen, 2017; Verreault-Julien, 2019; Grüne-Yanoff & Verreault-Julien, 2021) and the strategies of exploratory and hypothetical modeling (e.g., Gelfert, 2018; Massimi 2019). This overall strategy has been dubbed "modal modeling" in the recent literature (Sjölin-Wirling and Grüne-Yanoff, 2021a). While their details and specific targets differ, all of these accounts seem to track some kind of interesting shift from the study of the actual to that which is possible. This is partly driven by developments within the field of philosophy of science itself and especially in the area of the philosophy of modeling, but also by the emergence of new scientific fields and research practices, like data-intensive computational models in physics and elsewhere (e.g., Massimi 2019) and engineering-inspired fields like synthetic biology (Knuuttila & Loettgers, 2013; Knuuttila, 2021), to name just a few examples. These technological advancements have opened up novel possibilities in quite a literal sense as scientists gain power to both simulate and construct scenarios and systems that take us beyond what is readily found in nature.

But modalities encompass much more than mere possibility claims, a fact that also bears on models and modeling. Firstly, besides possibilities, modal models can also be used to investigate contingencies, necessities or impossibilities. This has been recognized by philosophers contributing to the recent modal modeling literature (see, e.g., Grüne-Yanoff, 2009; Koskinen, 2017). Indeed, this fact may even seem quite obvious, as all of these modal concepts are logically connected to the notion of possibility. However, the paper argues that not all modal models are equal in their affordances for these richer modal inferences, a fact that shapes the philosophy of modal modeling considerably. Genuinely modal modeling strategies situate particular possibilities within larger modal spaces and study their interconnected relationships within them. Secondly, it is suggested that some important Scientific models that are not explicitly modal - like those of biological robustness - can also be understood modally through their relational nature to a background space of possibilities. Although the target of investigation is not any specific possibility claim as such, the paper shows that these kinds of models are still distinctly and interestingly modal in nature.

The purpose of this paper is to draw explicit attention to this multitude of ways in which modalities can figure in the context of modal modeling and provide a sketch of a framework to discuss the different features that facilitate, or are required by, *different kinds* of modalities. The paper investigates especially the phenomenon that I call modal extent. Roughly, this means how strong or weak a particular modal claim is relative to a simple possibility claim. Finally, I argue that analyzing singular possibility-probing model-target pairings by themselves is typically not enough to explain their larger modal aptness. The paper gives three examples from recent natural and engineering sciences that showcase different ways in which modal modeling can be interpreted and also unravels their connection to the basic axiom of modal modeling, namely, that it in an important sense is about that which is possible.

The structure of the paper is as follows. Section 2 considers the question of how models can become modal. It is noted that most modeling practices have at least *some* modal dimension. However, to be philosophically interesting and informative, as well as paving the way for a better understanding of how modalities figure in scientific practice, the epistemology of modal modeling should point to something that is less mundane. The following sections aim to amend the situation by drawing attention to a variety of recent modeling work. Section 3 considers the cases of superionic water and synthetic genetic systems. The modeling of these kinds of possible entities is a strong prima facie candidate for modal modeling. However, it is not the mere fact of possibility-probing that tells the whole story, but rather the way these possibilities are connected to other consideration, like the question of chemical necessity or biological contingency, typically situating them in a larger modal space. Taking note of this larger context highlights how and why these practices become cases of a dedicatedly modal modeling strategy. In Sect. 4, a case of biological robustness is presented which highlights yet another role for possibilia in modeling, this time not as the target of modeling, but rather as a reservoir for explanatory power. Section 5 draws together the philosophical lesson from the different cases while Sect. 6 concludes the article.

2 What makes models *modal*?

Philosophers of science have for long recognized the important modal-dimension of model-based reasoning. For instance, this is evident in the contrafactual "what-if-things-were-different" characterization of how causal mechanistic models are supposed to provide scientific understanding (Woodward, 2003). Godfrey-Smith (2019, 155) also stresses the intimate connection between models and modalities: "The most *obvious* role for something beyond the actual in science, though, is the kind of model-building in which the merely possible is overtly on the table – the science of infinite populations, frictionless planes, and wholly rational economic agents", continuing that "The push of causation, the organization of clouds of possibilities, and overt detours through fiction can all be understood as *some* sort of scientific employment of the merely possible. Science takes possibility seriously. That is not to say that science takes the non-actual to be in some way *real*, but it treats possibility in an apparently weightbearing way."

Indeed, it is difficult to find models or modelling practices that would be entirely devoid of modalities – or, that could not, at the very least, be ascribed a plausible modal interpretation. To see this, let us sketch a simple recipe for "modalizing" practically any model use. Let M be a model. Plausible identifications for the common modal operators could include the following (Hirvonen et al., 2021):

Necessary states = M core assumptions.
Possible states = M consistencies (e.g., in relation to core + initial values).
Impossible states = M inconsistencies.
Contingent states = M states s, such that neither s nor $\sim s$ is inconsistent in M.

This simple identification, or something close to it, could be easily used to give a baseline modal semantics for numerous models in the sciences, no matter their intended subject matter or inherent formal complexity (e.g., Quine, 1982; Fischer, 2017; for a more detailed presentation, see Hirvonen et al., 2021, 13832). The key point regarding scientific models is the difference between (i) what is being fixed throughout different uses of the same model and (ii) what different results the fixed assumptions allow for in different uses of the model. Indeed, for heuristic purposes, we could even apply it to a game like chess, where necessities correspond to the rules of the game, what is possible in a given situation to the state of the particular game, and so on (see also Fischer, 2016).[1]

It is important to notice that all of the previous "modal results" only hold *within* the particular model *M*. It amounts to a rather thin view of modality, as no attention was paid to the modelling practices or the world outside models (this includes things like the target(s) of the model, its overall goals, particular modelling methodologies, etc.). Still, the view is not totally vacuous. For even after fixing the core assumptions of a model (e.g., "the rules of the game"), it is often far from clear what *exactly* is possible given these assumptions. Think of the element of epistemic opacity and occasional surprise that is characteristic of many complex mathematical simulations. These can be used to probe a thin category of modal facts even without being applied to any natural or social target systems. Before their run, it is sometimes not known apriori if a particular outcome is possible *even within* the model itself. Furthermore, that such and such result has been attained within a simulation is not a case of mere *epistemic* possibility[2], either, even if it is another question entirely whether the simulation can be taken to represent anything in the real world.[3]

So far so good. Practically any model can be reasonably given a modal reading and even interpreted in some sense as giving information about possibilities. What is more, this modal dimension need not be entirely without content. However, many would probably not be ready to equate this thinly modalized understanding of models and modeling practice as a dedicated form of *modal modeling* that calls for its own methodology and philosophical account in order to be properly understood. For this, arguably, a thicker, more pragmatically-oriented view of the relationship between models and modalities is required.

Of course, there are many different views in the existing literature that offer a thicker view of modal modeling, some overlapping, while some could be in conflict with each other. However, a central idea often emerges: models are modal when their *targets* are possible systems/states/properties, that is, when the models are *about* possibilities that lie outside them. The present paper is going to take this view for granted. But, in a sense, it is still quite uninformative, as a vast amount of models and modeling practices could be read under it. In what follows, the goal of the paper is to try and amend the picture by suggesting other ways how models can become modal. In a sense, they are often still about possibilities. But attention is now paid also to

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[1] For example, we could wonder whether – given the rules of chess – it is *possible* for the blacks to win from such and such a position in under ten moves.

[2] See Sjölin Wirling and Grüne-Yanoff, (2021a, 2021b) who argue for the importance of distinguishing epistemic and objective possibility in the recent work on the philosophy of modal modeling.

[3] Here, the analogy to the relationship between the game of chess and its accompanying model is very different to the relationship between, say, a complex physical system and a model that is being used to understand it. This is because the game of chess, as a game, is basically defined by the formal properties of the model. No such relation typically exists between models and their targets in the physical and social sciences. Of course, one could also approach chess from the point of view of human cognitive competence (i.e., what is possible given the rules of chess plus the limitations of the human mind), but this would be another kind of question altogether.

forms of modelling that are mainly aimed at other modalities: contingencies, necessities, impossibilities (see also Grüne-Yanoff 2009; Koskinen, 2017). The purpose of this move is to give more beef to the "modal aboutness" of purported cases of modal modeling and shed light on the kinds of consideration that effect its overall practice and methodology.[4]

Because of the logically interconnected nature of modal concepts, any given modal claim or model is by itself typically ambiguous as to how we should interpret its "modal message". For example, a model of a possible future climate scenario may be just that: a claim about a particular possibility. On the other hand, the establishing of a novel possibility in a field like, say, economics might be used to rebuke a previously held necessity (perhaps limiting our conceptualization of viable economies), while models of possible evolutionary pathways in biology might concern the relative contingency of actualized species or their traits. Sometimes models contain clues about these enriched modal uses in the inclusion of comparative and contrasting information sets to which the particular possibility is then matched against; but this need not to be the case. Theoretically, it is enough for all of these models that they simply present a transparently evaluable consistency state. The *selection* of this or that particular possibility as the model's state of interest, its structure, parameter values, and the *use* it is put in a larger inferential context after its validation, is ultimately what constitutes an interesting case of *modal modeling* here – or so I will argue. The paper will now turn to examine this more closely through the cases of superionic water and synthetic genetic systems.

3 Different kinds of modalities

Based on some highly theoretical simulation work, scientists were recently able to experimentally show that water can exist in the new form of so-called superionic ice (Zhu et al., 2020). The technical properties of this new phase of water need not concern us here; suffice it to say that it is a form of iced water that exists in only extremely *high* temperature and pressures. It is natural to interpret the modeling work that was put into the probing of this form of water as in some important sense modal. Indeed, the straightforward interpretation of this work is to arguably think of it as investigating whether superionic ice is physically or chemically *possible*.

However, while true, this characterization alone does not seem to be able to uniquely specify some distinct strategy of modal modeling. After all, most modeling in the physical sciences arguably deals with possibilities, as all one has to do "is treat the set of mathematical models of the basic dynamical equations as the 'possible worlds' in standard modal semantics" (Maudlin, 2020, 525). For example, calculating the trajectory of a comet given differing initial values would count as modal

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[4] While it is true that my account can be seen as having a critical message for existing accounts of modal modeling, I do not see this message as negative in spirit. In particular, I do not by any means want to claim that existing accounts of modal modeling have *only* focused on mundane cases - they often have not. Rather, my point is that there is a *looming triviality problem* which should be dealt with, if modal modeling is to carve its own dedicated role in understanding scientific practice that is separate from general philosophy of modeling (which often also contains modal elements).

modeling here (see Hirvonen et al., 2021, 13834). Of course, there is nothing wrong per se in the view that a large part (perhaps even most) of modeling work in the natural and social sciences is engaged in the activity of modal modeling. Certainly, no absolute criterion of demarcation is likely to be attainable. But from a pragmatic perspective, there is more to be said about cases of modeling that are more heavily invested in modal reasoning than others. This becomes clearer when we take into account the strategy behind the modeling of superionic ice and see how it is being situated in a larger modal space, probing not only singular possibilities, but rather the overall phase space of water.

Indeed, the work on superionic ice could be described as the probing of the *necessity* of certain structures imposed by Nature. For example, beyond existential proofs of the form “superionic ice is possible simpliciter” the results could be used to show that low temperature is *not necessary* for the formation of iced water. Furthermore, it is worth noticing that the modeling work happened in a context where large areas of the entire phase diagram of water were already known (this includes of course all the familiar forms of water that one encounters in everyday life). The existence of these known and mapped-out forms effect in a crucial way the kind of modal inferences that the superionic ice example allows for. The particular possibility-probing features of the superionic model can hardly be separated from models of water as a whole. Indeed, the scientific goal of the whole enterprise is arguably to map out the entire phase diagram of water and not just probe isolated possibility claims or, at the very least, to show how the possibilities are connected in the larger thermodynamic picture (Zhu et al., 2020, 7449–7450). Ultimately, this could not only tell us about relevant possible forms of water, but also what kinds of structures are necessary or impossible.

In fact, for some the interpretation of the new form of superionic ice has started a semantic negotiation of sorts regarding the proper extensions of basic chemical terms like “water”: “Depending on whom you ask, superionic ice is either another addition to water’s already cluttered array of avatars or something even stranger. Because its water molecules break apart, said the physicist Livia Bove of France’s National Center for Scientific Research and Pierre and Marie Curie University, it’s not quite a new phase of water. “It’s really a new state of matter,” she said, “which is rather spectacular.”” (Interview of physicist Livia Bove on *QuantaMagazine*, 2019.) The potential implications for the sufficiency and necessity conditions of basic chemical terms highlights the modally-interlinked nature of the result. Even though at its heart the modelers helped to establish a novel possibility, there is much more at play than that: it is about contrasting models in the entire phase space.

Let us take another example from the emerging field of synthetic biology. Sjölin Wirling and Grüne-Yanoff (2021a) suggest that objective scientific possibility is especially suited to cases where we have a reason to think that things are in some important sense contingent: the world could be different to the way it actually is. Biology is certainly a good candidate science here. Even though the exact nature of biological contingency is debated, many seem to agree that there is a great deal of contingency in the function and structure of biological systems which is reflective of their evolutionary origins. According to popular views, many facts of biology could have turned out differently in the history of life (Gould, 1989; Beatty, 1995). This is of course a complex debate that we cannot fully engage here. What is of special interest is the novel way to potentially explore the nature and limitations of this contingency in the recently emerged field of synthetic biology which combines mathematical modeling with concrete engineering practices (Koskinen, 2017; Knuuttila, 2021). Drawing from fields as diverse as physics, electrical engineering and biochemistry, the goal of the approach is to be able to design and, ultimately, materially realize new forms of living systems and their parts (Elowitz & Lim, 2010).

As with the case of superionic ice, it is quite straightforward to interpret many synthetic systems as probing biologically possible configurations – theoretically even whole organisms. However, if we look at the way many of the models in the field are constructed, we can see that there is often a richer modal context that is informing their particular structural and functional properties. For example, so-called XNA molecules are used to study whether it is possible to construct artificial genes out of "unnatural" molecular material (Anosova et al., 2016). However, in order to function as a sensible model for genetic material, it is not simply enough that a particular XNA system is somewhat functional, or just chemically realizable simpliciter. For we already have DNA which is known to be a highly-functional solution to the problem of storing and transmitting genetic information. To be of any real *biological* interest, in modeling the feasibility of these systems, synthetic biologists who work with XNAs are typically careful to impose strong parameter values for these possible systems that try to mimic as faithfully as possible the actual functional properties of natural DNA. The models of potential XNA molecules take into account several limiting factors, like: the overall thermodynamic stability of the proposed structure (Benner et al. 2016); linear ordering of the genetic code (Szathmáry 2003); biochemical feasibility in a cellular context (Marlière et al. 2011); and evolutionarily sensible mutation levels (Benner et al. 2016). Without these modeling assumptions, the potential for modal inferences would be greatly reduced, as the resulting systems, even if chemically successful, would be rendered less relevant to biology.

In other words, the idea is to change the building blocks of life, but still retain the functions of living systems (Koskinen, 2020). In fact, one common way of expressing the whole strategy behind the study of artificial genetic systems is through functional equivalence: as an ideal, an XNA system should be in theory *interchangeable* with DNA, making it a genuine biological function-equivalent alternative instead of a mere chemical possibility. Although this might not be yet always practically attainable, what this strategy essentially allows for is the study of the relative *contingency* of DNA. If we know that DNA and XNA could in theory be used to solve the *same problem* (Koskinen, 2017, 2020), it gives us reasons to treat XNA as a genuine genetic *alternative* and not just a mere artificial curiosity. If done carefully, these model systems could help us to study the modal properties of biological systems that go beyond singular possibility claims.

The cases discussed in this section have sought to explore what kinds of systems are possible in Nature and how these are related to actual systems. In the next section, I focus on a contrasting case of modal modeling where modalities figure not as the primary *target* of investigation as such, but rather as a *background space of possibilities* that grants the model much of its explanatory power. As an example, I will examine biological robustness as a modal concept which will exemplify this kind of modal modeling strategy.

4 Using the possible to model things

Biological systems are characterized by their ability to maintain their functions in the face of constant environmental changes, genetic mutations, and fluctuations in their rate of metabolism; this is often expressed by saying that they are *robust* systems. According to an influential view in systems biological theorizing, a key element behind robustness is that biological functions are often realizable through many different kinds of structures and processes (e.g., Edelman & Gally, 2001; Greenspan, 2001; Chouard, 2008). I focus here on a particularly salient approach to the modeling of biological robustness through the help of topological possibility spaces (e.g., Wagner, 2005; Fontana, 2006).

Ultimately, the source of robustness in biology can be traced all the way to the level of the genetic code. The central use of genetic material in cells is to code for the construction of different amino acids. These in turn are turned into more complex proteins that are essentially the building blocks of living systems. Because there are 20 different standard amino acids, single base letters are clearly insufficient for this task. That is why the genetic code is interpreted in triplets of nucleotides, called codons. For example, a three-place mRNA codon CUG codes for the amino acid leucine. Expanding the basic unit of information to the level of codons makes the genetic code quite expressive. Indeed, in the case of basic amino acids a form of "semantic" redundancy is already taking place: Because there are 64 different 3-letter combinations of the nucleotides A, C, G, and U, some of the syntactically different triplets must code for the same amino acid.[5] This increases the code's robustness (Wagner, 2005, 25). However, as with the case of single nucleotide bindings, the system is completely unequivocal: A single codon cannot ever code for more than one amino acid. In other words, the functional mapping between codons and amino acids is that of many-to-one.

In order to form more complex building blocks, and ultimately biologically meaningful functions, however, the genetic material must form longer *sequences*. A particular biological function might be robust because its corresponding genetic sequence is located in such-and-such a place in the overall space of possibilities (Wagner, 2005, 201). The basic idea here is related to the distribution of neutral solutions in neighboring areas of the genetic space, resulting in differing probabilities for function-preserving mutations. For present purposes, what is noteworthy is that the modeling of a property like robustness often simply takes these relevant possibilities for granted. It is a case of modal modeling, but the main question does not concern the possibilities themselves (e.g., whether predicted sequences correspond to genuine biochemical possibilities or not), but rather, how the sequence of interest relates to the relevant possible ones (the sequence of interest itself can be actual, or a merely possible one). Some biologists even quantify over these abstract possibilities and

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[5] There are also three dedicated stop codons in the standard genetic code.

regard them as in some sense “real”[6], even though the vast majority of them are not realized in nature:

> [I]t is useful to think of all possible sequences of a given length as related to one another by a notion of distance. The distance between two sequences is the smallest number of mutations required to convert one sequence into the other. The direct neighbors of a sequence are all sequences one mutation away. For example, a sequence of length 100 has 300 neighbors. This results in a very high-dimensional metric space. Despite its abstract nature, this so-called sequence space […] *is real* in the sense that mutations are chemical events interconverting sequences with a certain probability. (Fontana, 2006, 73, italics added)

The above “modal realist” understanding of sequences is reminiscent of Godfrey-Smith’s (2006) idea about some fictional model systems that, while abstract, would consist of concrete entities, if they were real. It is partly this tangible, biochemically grounded, nature of sequences which allows scientists a certain confidence in quantifying over them. Indeed, because of the vastness of the entire sequence space, some general properties of possible sequences might be even easier to track than the exact properties of a particular actual sequence. This makes the topological analysis of robustness a compelling case of modal modeling, but of a kind where the role of the possible is considerably different to some of the cases typically discussed in the recent literature.

I argue that biological robustness here is simply seen as a non-standard modal predicate of sorts: similarly to the notion of contingency, which depends on there being alternative states that could possibly hold, robustness is never an intrinsic property of any individual sequence. It is interesting to note that Wagner uses essentially the same framework also in his analysis of the notion of *evolvability*.[7] Even though high genetic redundancy acts as a buffer against mutation-induced change, the same phenomenon can also allow for the discovery of novel functions. This is because expanded networks of neutral sequences allow for the exploration of larger neighborhoods. Even though most areas in the genetic space are biologically meaningless and lead to deleterious changes, every now and then a novel sequence with fitness-enhancing benefit is discovered. The technicalities need not matter us here. The important thing is that evolvability can also be treated as a relational topological property of sequence spaces.

Like with robustness, no amount of modelling work will reveal the evolvability of a sequence if we just study it in isolation. But once we link the sequence with its relevant neighbors, things become quite straightforward. The only problem is that these neighbors are not actual, but rather merely possible ones. However, they are still

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[6] Cf. with the quote from Godfrey-Smith (2019) on page 4, though.

[7] Notice that, unlike robustness, evolvability is more explicitly a modal concept, indicating a *potentiality* for change. Many traditional analyses of potentiality have made reference to the intrinsic nature of objects, like invoking their essences, to explain this capacity. Wagner differs here in that his analysis for evolvability follows the *extensional* route. This is allowed by quantification over possible sequences.

extremely tractable, as many of their properties can be predicted with relative confidence from the basic combinatorics of the genetic code, together with computational models of the resulting protein folding. This is a case of modal modeling where the target of explanation is not necessarily a specific possibility, but where the possible is rather invoked in order to give meaning to important scientific concepts.

5 Discussion: modal modeling as the exploration of modal spaces

Models of superionic ice and synthetic genetic systems both track possibilities, but they are construed in a way that they can also be used to reveal new insights about other kinds of modal questions. These modal inferences typically take place in a larger space of possibilities that is characterized by background models and theories, like the phase space of water or the equivalence class of viable genetic systems. Both raise potential semantic questions about the types of entities they concern: What's the proper extension of "water"? How about "genes" – or "life"? In other words, they do not simply examine isolated possibilities, but rather the kinds of necessities that belong to the core modeling assumptions. I suggest one way to draw the distinction between modal and non-modal forms of modeling is precisely how they treat these kinds of questions. Tentatively, a non-modal case of scientific modeling could be distinguished by its lack of interest in challenging the basic structure of the modal space that is provided by the key theories and models it relies on. As shown previously, practically any model contains modal elements. But the modal extent of these elements does not necessarily reach far beyond mundane facts like "such and such population dynamic is consistent with the modelling assumptions and thus (logically) possible". But when modelling is directly influenced by modal consideration, like those of contingency or robustness, the potential for inference-making is greatly enhanced.[8]

Modalities, especially more substantial accounts of them, have often been met with skepticism especially amongst scientifically oriented philosophers. A classic example of this attitude is Quine (see, e.g., Quine 1982, 121). However, there has been a recent revival of interest in modal epistemology in philosophy of science, especially in relation to scientific modeling (see Williamson, 2017, 2018; Sjölin Wirling and Grüne-Yanoff 2021a, 2021b; Hirvonen et al., 2021). Although the discussion in general is quite heterogeneous and distorted even, there seems to be an emerging consensus that objective modalities are not something to be afraid of anymore in respectable scientific epistemology. Williamson (2018, 197) goes as far as to state that "it is an illusion that objective modalities play no role within natural science. They are integral to its subject matter. In effect, much of natural science is an exploration of objective modal space."

Not all possibility spaces need to be interpreted objectively. For example, Craver (2007) talks about a space of possibilities in his analysis of the strategy of mechanis-

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[8] Although I do not wish to push the analogy too far, the situation bears resemblance to the Kuhnian idea of normal science. In a sense, we could think of non-modal modeling as part of the normal science paradigm where (major) questions concerning modalities have been solved or agreed upon.

tic modeling and explanation in neurobiology. At its most general, this space contains all the mechanisms that could possibly explain a phenomenon (Craver, 2007, 31). It is clear from the outset that, for Craver, this space of possibilities is epistemic, rather than objective, in nature. Craver's account is characterized by the evidential relationship between different hypotheses – or, as Craver calls them, how-possibly models – of a phenomenon. This exploration of the space of possibilities – from possible, to plausible, to actual – is best interpreted as mostly epistemic in nature.

However, it has been argued that it is possible to reorient this kind exploration of epistemic how-possibly models and use it to probe objective possibilities instead. In theory, the same how-possibly models that were originally used as evidential scaffolds towards a single how-actually model can become the targets of analysis in themselves, posing the question whether they (or some other non-actual ones) could present genuine possibilities in Nature or even become materially realized one day. Koskinen (2017) interprets some areas of synthetic biology in this way. Simons (2021, 96) is also explicit in that when he talks about the recent turn towards the possible in the life sciences, what he has in mind is metaphysical instead of mere epistemic possibility. For purposes of space, I am not going to delve deep into the vexed nature of metaphysical possibility and its relation to objective possibility in general. Instead, I simply interpret Simons as saying that he sees synthetic biologists as probing some kind of objective, or mind-independent, possibilities. While some argue that metaphysical possibility can go beyond more mundane forms of objective possibility (like, say, physical or biological possibility), others are ready to simply equate them (see Williamson 2017).

Without committing us to any heavy metaphysical story of modality, it seems that at least a pretheoretical understanding of objective possibility is supposed by a lot of science. For example, it would be difficult to understand evolution, if we could not make any difference between actual species and possible ones. Evolution is a process, and many species that were once actual are now extinct. However, this must mean that there was a point in the history of Earth when these species at least were biologically possible. The same hold for the future, as we can be quite certain that hitherto unactualized forms of life will appear given enough time. Although it is extremely difficult to quantify these species and their exact traits in advance, the possibility of some such life is virtually guaranteed independent of our epistemic situation. Similarly, the possibility (impossibility) of superionic ice, not to mention the genetic sequences utilized in topological models of robustness and evolvability, are not simply socially constructed byproducts of our epistemic limitations.

Synthetic biologists also speak about biological possibility and sometimes even give it a constitutive theoretical role: "Biology is not limited by what is natural, but by what is possible" (Torres et al., 2016). What this statement is getting at, is that life as we know it is at least somewhat contingent. Ultimately, there are limitations to the kinds of biological systems that could exist, but we cannot learn these limitations by only studying actualized life on Earth. Furthermore, reference to what is "natural" does not – indeed, cannot – help here, since what people deem as natural is heavily influenced by the set of actual organisms and their features that are easily accessible, leading to a case of circular reasoning at best. What is certain, however, is that evolution and biology itself is not limited by our epistemic situation, but by something more objective.

Sjölin Wirling and Grüne-Yanoff (2021a, 2021b), are thus right to point that, generally, more care should be put into the conceptualization of different kinds of possibility claims. However, in practice, the distinction between epistemic and objective possibilities is not always razor-sharp. Importantly, in the case of objective possibilities, it is easy to forget that they also need a story of epistemic access in order to be justified. In this basic sense, our representations of objective possibilities resemble epistemic ones in that they, too, are true as far as we know. [9]

Which brings us to a caveat. The puzzle with objective modality is that if we already knew that something is an objective possibility (biological, physical, economic, etc.), why the need to model it in the first place? Perhaps one could argue that we might know that something is an objective possibility without knowing all of its properties. Although this might sometimes be the case, in general it is a dangerous route to modal knowledge. For example, the history of science and philosophy is full of examples where something was deemed possible on the basis of imagination or mere intuition, only to be revealed as totally wrong-headed by subsequent scientific work. The problem with simply assuming that what we are dealing with belongs to the realm of objective possibility is that it is often precisely the details, or exact properties of the purportedly possible system, that are crucial. Because these details are often lacking in the original mental exercise, the objective status of many a possible system is deemed deeply suspect at best.[10] Thus, the need for a dedicatedly modal modeling strategy often arises precisely in situations where we are trying to establish *whether* something is an objective possibility or not – not so much in situations where this has already been settled – and in this way probe novels kinds of spaces for further possibilities.

Our access to objective possibility feeds on generally accepted scientific facts that are kept fixed and act as the basis on which to build our models and theories (Hirvonen et al., 2021). Combined with the idea that objective modalities form a nested hierarchy where biological and chemical possibility, for example, are more restricted than physical (and perhaps metaphysical) possibility (Sjölin Wirling and Grüne-Yanoff 2021a), and thus deal with smaller regimes of possibilities, the situation starts to look more manageable. Although limited, often local, and piecemeal, various modal spaces can be used to better conceptualize how modal modeling proceeds in scientific practice. It is in the contrastive and relational way how possibilities

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[9] Generally speaking, the contrast between epistemic possibility and objective possibility is easier to grasp and justify when we are talking about the situated knowledge of particular epistemic agents (with sometimes highly erroneous beliefs). In situations like this, it is easy for us to appraise the agent's modal claims because we (presumably) have independent means of checking the (objective) status of these claims. But when we are talking about knowledge pertaining to whole scientific communities, the distinction between the epistemic and the objective becomes more entangled.

[10] A related worry concerns purported cases of objective possibility that turn out be false. What to make out of those? One way to answer this would be to simply see failed claims of objective possibility as implicit claims about objective impossibility. After all, if something is not possible, it must be impossible. However, the problem with this approach is that it is often extremely difficult to establish that something is genuinely impossible. Mere failure to establish possibility is typically not enough. Also, some modal inferences might simply remain undecided.

are being used to probe other modalities like contingency, or give explanatory power in the case of non-standard ones like robustness, that gives the modal modeling strategy a more distinctive character.

6 Conclusions

Because of the logically interconnected nature of modal concepts, any given modal claim or model is by itself typically ambiguous as to how we should interpret its "modal message". Focusing on isolated models or model-target parings might not always reveal the whole picture as it tends to highlight the notion of possibility at the expense of other modal categories. Models can become more interestingly modal, when the above is amended with an analysis of the research context and the contrastive-relational nature of modal modeling strategies: Is the model primarily aimed at establishing a predicted possibility? Is it a case of more free-form exploration? Is the model contrasted to an actual system in order to gain insight into the relative contingency of nature – or do we perhaps aim to dethrone a previously held necessity? Different kinds of modeling assumptions need to be made in order to have the proper connection between the modelled possibility in question and the relevant modal category we want information about. Some modal models can also not be primarily about possibilities, but instead draw upon possibilities to explain and predict properties of actual systems. Although no demarcation criteria is likely in sight (or even needed) to sharply distinguish modal from non-modal forms of modeling, this paper has nevertheless drawn attention to a variety of strategies that do rely on distinctly modal forms of reasoning without resorting to the simple recipe that any possibility claim would do. It is an invitation for philosophers of science and epistemologists of modality to dig deeper into the ways in which considerations of different kinds of modalities continue to shape modeling work in the sciences.

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References

Anosova, I., Kowal, E. A., Dunn, M. R., Chaput, J. C., van Horn, W. D., & Egli, M. (2016). The structural diversity of artificial genetic polymers. *Nucleic Acids Research*, *44*(3), 1007–1021.

Benner, S. A., Karalkar, N. B. , Hoshika, S., Laos, R., Shaw, R.W., Matsuura, M., Fajardo, D., & Moussatche, P. 2016. Alternative Watson–Crick synthetic genetic systems. Cold Spring Harbor Perspectives in Biology. doi: 10.1101/cshperspect.a023770

Beatty, J. (1995). The evolutionary contingency thesis. In G. Wolters, J.G. Lennox, & P. McLaughlin (Eds.), *Concepts, theories, and rationality in the biological sciences*. The second Pittsburgh-Konstanz colloquium in the philosophy of science (pp. 45–81). University of Pittsburgh Press.

Chouard, T. (2008). Beneath the Surface. *Nature*, *456*, 300–303.

Craver, C. F. (2007). *Explaining the brain: Mechanism and the mosaic unity of neuroscience*. Oxford University Press.

Edelman, G. M., & Gally, J. A. (2001). Degeneracy and complexity in biological systems. *Proceedings of the national academy of sciences*, *98*, 13763–13768.

Elowitz, M. B., & Lim, W. A. (2010). Build life to understand it. *Nature*, *468*(7326), 889–890.

Fischer, B. (2016). A theory-based epistemology of modality. *Canadian journal of philosophy*, *46*, 228–247.

Fischer, B. (2017). *Modal justification via theories*. Springer.

Fontana, W. (2006). The topology of the possible. In A. Wimmer, & R. Kössler (Eds.), *Understanding change: Models, methodologies and metaphors* (pp. 67–84). Palgrave Macmillan.

Gelfert, A. (2018). Models in search of targets: Exploratory modelling and the case of Turing patterns." In A. Christian, D. Hommen, N. Retzlaff, & G. Schurz (Eds.), *Philosophy of science. Between the natural sciences, the social sciences, and the humanities*, Springer 2018.

Godfrey-Smith, P. (2006). The strategy of model-based science. *Biology and philosophy*, *21*(5), 725–740.

Godfrey-Smith, P. (2019). Models, fictions, and conditionals. In A. Levy, & P. Godfrey-Smith (Eds.), *The scientific imagination*. Oxford University Press.

Gould, S. J. (1989). *Wonderful life: The Burgess Shale and the nature of history*. W. W. Norton.

Greenspan, R. J. (2001). The flexible genome. *Nature reviews genetics*, *2*, 383–387.

Grüne-Yanoff, T. (2009). Learning from minimal economic models. *Erkenntniss*, *70*, 81–99.

Grüne-Yanoff, T., & Verreault-Julien, P. (2021). How-possibly explanations in economics: Anything goes? *Journal of economic methodology*, *28*(1), 114–123.

Hirvonen, I., Koskinen, R., & Pättiniemi, I. (2021). Modal inferences in science: A tale of two epistemologies. *Synthese*, *199*, 13823–13843.

Knuuttila, T. (2021). Epistemic artifacts and the modal dimension of modeling. *European journal for philosophy of science*, *11*, 65.

Knuuttila, T., & Loettgers, A. (2013). Basic science through engineering? Synthetic modeling and the idea of biology-inspired engineering. *Studies in history and philosophy of biological and biomedical sciences*, *44*(2), 158–169.

Koskinen, R. (2017). Synthetic biology and the search for alternative genetic systems: Taking how-possibly models seriously. *European journal for the philosophy of science*, *7*(3), 493–506.

Koskinen, R. (2020). Could we really be made of swiss cheese? Xenobiology as and engineering epistemology for biological realization. *Chembiochem*, *21*(18), 2591–2594.

Marlière, P., Patrouix, J., Döring, V., Herdewijn, P., Tricot, S., Cruveiller, S., Bouzon, M., & Mutzel, R. 2011. Chemical evolution of a bacterial genome." Angewandte Chemie International Edition 50: 7109–7114.

Massimi, M. (2019). Two kinds of exploratory models. *Philosophy of science*, *86*(5), 869–881.

Maudlin, T. (2020). A modal free lunch. *Foundations of physics*, *50*, 522–529.

Quine, W. V. O. (1982). *Theories and things*. Belknap Press.

Simons, M. (2021). Dreaming of a universal biology: Synthetic biology and the origins of life. *Hyle: International journal for philosophy of chemistry*, *27*, 91–116.

Sjölin Wirling, Y., & Grüne-Yanoff, T. (2021a). The epistemology of modal modeling. *Philosophy compass*. https://doi.org/10.1111/phc3.12775.

Sjölin Wirling, Y., & Grüne-Yanoff, T. (2021b). Epistemic and objective possibility in science. *The British journal for philosophy of science*. https://doi.org/10.1086/716925.

Szathmáry, E. 2003. Why are there four letters in the genetic alphabet? Nature Reviews Genetics 4: 995–1001.

Torres, L., Krüger, A., Csibra, E., Gianni, E., & Pinheiro, V. B. (2016). Synthetic biology approaches to biological containment: Pre-emptively tackling potential risks. *Essays in biochemistry*, *60*, 393–410.

Verreault-Julien, P. (2019). How could models possibly provide how-possibly explanations? *Studies in history and philosophy of science*, *73*, 22–33.

Wagner, A. (2005). *Robustness and evolvability in living systems*. Princeton, NJ: Princeton University Press.

Williamson, T. (2017). Modality as a subject for science. *Res philosphica*, *94*, 415–436.

Williamson, T. (2018). Spaces of possibility. *Royal Institute of Philosophy supplement*, *82*, 189–204.

Woodward, J. (2003). *Making things happen: A theory of causal explanation*. Oxford University Press.

Zhu, C., Gao, Y., Zhu, W., Liu, Y., Francisco, J. S., & Zeng, X. C. (2020). Computational prediction of novel ice phases: A perspective. *The journal of physical chemistry letters*, *11*(17), 7449–7461.