Philosophy of Science (2023), **90**, 880–900
doi:10.1017/psa.2023.72

ARTICLE

Motivating a Scientific Modeling Continuum: The Case of "Natural Models" in the COVID-19 Pandemic

Ryan M. Nefdt

Department of Philosophy, University of Cape Town, Cape Town, South Africa
Email: ryan.nefdt@uct.ac.za

(Received 18 February 2022; revised 31 March 2023; accepted 08 April 2023; first published online 19 April 2023)

Abstract

The COVID-19 global pandemic had a profound effect on scientific practice. During this time, officials crucially relied on the work done by modelers. This raises novel questions for the philosophy of science. Here I investigate the possibility of 'natural models' in predicting the SARS-Cov-2 virus's trajectory for epidemiological purposes. I argue that to the extent that these can be considered scientific models, they support the possibility of a continuum from scientific models to natural models differing in artifactual commitment. In making my case, I draw from work on both model organisms and natural experiments as well as recent work in epidemiology.

1 Introduction

The COVID-19 pandemic has had significant effects on society, global politics, and health systems around the world. The scientific community has especially been affected by the exigency of treatment and vaccine production and a generally challenging epistemic environment. In dealing with the crisis, the field of epidemiology has taken center stage in modeling, predicting, and explaining the data as they arise in an ever-changing landscape of dispute and discovery.

The focus of the present work is on one tool in the scientist's arsenal that has become especially relevant in the current situation, namely, the tool of scientific modeling. Specifically, I aim to explore the nature and use of what I call *natural models* in confronting the COVID-19 pandemic. The article is split into two motivating arguments. The positive argument aims to make a direct case for a distinct modeling strategy, *natural models*, in the philosophy of science based on evidence from the COVID-19 pandemic. The second part is more typological in nature. It motivates a continuum from classical scientific models through model organisms and natural experiments to natural models. In other words, the argument is negative in that it argues for a missing possibility in logical space, one I claim is occupied by natural models.

Thus, in the opening section, I describe three important components of scientific modeling, namely, surrogate reasoning, modeler's intentions, and what I call the *construction assumption* (CA). I claim that these components drive much of our understanding of the general practice, but they come apart. In section 3, I make the case for natural models in the COVID-19 pandemic. I argue that these kinds of models reject CA while embracing surrogate reasoning and modeler's intentions. Specifically, I draw from the recent scientific work on COVID-19 modeling in epidemiology involving cruise ships; fishing vessels; and small isolated populations to show how natural models work. The conclusion is that scientific modeling *should* include natural models, theoretical surrogates that are free of explicit design or intention, to fully appreciate the nature of the broader modeling practice. Before moving to a novel continuum argument, I defend the possibility against some possible objections, especially one that suggests that it's just a matter of sample-to-population generalization. Lastly, in section 4, I argue that natural models fit in at the end of a continuum of modeling practices in the sciences. The resulting picture connects various kinds of scientific modeling strategies, including the use of model organisms, natural experiments, and, of course, classical models.

2 Three features of scientific modeling

The modeling literature is vast; however, certain related themes have emerged across accounts and frameworks. The first is that modeling involves indirect representation via a form of surrogate reasoning. The second is the idea that model identification and individuation depend in part of the intentions of the modelers. The third is that models themselves are artifacts constructed for particular theoretical purposes. We'll take each in turn. In what follows, I provide a brief contemporary overview for the sole purpose of highlighting these three relevant features. A more comprehensive account would include mention of the seminal work of Cartwright (1983), Suppes (1960), and van Fraasen (1980) and delve deeply into the intricacies of a large body of scientific work.

2.1 Indirect representation

What is an "indirect" representation? The standard interpretation involves a kind of methodological "surrogacy" via idealization or abstraction. In other words, a modeler can create a model that not only ignores certain factors of the actual target system but also distorts the nature of that system. For instance, Fisher's model of a nonexistent three-sex organism was designed to explain the emergence of the more evolutionarily stable two-sex prototype prevalent in most ecosystems (cf. Fisher's principle). The model bears resemblance relations to the target system such that stipulations within the model reflect aspects of the target system. Godfrey-Smith (2006, 726) claims that "the modeler's strategy is to gain understanding of a complex real-world system via an understanding of a simpler, hypothetical system that resembles it in relevant respects." "Relevant respects" is often indirect, as in the Fisher case. In addition, the resembling system need not be "hypothetical." Many models are either physical systems that mirror the target in miniaturized form, as in the San Francisco Bay Area model (Weisberg 2013), or idealizations thereof, such as a simplified Styrofoam model of a double helix strand of DNA.

https://doi.org/10.1017/psa.2023.72 Published online by Cambridge University Press

Additionally, models are multifarious not only in their representational tasks but also in their targets. As Weisberg (2013, 74) notes,

> models can be used to study a single target, a cluster of targets, a generalized target, or even targets known not to exist. One can even engage in the study of a model without any target at all.

Following Godfrey-Smith (2006) and Weisberg (2013), it may be more useful to talk about the "strategy" of modeling. Thus a part of this strategy involves a form of reasoning called *surrogate reasoning* (Suárez 2004), by which a modeler uses a model to work out a solution and then "reads back" information from that model into the target system with the relevant adjustments made to accommodate differences between the two.

The idea of a modeling strategy is not directly committed to a specific answer to the ontological question about what models are, favoring neither an abstract object nor an imagined concrete view. Some accounts of modeling under the banner of indirect representation combine the functional role of models with the ontological question. On such views, models are fictions akin to literary fictions or ways that the world could have been (Frigg 2010). Whereas Godfrey-Smith (2006) takes model systems to be systems that would have been concrete if they were real, fictionalists emphasize the fact that "models are not like things in the world" (Frigg and Nguyen 2017, 112). Thus there is a distinct notion of "abstract" at play in each view. On the former accounts, "abstract" is based on abstraction from certain features of reality (e.g., for tractability or simplicity), whereas the latter accounts emphasize the distance between real-world objects and theoretical objects.

For fictionalists, models are fictions or fictional worlds like the fictional world inhabited by Sherlock Holmes or Walter White. Not only this, but to understand scientific representation, one has to understand this latter property of models. Theorists in this camp have thus unsurprisingly mined the resources of aesthetics, especially Waltonian mimesis, in which fictions are games of make-believe. "Such games are facilitated by props: material objects which, in combination with various 'rules of generation' demand that players imagine certain propositions as true" (Currie 2017, 766). The DEKI account furthers this picture to account for representation in terms of exemplification and denotation (Frigg and Nyguyen 2016). A "vehicle of representation" both denotes a target system and exemplifies a subset of its properties, allowing one to attribute the latter to the former. This process of attribution or imputation is indirect because the model is of a different kind to the target in most cases. This is where the "key" comes in. A key is needed to transpose the properties of the model to that of the target. Here the cartographic analogy is meant to take force.

From the foregoing, one might attribute what Knuuttila (2009) calls the "model–target dyad" to these indirect representational accounts, both the abstract object and fictional versions. Of course, many contemporary accounts offer a more nuanced analysis of scientific modeling not exclusively focusing on the model–target relationship but also focusing on the modeler and even other environmental factors.

Some fictionalists, however, dispute the need for intervening structures or intermediate systems of representation (Toon 2011; Levy 2015). Part of the reason for this move is based on issues of how models qua nonactual objects can be the objects of our knowledge or observation in the first place. As Levy notes, "if models are concrete hypothetical objects, then by virtue of their non-actuality, they are not the kinds of things we can observe and come into contact with" (784). This kind of issue has long roots in the epistemology of Platonic objects, Cartesian *res cognitans*, Fregean "Senses," and so on. Thus direct fictionalists advocate a more planetary application of Walton's theory:

> My suggestion is that we treat models as games of prop orientated make-believe —where the props, as it were, are the real-world target phenomena. To put the idea more plainly: models are special descriptions, which portray a target as simpler (or just different) than it actually is. (Levy 2015, 791)

Direct approaches eschew the idea of surrogacy as the core of modeling. As we will see, natural experiments share some features with such views. However, indirect representation via surrogate reasoning remains an important aspect in the literature on models in science. It marks a strategy for dealing with real-world complexity via the construction of intervening structures within which hypotheses and inferences can be tested and represented. We turn to the construction part of the practice in section 2.3. But before then, let us pause on the property evoked when philosophers talk about the intention of modelers.

2.2 Modeler's intentions

Consider the case of two models identical in mathematical structure: the models of a given electrical circuit or spring and a pendulum. If models were identified merely by ontology or model–target relation, then from a mathematical perspective, these systems would be indistinguishable. But as Thomson-Jones (2012, 768) notes,

> the mathematical structures view seems committed to identifying both the pendulum model and the model of the electrical circuit with the mathematical structure they have in common and, thus, to insisting that the pendulum model and the model of the circuit are one and the same model.

One standard way in which to distinguish such models is by means of the intentions of the modelers.[1] Without some account of the "construal" or interpretation of the model, there would be no telling these models apart. This is the view held by Weisberg (2013, 72), in which "we can say that these models share a common core mathematical structure, and what differs are theorists' construals." A construal for Weisberg is composed of an assignment, an intended scope, and two fidelity criteria, where the latter are "the standards that theorists use to evaluate a model's ability to represent real phenomena" (76). So we ask what the modeler intended and how they constructed the model to fulfill that intention. I will briefly describe the components of Weisberg's notion of "construal" before moving on to the construction assumption.

[1] On the flip side, one often touted advantage of the fictionist account is its ability to identify two (or more) different mathematical representations as the same fictional or imagined system under a different description. Here again, construal or intention plays an important role. See Frigg and Nguygen (2016).

https://doi.org/10.1017/psa.2023.72 Published online by Cambridge University Press

The assignment specifies the intended target phenomenon in the world to be studied. It also marks the intended coordination between features of the model and features of the target. You might think that models are preconceived with resemblance relations between themselves and the target phenomena, that they are "fit for purpose," if you will. However, this isn't always the case. Mathematical models, for instance, can be used for a number of modeling purposes for which they were not intended. As Weisberg (2007) notes, harmonic oscillators were initially developed to capture the motion of physical systems but were later expanded for use in chemistry to model vibrations in molecular bonds. In the process of coordinating the model with the target system, a series of adjustments (on both sides) is needed. Mathematical models can possess more structure than the physical system, and the physical system can contain superfluous or irrelevant mechanisms that need to be omitted in the model. The assignment feature of intention handles this process.

Scope and assignment are related. However, the former does not specify the *how* of coordination but only the particular aspects of the world that are to be represented by the model. Formal generative linguistic models tend to abstract over so-called performance data (Chomsky 1965). This is due to their scope being linguistic competence, or the properties of an innate cognitive module of the language faculty, and not the many dysfluencies in actual speech and communication.

Lastly, fidelity criteria describe the degree to which the model and world must be related for the sake of representation. They come in two flavors, according to Weisberg: (1) dynamical and (2) representational. Dynamical fidelity criteria evaluate the closeness between the output of the model and the output of the real-world phenomenon under study. In this case, contemporary artificial neural network models are remarkably dynamically faithful (Sullivan 2022). What they lack, as is evidenced by the explainable AI movement, is representational fidelity or the "standards for evaluating whether the model makes the right predictions for the right reasons" (Weisberg 2007, 221). Of course, in engineering settings, such as artificial intelligence, this might not be the most important aspect of the work. In scientific or explanatory settings, both sets of fidelity criteria are essential.

With a more defined role of intention in hand, we can move on to how these intentions are put to work in constructed models.

2.3 The construction assumption

Earlier, we discussed a prominent property of modeling in indirect or surrogate reasoning and a less prominent one in modeler's construal. In this section, we'll focus on a different side of modeling: its artifactual nature. Tarja Knuuttila's (2009, 2011, 2020, 2021) work has especially motivated the dual surrogacy and artifactual natures of scientific modeling in general.

The idea behind the artifactual component is that models are artifacts that are human-made and intentionally produced for particular purposes. Thus their natures can be revealed in terms of their purposes and design features. The view shares the idea that models are objects with the fictional accounts but differs in rejecting the distinction between concrete and abstract mathematical models. "There is no need for it: the artifactual view offers a unified account of modeling covering both abstract/nonconcrete and 'concrete' models" (Knuuttila 2021, 12). Knuuttila claims that the material nature of models allows for a variety of representational inferences.

Whether models are abstract objects with resemblance relations or morphisms, as Giere (1988) viewed them, fictional worlds, or physical molds, there seems to be an assumption that models are constructed and artifactual to a large degree. Let us call this the CA.

> **Construction assumption**. Scientific models are specifically constructed or explicitly designed in order to directly or indirectly represent a target phenomenon (or set of phenomena).

This assumption does not preclude the possibility of models being initially designed for one purpose and then subsequently used for another.[2] CA does, however, imply that models are not generally "found art." Whatever their ontology, they are tools honed for specific scientific purposes. In other words, the intentions of modelers qua constructionists matter to their status as models.

Whether models are understood as fictions, abstract objects, mediators, or sets of propositions (Thomson-Jones 2012), there is a distinctive artifactual or intentional element present across the board. In other words, models are things that are designed by modelers to fit a certain purpose. Again, Knuuttila (2020, 9) describes this situation as follows:

> Models are like any other artifacts in that they are human-made, or altered objects intentionally produced and used for some purposes within the sphere of particular human activities. They are concretely constructed things, making use of various representational tools and material media. As artifacts they are constructed for certain purposes, although they may also be repurposed for other uses.

Knuuttila's own account (see later), Currie's tool account, and even the DEKI framework of Frigg and Nyugen assume that models are explicitly constructed for particular theoretical purposes. However, if the core claim of modeling, what sets it apart from other scientific practices, is the surrogate reasoning it employs, I think it possible either to attenuate or even to abandon CA while retaining the core of the practice.

Knuuttila herself focuses on scientific practice in which a modeler employs "representational modes," such as 3-D models, mathematical equations, or diagrams, and "representational media," such as paper drawings, computer simulations, and other artifacts. No correspondence is needed between the former and the latter. The mode is the abstract level, and the media are its embodiment. However, that configuration bears fruit for a modeler. Lean to either side and you get either more

[2] Modeling in the cognitive sciences often makes use of templates drawn from the natural sciences to model specific mental operations or processes. Winsberg (2010) describes a number of cognitive scientific models taken from templates in physics, biology, chemistry, computer science, and so on, while Ortega and Braun (2013) discuss specific cases in which machine learning and thermodynamic templates are used to model decision-making and the costs of cognitive processing, respectively.

https://doi.org/10.1017/psa.2023.72 Published online by Cambridge University Press

mathematical mode–level modeling or more physical media–level modeling as is appropriate for a given task or scientific discipline. It's a neat picture of the process.

This is an indirect surrogate modeling account in that it takes models to be epistemic artifacts or "erotetic devices." The idea is that models are designed not only to answer certain theoretical questions or test hypotheses but also to generate questions (Knuuttila and Merz 2009). Knuuttila (2021, 14) describes the position in the following manner:

> Scientists learn from models by constructing and manipulating them. From the perspective of learning, the epistemic value of modeling can be attributed to their manipulability instead of (a more or less) accurate representation. To be sure, something is represented in the model . . . . In this the artifactual account agrees with the fictional ones, and those analyses of models that emphasize their surrogate or indirect nature.

Where the view diverges is in embedding constructed models within a larger sociocultural scientific knowledge background. Thus models are richer systems that either the intention or the "pretense" of modelers would allow. In addition, they are not direct representations of target systems or even primarily representational on this account. But the idea of an erotetic or question-generating device can be separated from CA, as the next section shows.

In contrast to this picture, Currie (2017) claims that the constructed class of models is beyond the scope of the standard indirect fictionalist accounts. For him, a better account of models views them as tools in a more pragmatic sense. After introducing his father's hydraulics models for large water pumps, he states of the view,

> A model's content, by contrast, depends upon what use it is put to. Sometimes, my father might use the mass-flow equation in an explanatory context, for instance, in accounting for how some pump has malfunctioned . . . . In other contexts, the mass-flow equation is a preliminary model . . . . It is my claim that understanding models qua tools is deeper, more unified, and more metaphysically kosher than understanding model qua fictions. (773)

Tools are described in terms of artifacts or objects used to manipulate other objects (materially). Currie offers sewing needles and hammers as the paradigmatic cases of artifacts. He defines a number of success conditions based on the degree of fit between the artifactual object and its function, purpose, and character. This clearly adheres to CA.

Of course, one rationale for the fictional approach is that by adopting some sort of Waltonian framework, highly abstract mathematical models can be characterized analogously with physical model systems, thereby presenting a unified view of the practice. This appeal might be lost with the purely artifactual approach that seems to incorporate a more material-based understanding of models. Nevertheless, a common understanding of modeling involves the idea of construction or CA, whether in an abstract mathematical model or physical model construction. We will challenge this idea in the next section for a particular subset of previously unexplored models, namely, natural models.

https://doi.org/10.1017/psa.2023.72 Published online by Cambridge University Press

3 Natural models

Positing the existence of natural models is motivated partly by scientific practice and partly by logical possibility. My argument is that the former exploits the latter. In this section, we will delve into the proof of concept by investigating how natural models were used in the early stages of the COVID-19 pandemic. Of course, this is merely an existence proof and a starting point for future discussion; it is not meant to be exhaustive of the practice.

Basically, the scientific strategy shares characteristics with classical modeling, especially the mechanism of surrogate reasoning (section 2.1.) and model organisms (section 4.1) in that they are not artificial systems. It also shares features with natural experiments in that they are unconstructed or provided by nature/society (see section 4.2).[3] We will call this practice *natural modeling* and its products *natural models*.

3.1 Natural models and the COVID-19 pandemic

The main line of argument for this novel position will draw from the actual practices of scientists, within the epidemiological setting, during the early stages of the COVID-19 pandemic. The focus will be on three properties assumed by the scientists themselves: (1) surrogate or indirect representation, (2) whether the tool was used as an erotetic device, and (3) whether or to what extent construal played a role in the use of the tool.

COVID-19 is the respiratory disease caused by the SARS-CoV-2 virus, which is a member of the coronavirus family of pathogens. Since its emergence in late 2019, the virus and its related disease have caused unprecedented suffering and loss of life and have wreaked havoc on global economies, especially in developing nations. The COVID-19 pandemic has also had numerous effects on our everyday lives and scientific practices. In epidemiology, the data-driven study of illness and disease in different populations, scientific practice was especially impacted. Procedures that usually take years, such as vaccine approval or clinical trials, were rapidly accelerated under various emergency authorization protocols (Doshi 2021). Even controversial stratagems, such as human challenge trials, have entered the public discourse and become viable options (Su, Shao, and Jiang 2021). Given the exigency of the situation, the data can often be impoverished or limited, and scientists are forced to find innovative sources of information for their models and eventual policy recommendations. The early days of the pandemic saw much focus on the cruise ship industry as the international "population zero" outside of Wuhan, China. Essentially, these were small, isolated, and selective populations of individuals trapped for various periods of time with a highly infectious disease spreading relatively uncontained through the decks and corridors.

Many of the early inferences that informed various policies and lockdown procedures across the globe were based on witnessing and determining the R rate (or reproduction rate) on the *Diamond Princess* cruise ship, which at one time had a larger number of infections than some affected countries. Thus, as per (1), inferences based

[3] Mäki (2005) makes a stronger connection between models and experiments by identifying them. If this were true, then natural experiments would just be natural models, and we would not have to motivate the position further. But this is a controversial claim, and it isn't clear that models and experiments share all of their features.

https://doi.org/10.1017/psa.2023.72 Published online by Cambridge University Press

on them were by nature indirect, because there were in some cases no cases on land as yet. The inferences were made from the actual to the possible in a sense. The natural model was thus used as a surrogate system that could be manipulated and controlled in a more tractable manner. As is often the case with classical models, the implications could be read off the system more clearly than noisier data from other populations of infected individuals. In addition, the possibility of the transmission of the virus taking place in presymptomatic or asymptomatic cases first presented itself in this setting (Furukawa, Brooks, and Sobel 2020). In some cases, the inferences resembled those of model organisms in that containment strategies used aboard one vessel were initially considered useful to other similar vessels in similar circumstances. As Takuya et al. (2020, 5) discuss,

> this report details the early phase of the outbreak investigation on a cruise ship quarantined in Yokohama Port that followed the confirmation of a disembarked passenger having COVID-19. This event required a large-scale quarantine that we had not experienced before, with a large number of international passengers and crew members further adding to the public health challenge. We believe that the findings from our experience are useful to respond to a similar COVID-19 event in an international cruise ship such as that quarantined at California in March 2020 or Nagasaki in April 2020.

They noticed, among other things, that infection rates among passengers were similar across the decks, where beverage (3.3 percent, 2/61) and food service staff (5.7 percent, 14/245) were the most affected. In addition, they also noticed that infection rates increased with age—a datum that would go on to become pivotal in vaccine distribution and quarantining protocol well into the height of the pandemic. Using RT-PCR tests, the scientists were able to collect data almost completely inaccessible in a normal population. For instance, consider their definition of a "close contact" as "someone who joined the Kagoshima tour with the index case, who shared a cabin with a confirmed case or who shared the same cabin with a suspected case" (Takuya et al. 2020, 2). Such a definition is as close to ideal as it could be in the real world. Defining close contacts in terrestrial populations (pre-lockdowns) is extremely difficult given the sheer number of casual and intimate interactions people encounter daily. On the cruise ship, this parameter could be set and measured with near precision, producing a more ideal R rate estimate.

The use of cruise ships involved not only inferences concerning spread and containment at the population level but also biological processes, such as viral shedding or the discharge of infected particles in speech, expectoration, and other bodily functions. In such a study, Hung et al. (2020, 1051), again focusing on the *Diamond Princess*, come closest to identifying the modeling analogy I am advocating when they state,

> A cruise ship is a closed-off environment that simulates the basic functioning of a city in terms of living conditions and interpersonal interactions. Thus, the *Diamond Princess* cruise ship, which was quarantined because of an onboard outbreak of COVID-19 in February, 2020, provides an opportunity to define the shedding pattern of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and patient antibody responses before and after the onset of symptoms.

https://doi.org/10.1017/psa.2023.72 Published online by Cambridge University Press

They tested patients under quarantine who had disembarked from the cruise ship with negative RT-PCR tests at four-, eight-, and twelve-day intervals. Their findings showed that "patients with COVID-19 can develop asymptomatic lung infection with viral shedding and those with evidence of pneumonia on imaging tend to have an increased antibody response" (Hung et al. 2020, 1051). Their recommendations involved some of the earliest suggestions of the role contact tracing and serology can play in the mitigation of the virus. Thus, in terms of (2), these models were used not only to ask questions of larger populations qua erotetic devices but also, as Knuuttila emphasizes, to generate questions such as what role asymptomatic viral shedding *might* play in larger populations.

Like classical models, the resemblance relations between the model and reality are not perfect or close to identical. As Rocklöv, Sjödin, and Wilder-Smith (2020, 1) indicate, "cruise ships present a unique environment for transmission of human-to-human transmitted infections." In fact, given the close quarters and confined spaces, they tend to increase the R rate of various infectious diseases (e.g., noroviruses were quite common on cruise ships prior to the pandemic). "The basic reproduction rate was initially 4 times higher on-board compared to the R0 in the epicentre in Wuhan, but the countermeasures lowered it substantially" (Rocklöv, Sjödin, and Wilder-Smith 2020, 1). They explicitly use a model based on the cruise ship to estimate the effect interventions like isolation and quarantine would have on the R rate of normal populations. Similarly, Batista et al. (2020) use cruise ships to model control measures for R0 or the reproduction number with no immunity in the affected community. They claim,

> The motivation for developing mathematical models of infection in a closed system such as a nursing home or cruise ship is to evaluate possible control strategies that may be put in place in case of an emergency. (5)

Finally, Russell et al. (2020) estimate the CFR, or case fatality rate, of the Chinese population based on the same rate on the *Diamond Princess*, adjusting for age and delays between confirmation and death (a "real"-world population problem). In other words, they use features of the closed model system to infer actual features in larger populations. One might consider these cases to exclusively involve inferences based solely on epidemiological needs. However, Addetia et al. (2020) go further to apply natural models to microbiological investigation. They challenge the exclusive focus on animal models in determining protective immunity in humans. Instead, they perform a retrospective analysis of a SARS-CoV-2 outbreak on a fishing vessel that departed from Seattle, Washington, in May 2020. They were interested in what immunity the presence of neutralizing antibodies provided to sailors who possessed them prior to embarking on a voyage that resulted in a high attack rate. They insist that "in particular, outbreaks on confined shipping vessels are particularly useful candidates for assessing protection from SARS-CoV-2 infection" (Addetia et al. 2020, 2). Given the high density and unavoidable close contact, the entire population quickly becomes infected, providing a natural setting for the evaluation of the effect of things like antibody protection.

In a similar vein to the fishing vessel model, studies on the little-known humoral immune response to SARS-CoV-2 were made possible by the relatively isolated nature of the Icelandic population early in the pandemic (Gudbjartsson et al. 2020). Such studies are vital for determining the susceptibility of larger populations to second waves because the antibody prevalence can be tested and controlled for more easily in these latter cases. We have seen similar information emerging from islands like the Seychelles in terms of vaccine efficiency. Compare this to von Thünen's 1826 economic model of an isolated state on fertile land but wholly cut off from contact with the outside world used to highlight the relationship between land and transportation costs.

These are just some of the models that were used by actual scientists on the ground during the early days of the pandemic. In some cases, scientists tested existing models on cruise ship data; in other cases, they used a cruise ship to directly define strategies for containing the virus in other similar systems qua model organism; and in the majority of studies, they used the cruise ships, fishing vessels, and small populations as models of the infection rate, death rate, and mitigation factors in larger terrestrial populations. Most researchers explicate the strategy as one in which a closed, isolated system with similar but distinct features is used to infer the effects of contagion in larger, more normalized populations of individuals. The former natural conditions are at times as close to ideal as they could be. I have presented only a sketch of the research landscape here as proof of concept. The idea is that natural models exist and were used widely during the early stages of the COVID-19 pandemic.

As we saw in section 2.3, following Knuuttila (2021), one core aspect of models is their epistemic status as erotetic devices. And part of this status involves learning 'from models by constructing and manipulating them.' I have shown that natural models can be used for surrogate reasoning in a theoretical sense, but these examples also showcase the abilities of modelers to manipulate natural models by altering the interventions onboard certain vessels and witnessing the real-time effects thereof. In other words, we can ask questions of cruise ships, fishing vessels, and so on, and by doing so, we are asking about other larger systems.

In addition, in terms of (3), modelers can construe the same natural model as a device for public health intervention strategies or a testing ground for immunity in larger populations analogously to the pendulum-circuit case of Thomson-Jones (2012). As we saw with the *Diamond Princess*, modelers focused on different aspects and features and draw different conclusions from the same system. Thus construal played a major part in the development of natural models in this case. Modelers first needed to identify the real-world target phenomenon, for example, infection rates, then assign aspects of the cruise ship or other natural model to coordinate with the real world, such as contact spreading or the effects of various intervention strategies. Because the population demographics of these natural systems often differed from terrestrial populations (such as average age), the scope would need to be limited in some cases. Furthermore, both dynamical and representational fidelity criteria were essential. Generating the correct output was necessary for the measurement of potential mitigating public health strategies, but finding the particular triggers for the explanation of the output was the overarching scientific goal.

The intentions of the modelers are thus relevant to the practice as is the case with modeling in general. In fact, two of the three properties of standard modeling strategies were present in work on cruise ships, fishing vessels, and other actual isolated physical systems during the early pandemic.

https://doi.org/10.1017/psa.2023.72 Published online by Cambridge University Press

Before I discuss where natural models might fit into the larger practice of modeling, I will consider three possible objections to the position advocated here.

3.2 Three potential objections

Three immediate philosophical worries might provoke caution in the positing of natural models. First, one might worry that all of this natural models talk is very well in an unprecedented emergency, such as the COVID-19 pandemic, but that in cases of "normal science," natural models are less likely to be harnessed. This does not deny the possibility, but it seriously attenuates its status as a stable occupant of the missing scientific modeling typology and perhaps casts doubt on the continuum itself. The concern might further be expressed as the claim that philosophers of science are interested in "normal scientific practice," whatever that may mean.

This line of reasoning would, of course, expose a bias on the part of the philosophy of science—specifically, a bias toward natural sciences like physics and chemistry, in which the targets of models are often relatively static and less contingent. The philosophy of epidemiology, on the other hand, finds itself placed precisely in the world of outbreaks, emergency vaccinations, and fast-paced science. Ruling such circumstances out by fiat seems like an arbitrary stipulation. In addition, the innovations and data drawn from pandemics, and this pandemic in particular, will go on to inform not only epidemiology but microbiology and related disciplines. Broadbent (2013, 4) suggests that epidemiology is striking in terms of "its nonconformity to standard philosophical images of science" in which experiment and theory play a much more prominent role. Rather, the field "makes central use of 'observational' methods, meaning methods that do not involve controlled experiments" (4). Natural models as I have described them certainly fit with this expanded picture of science.

The next objection is more serious and concerns CA. Some people might insist that natural models are not models by definition. On this view, models are contrived or artifactual devices used either directly or indirectly to represent features of the real world. Thus models are hypothetical systems (as per Godfrey-Smith's [2006] account), not actual ones. Some of this kind of thinking might be behind resistance to the idea that model organisms are indeed theoretical models, as we will see. Nevertheless, to this point, I claim modal discrimination.

Consider the following argument. You are faced with the emergence of a novel pathogen with an unknown impact on human populations. The data are slim, and various international bodies are looking to you for policy guidance. Thus you decide to imagine a scenario in which you can determine possible R rates, CFRs, the effect of immunity, and the efficacy of various intervention strategies. So you stipulate a model that involves a group of strangers boarding an isolated vessel that acts as a closed system for the spread and containment of the virus. If you are concerned about the correlation between severity of infection and the age of the population, you might fix the average age of the participants to older than sixty years. You infer how a newly introduced pathogen would act in this population and monitor its activity. At some point, you attempt to measure which preventative strategies are most effective at lowering the infection rate. Again, the isolation and close quarters of the group assist in determining the immediate impact of each stratagem. You have historical data of

https://doi.org/10.1017/psa.2023.72 Published online by Cambridge University Press

similar outbreaks in similar vessels to add to your model construction. If this is too abstract, you could model these features within a computer simulation.

If this sounds familiar, it is because you have just contrived the cruise ship scenario. CA is overtly respected. What remains to be shown is why the invented model or simulation is more scientifically legitimate than the use of an actual situation with all of the features you stipulated in your surrogate reasoning. To me, it would be no different, except in modal character; that is, your model would be unactualized, and the *Diamond Princess* was real. Why its actuality should count against it as a model is unclear, especially if similar intentions and surrogate reasoning are present—and similarly for cases involving natural experiments discussed in section 4.3.

In fact, it would be especially hard to follow Godfrey-Smith's (2006) claim that a model is a system that "would be concrete if it were real" and then to deny a model that turns out to be concrete. It is not the ontology of hypothetical models that makes them models but rather their features. These features can often be shared by real-world systems, as is the case of natural models.

Last, one might object to the present argument by insisting that the process involved is not surrogate reasoning but rather a common statistical technique called generalization from "sample to population." In a landmark paper on the *Diamond Princess*, Mallapaty (2020, 18) quotes noted epidemiologist John Ioannidis as saying that "cruise ships are like an ideal experiment of a closed population. You know exactly who is there and at risk and you can measure everyone." In fact, some publications have since followed the claim that cruise ships are natural experiments. Although this might be true of some of the research on cruise ships during the pandemic, is doesn't preclude the present analysis in others. Currie and Levy (2019, 1075) hold that the difference between models and experiments is a special case of the difference between the theoretical and the empirical:

> Models, and theoretical devices more generally, are representations of the world —attempts to say something about some range of phenomena. In representing some natural system, a theory or model tells us to expect, or to entertain the possibility, that the system is a certain way. In contrast, empirical work, like experiment and observation, is a means of making causal contact with the world.

They don't preclude the possibility that one scientific object can be construed in different ways or according to different functions (both theoretical and empirical). One way of appreciating the present argument is that the cruise ship data were very often *theoretically* construed during the early days of the pandemic, thus making the investigative practice more model-like than experiment.

Additionally, the kind of statistical generalization associated with natural experiments also requires a direct representational relationship to hold between tool and target. Sample populations, whether selective or random, tend not to admit theorists' construal or the possibility of nonveridical inferences. In other words, we look at what the sample tells us directly, not what it indirectly indicates. In many cases, the cruise ship or fishing vessel data were never meant to inform us about the exact effects of outbreak on larger populations, because many of the features of these models are not shared by such populations. For instance, the R rate of cruise ships tended to be considerably higher than among normal populations. This would be a bad sample if it were meant to be one. Consider the parallel worry concerning model organisms—one could object that they are primarily sampling inferences. But the samples in this case are not of the same kind (of population) and thus would constitute bad statistical practice if they were merely taken as such. As we will see in section 4.2, model organisms can be used directly in some cases, but given their contrived breeding and generalization beyond their species, they tend not to be. Similarly, what these natural models allow us to do is to make inferences while adjusting for the distance between the model and the reality we are aiming to understand. This is closer to the surrogate reasoning employed in classical models—a surrogacy absent in the case of experiment or sampling generalizations.[4]

Furthermore, there is a certain counterfactual flavor to natural models. In the early days of the pandemic, cruise ships had infection rates that terrestrial populations did not. In fact, many of the former had no known cases at the time. The inferences were from the actual to the possible. In sampling generalization, the inferences run from the actual to the actual. Generalization from sample to population has a few common features. The scientist first identifies a target population and an accessible population. The former is the entire group of individuals to which the researcher hopes to generalize based on a set of criteria (e.g., presence of a particular disease, low income, birthrate etc.). The accessible population is a subset of this domain that exemplifies local instances of the target properties. The sampling itself, that is, the process of selecting a set of participants for the study, generally involves two important criteria: *randomization* and *representativeness*. Sampling randomization ensures that each individual in the population has an equal chance of being selected (within certain parameters determined by the target). Representativeness, on the other hand, requires that the sample resemble the target population in important (and numerous) ways. Randomization can be the most effective means of achieving representativeness. It is clear from the way that cruise ships and other such systems were used that both of the criteria were missing. The samples were not randomized, nor were they particularly representative. Again, according to the reasoning of the present article, this was because they were being used for indirect representation or surrogate reasoning, not direct sample-to-population generalization. Another way of putting the point is that if what I have been calling natural models were merely sample-to-population generalizations, then they would be risking both *sampling error*, in which a chosen sample does not represent the entire target population, and *sampling bias*, in which certain members (e.g., the elderly) are more likely to be selected than others in a sample.

Of course, there are many different kinds of sampling methods, and generalizability is a major topic in the philosophy of science (Firestone 1993; Woodside 2010). Natural models, as well as many other scientific techniques, involve some form of generalization or an attempt "to learn from one [case] and understand many [cases]" (Campbell 1986, 15). My claim is that this kind of generalization is more

[4] You could argue, with Parker (2009), that experiments do indeed involve some sort of surrogacy. Even so, natural experiments very often still maintain a distinction between a control group and an experimental or treatment group, something absent in the case of many of the natural models cited in this text. See section 4.2.

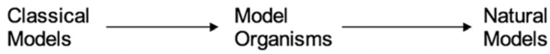

Figure 1. Scientific modelling continuum.

closely associated with scientific modeling strategies than with sampling generalizations and similar statistical techniques. In the last part of the article, I argue this point by means of analogy with other classes of models, ranging from classical to model organisms. Moreover, the underlying issue of extrapolation or "external validity" affects various accounts from classical models to model organisms. External validity "refers to the approximate validity with which we can infer that the presumed causal relationship can be generalized to and across alternate measures of the cause and effect and across different types of persons, settings, and times" (Cook 1979, 38). Basically, it asks us to which domains, populations, variables a given effect can be generalized. This presents a challenge for all accounts of modeling, as well as experiments (Jiménez-Buedo and Russo 2021), and I cannot pretend to solve the issue here.

4 Motivating a modeling continuum

In the last section, I plan to proffer a continuum view of scientific modeling based on different degrees to which the practice relies on explicitly constructed devices. In section 2, I discussed the literature on classical models and drew three important features. Thus classical models occupy the first point of the continuum, in which indirect representation, modeler's intentions, and CA characterize much of the practice. In section 4.1, I motivate the idea that model organisms, sometimes considered to be models themselves, fall within the midpoint of a continuum in that they are not generally explicitly constructed but still involve surrogate reasoning. In section 4.2, for the sake of analogy, I suggest that natural experiments mirror aspects of CA but deviate from other aspects of canonical cases of scientific experimentation in ways similar to what I've argued for natural models.

It is important to note that I am not here attempting to define scientific models directly or provide an ontological account; rather, the aim is to describe the practice or strategy of scientific modeling similar to the remits of Godfrey-Smith (2006) and Weisberg (2013). The motivated continuum is represented in figure 1.

From figure 1, each step (indicated with arrows) weakens the commitment to CA. For instance, if we take "classical models" to be the standard cases, such as the Lotka–Volterra model of predation (Weisberg and Reisman 2008), Schelling's (1978) computational model of segregation, and Fisher's three-sex organism, then we have highly constructed models. Model organisms involve some construction but emerge from natural biological systems, whereas natural models, similarly to natural experiments, do not involve construction (or CA) at all.

4.1 Model organisms

The topic of model organisms is a large one in the philosophy of science, specifically in the philosophy of biology. The practice involves studying some aspect of a biological system or organism by means of studying a simpler, more tractable

https://doi.org/10.1017/psa.2023.72 Published online by Cambridge University Press

organism. For instance, instead of attempting to use human cells or subjects to study mammalian molecular structure or development, one studies a bacteriophage or yeast for the former and mice or fruit flies for the latter. This theoretical choice is not only extremely cost-effective but allows more readily for information transfer and the creation of large databases. It is important at the outset to mention that model organisms are not studied for the sake of understanding the biological mechanisms of the specific species chosen but rather a more general target. "The term 'model organism' was used to indicate a simplified, tractable system that could be used to study a larger theme of biology, and indicated not so much as a feature of the system itself, as an attitude on the part of the researcher" (Marshall 2017, 1). So, if a scientist wants to understand gene regulation in general, they can make use of bacteriophage as a proxy for the process. The underlying idea is evolutionary in nature, "according to which all life forms are related through common evolutionary history and thus share a smaller or greater amount of genetic make-up and a number of developmental features" (Ankeny and Leonelli 2020, 2). And the most common species to act as model organisms are fruit flies, mice, rats, zebra fish, baker's yeast, and nematodes or roundworms.

There are advantages and drawbacks of using model organisms to investigate biological phenomena. Some of the benefits have been gestured at earlier—the systems are smaller and more tractable. They are easier to breed and manipulate genetically. They are relatively cost-effective, and they aid in the creation of large databases for comparison and extraction. But a focus on model organisms has also led to a general neglect of organisms and systems not on official lists, which in itself is a very limited set. In addition, in systems biology, the emphasis is on biological systems, which are considered to outstrip individual organisms isolated from their constitutive environments (see Dupré and O'Malley 2007). This perspective is lost in part with the focus on model organisms.

Given the earlier positive description of model organisms, one might be tempted to unequivocally consider them to be scientific or theoretical models. The study of larger systems via smaller, more tractable ones seems to fit the general practice. Indeed, many have taken model organisms to fall within the remit of scientific modeling (Ankeny and Leonelli 2011; Weisberg 2013; Frigg and Hartmann 2018). For Weisberg, the major and perhaps only difference between model organisms and classical models is that the former do not involve anything like CA. This point is debatable. Indeed, many model organisms, such as fruit flies or *Drosophila*, were initially found in the wild. But model organisms are often precisely chosen for their easy reproducibility under laboratory conditions. This has resulted in selective breeding and genetic manipulation to the extent that many lab specimens are now considerably distinct from their wild counterparts. In fact, this is exactly why they can be considered to occupy the midpoint of the continuum posited here. Ankeny and Leonelli (2011) argue that all experimental organisms can be understood as models qua the "models-as-mediators" framework (see Morgan and Morrison 1999).

For Ankeny and Leonelli, proper model organisms are experimental organisms and partly autonomous because they can act as mediators between theories. Note also that model organisms can serve as both direct and indirect reference points for the study of larger organisms or features. Take, for example, mice (*Mus musculus*). A scientist can use a mouse qua model organism to study aspects of rodents or mice directly or more indirectly to understand other processes, such as cancer or addiction in human beings.

However, despite these initial similarities, some theorists have recently disputed the idea that model organisms are related to theoretical models. Levy and Currie (2015) argue that they differ in "epistemic character." They claim that model organisms are empirical extrapolations more than theoretical surrogates. Furthermore, they suggest that the practice is localized to biology. They do highlight two kinds of "model-like" inferences based on cases in which generalized applicability is generated as circumstantial evidence, for example, the organism is treated as a specimen, and cases in which phylogenetic relatedness is assumed, respectively. They insist that the former cases are not the kind of proxy relations common with theoretical models because the model and target can often be of the same substance. Of course, identity of substance is not preserved in the phylogenetic case, which is by far more common in biology than the circumstantial case. However, the phylogenetic instances of model organism use are too parochial according to Levy and Currie; as they state, "this latter form of inference is distinctively biological, and we think it sets apart model organism work from other kinds of theoretical methods" (336).[5] In the majority of this article, I have argued that this kind of inference is not distinctive or exclusive to biology but surfaces in epidemiology through natural models.

Parkkinen (2017) agrees with the overall thrust of Currie and Levy's (2019) argument but maintains, by means of case study, that there are instances in the biomedical sciences in which modelers employ the strategies the latter authors attribute to theoretical models. Rather, his claim is that "theoretical models do have epistemic characteristics that differ from those of animal models, as Levy and Currie suggest, but this distinction does not robustly track differences in the strategies of justifying model-to-target inferences" (Parkkinen 2017, 472). He, by contrast, argues that unlike theoretical models, model organisms do not encode explicit assumptions on which to base inferences. Nevertheless, he maintains a core aspect of scientific modeling described so far, namely, surrogacy in terms of causal similarity.

This is to say that model organisms are surrogate systems for indirect (and sometimes direct) representation or inference from model to target. They are partly constructed but generally found in the wild, so to speak. Thus they occupy a position in the theoretical continuum in which surrogate reasoning meets partial construction. In the next section, we will take a slight detour to discuss a method that exploits conditions beyond the theorist's or experimenter's control but yields similar epistemic dimensions to constructed randomized experiments.

4.2 Natural experiments

In the final part of the paper, I hope to show that a similar pattern of reasoning or "common argument pattern" (Kitcher 1989) is relatively uncontroversial in the case of the relationship between experiments and natural experiments. In other words, if there already exists a natural kind of experimentation differing from regular

[5] Currie and Levy (2019, 1072) offer further nuance and suggest that model organisms like *E. coli* can act as models or "material theoretical devices," depending on the epistemic context. They further complicate the notion of "same substance" and note that "material similarity matters in some contexts, but we doubt this line of thought's generality."

https://doi.org/10.1017/psa.2023.72 Published online by Cambridge University Press

experiments in only its adherence to CA, then an analogous case can be made for theoretical models.

CA is generally important in experimentation. Experiments are explicitly designed tools for testing theories and evaluating scientific claims. Part of scientific training, both natural and social, involves learning to harness the skill of experimental design and avoiding various (and numerous) biases that go along with it. We'll consider a subset of experiments called randomized control trials, or RCTs, "in which subjects are randomly assigned to one of two groups: one (the experimental group) receiving the intervention that is being tested, and the other (the comparison group or control) receiving an alternative (conventional) treatment" (Kendall 2003, 164). The two groups are then compared to observe any differences in the outcome.

In many cases, RCTs are impractical or unethical for evaluating a particular intervention at a given time. Natural experiments are then evaluated based around the idea that a particular intervention has occurred beyond the control of researchers (Craig et al. 2012; Craig et al. 2017). Although there is no agreed-upon definition of the practice, its importance is appreciated by many theorists in public health and beyond. Concerning feasibility, for example, controlled or clinical trials of interventions involving suicide rates in general populations are prohibitively cumbersome and would involve enormous studies. On the other hand, "natural experimental approaches are important because they widen the range of interventions that can usefully be evaluated beyond those that are amenable to planned experimentation" (Craig et al. 2012, 3).

Despite the differences in implementation or rationale, there are some common features between RCTs and natural experiments. Both require comparisons to be made between affected and unaffected groups for analysis. If we are evaluating a longitudinal study of the effects of smoking, we need to compare groups of nonsmokers with smokers over that time period. But these "controls" are provided by nature or society and not by the researchers themselves. Morgan (2013, 344) considers this to be the defining feature of such experiments:

> I take the term to imply that those events we single out as Nature's (or Society's) experiments must not only have an intervention that stems from (is created or caused by) Nature or Society but also where controls—or valid substitutes for control—over the experimental environment are also instantiated in Society/Nature.

In some cases, such as "Genie," the linguistically challenged young girl held prisoner for the critical period of her language acquisition, the controls were cruel and enforced (Curtiss et al. 1974). In other cases, they are more naturally occurring, as it is with groups of nonsmokers and smokers. Either way, the conditions mimic the conditions one would select for in a laboratory setting (if ethics and feasibility were not considerations). For instance, RCTs involve the notion of "exchangeability." This means that, given that assignment to the control or intervention groups is randomized, "the intervention's average causal effect can be estimated from the difference in the average outcomes for the two groups" (Craig et al. 2017, 40). Natural experiments then need to be conditionally exchangeable to track possible influencing variables. More knowledge of the system helps in this regard (there are also techniques like matching, regression, or conditioning on covariates). Of course, these studies come with significant problems, especially in terms of bias and confounding variables. It is not my purpose to provide a full characterization of the scientific practice, and aside from Morgan (2013), Reiss (2008), and a handful of other studies, little philosophical work has been directed at understanding natural experiments.

What is important for our purposes is that natural experiments are nonconstructed scientific tools used in similar ways to controlled or laboratory experiments. They are the natural versions of devices in which explicit construction is considered essential. Although their circumstances of use are often different, and there are clear limitations, they perform a similar role to the standard forms of experiments found across the natural and social sciences. In other words, they are experiments that do not respect CA but still involve a number of other standard assumptions about experiments. This much is uncontroversial. What I have aimed to show in this work is that a similar strategy involving natural models is present in scientific practice.

5 Conclusion

Of course, more can be said here. The aim of the present work was to flesh out a novel position in the scientific modeling landscape and, in so doing, motivate a connected picture of various such surrogate devices found in scientific practice. In this article, I have laid out the assumptions of a number of prominent accounts of classical models. On this basis, I have argued for a scientific modeling continuum that incorporates model organisms in biology and natural models in epidemiology as they have been described here. The COVID-19 pandemic has changed the way in which we view many aspects of life; the suggestion offered here is that it might warrant the same level of reflection of our views in the philosophy of science going forward.

Acknowledgements. I would like to thank Alex Broadbent and Jonathan Fuller for invaluable early discussions on the topic. I am especially grateful to Harold Kincaid for his excellent feedback on a number of drafts. Lastly, I would like to thank an anonymous referee of this journal for useful comments and guidance. All remaining errors are my own. This research was funded by the National Research Foundation of South Africa.

References

Addetia, Amin, Katharine H. D. Crawford, Adam Dingens, Haiying Zhu, Pavitra Roychoudhury, Meei-Li Huang, Keith R. Jerome, Jesse D. Bloom, and Alexander L. Greninger. 2020. "Neutralizing Antibodies Correlate with Protection from SARS-CoV-2 in Humans during a Fishery Vessel Outbreak with a High Attack Rate." *Journal of Clinical Microbiology* 58 (11):e02107–20.

Ankeny, Rachel, and Sabina Leonelli. 2011. "What's So Special about Model Organisms?" *Studies in the History and Philosophy of Science* 42 (2):313–23.

Ankeny, Rachel, and Sabina Leonelli. 2020. *Model Organisms*. Cambridge: Cambridge University Press.

Batista, Berlinda, Drew Dickenson, Katharine Gurski, Malick Kebe, and Naomi Rankin. 2020. "Minimizing Disease Spread on a Quarantined Cruise Ship: A Model of COVID-19 with Asymptomatic Infections." *Mathematical Biosciences* 329:108442.

Broadbent, Alex. 2013. *The Philosophy of Epidemiology*. New York: Palgrave Macmillan.

Campbell, D.T. 1986. "Relabeling Internal and External Validity for the Applied Social Sciences." In *Advances in Quasi-Experimental Design and Analysis*, edited by William Trochim, 67–77. San Francisco: Jossey-Bass.

Cartwright, Nancy. 1983. *How the Laws of Physics Lie*. London: Clarendon Press.

Chomsky, Noam. 1965. *Aspects of the Theory of Syntax*. Cambridge, MA: MIT Press.

Cook, Thomas. 1979. *Quasi-experimentation: Design and Analysis Issues for Field Settings*. Boston: Houghton Mifflin.

Craig, Peter, Cyrus Cooper, David Gunnell, Sally Haw, Kenny Lawson, Sally Macintyre, David Ogilvie, Mark Petticrew, Barney Reeves, Matt Sutton, and Simon Thompson. 2012. "Using Natural Experiments to Evaluate Population Health Interventions: New Medical Research Council Guidance." *Journal of Epidemiology and Community Health* 66 (12):1182–86.

Craig, Peter, Srinivasa Vittal Katikireddi, Alastair Leyland, and Frank Popham. 2017. "Natural Experiments: An Overview of Methods, Approaches, and Contributions to Public Health Intervention Research." *Annual Review of Public Health* 38 (1):39–56.

Currie, Adrian. 2017. "From Models-as-Fictions to Models-as-Tools." *Ergo* 4 (27):759–81.

Currie, Adrian, and Arnon Levy. 2019. "Why Experiments Matter." *Inquiry* 62 (9–10):1066–90.

Curtiss, Susan, V. Fromkin, S. Krashen, D. Rigler, and Marilyn Rigler. 1974. "The Linguistic Development of Genie." *Language* 50 (3):528–54.

Doshi, Peter. 2021. "COVID-19 Vaccines: In the Rush for Regulatory Approval, Do We Need More Data?" *British Medical Journal* 373:n1244.

Dupré, John, and Maureen O'Malley. 2007. "Metagenomics and Biological Ontology." *Studies in History and Philosophy of Biological and Biomedical Sciences* 38 (4):834–46.

Firestone, William. 1993. "Alternative Arguments for Generalizing from Data as Applied to Qualitative Research." *Educational Researcher* 22 (4):16–23.

Frigg, Roman. 2010. "Models and Fiction." *Synthese* 172 (2):251–68.

Frigg, Roman, and Stephan Hartmann. 2018. "Models in Science." In *The Stanford Encyclopedia of Philosophy*, edited by Edward N. Zalta. https://plato.stanford.edu/archives/sum2018/entries/models-science/.

Frigg, Roman, and James Nguyen. 2016. "The Fiction View of Models Reloaded." *The Monist* 99 (3):225–42.

Frigg, Roman, and James Nguyen. 2017. "Models and Representation." In *Springer Handbook of Model-Based Science*, edited by M. Magnani and T. Bertolotti, 73–126. Berlin: Springer.

Furukawa, Nathan, John Brooks, and Jeremy Sobel. 2020. "Evidence Supporting Transmission of Severe Acute Respiratory Syndrome Coronavirus 2 While Presymptomatic or Asymptomatic." *Emerging Infectious Diseases* 26 (7):e1–6.

Giere, Ronald. 1988. *Explaining Science: A Cognitive Approach*. Chicago: University of Chicago Press.

Godfrey-Smith, Peter. 2006. "The Strategy of Model-Based Science." *Biology and Philosophy* 21 (5):725–40.

Gudbjartsson, Daniel, Gudmundur L. Norddahl, Pall Melsted, Kristbjorg Gunnarsdottir, Hilma Holm, Elias Eythorsson, Asgeir O. Arnthorsson et al. 2020. "Humoral Immune Response to SARS-CoV-2 in Iceland." *New England Journal of Medicine* 383:1724–34.

Hung, Ivan, Vincent Chi-Chung Cheng, Xin Li, Anthony Raymond Tam, Derek Ling-Lung Hung, Kelvin Hei-Yeung Chiu, Cyril Chik-Yan Yip et al. 2020. "SARS-CoV-2 Shedding and Seroconversion among Passengers Quarantined after Disembarking a Cruise Ship: A Case Series." *Lancet Infectious Diseases* 20:1051–60.

Jiménez-Buedo, Maria, and Frederica Russo. 2021. "Experimental Practices and Objectivity in the Social Sciences: Re-embedding Construct Validity in the Internal–External Validity Distinction." *Synthese* 199:9549–79.

Kendall, Jason. 2003. "Designing a Research Project: Randomised Controlled Trials and Their Principles." *Emergency Medical Journal* 20:164–68.

Kitcher, Philip. 1989. "Explanatory Unification and the Causal Structure of the World." In *Scientific Explanation*, edited by P. Kitcher and W. Salmon, 410–505. Minneapolis: University of Minnesota Press.

Knuuttila, Tarja. 2009. "Some Consequences of the Pragmatic Approach to Representation: Decoupling the Model–Target Dyad and Indirect Reasoning." In *Proceedings of the Founding Conference of European Philosophy of Science Association*, edited by M. Rèdei, M. Suárez, and M. Dorato, 139–148. Berlin: Springer.

Knuuttila, Tarja. 2011. "Modelling and Representing: An Artefactual Approach to Model-Based Representation." *Studies in the History and Philosophy of Science* 42 (2):262–71.

Knuuttila, Tarja. 2020. "Models, Fictions, Artifacts." In *Language and Scientific Research*, edited by W. Gonzalez, 199–220. London: Palgrave Macmillan.

Knuuttila, Tarja. 2021. "Imagination Extended and Embedded: Artifactual versus Fictional Accounts of Models." *Synthese* 198 (Suppl 21): 5077–5097. https://doi.org/10.1007/s11229-017-1545-2

Knuuttila, Tarja, and Martina Merz. 2009. "Understanding by Modeling: An Objectual Approach." In *Scientific Understanding: Philosophical Perspectives*, edited by H. de Regt, S. Leonelli, and K. Eigner, 146–68. Pittsburgh, PA: University of Pittsburgh Press.

Leatherdale, Scott. 2019. "Natural Experiment Methodology for Research: A Review of How Different Methods Can Support Real-World Research." *International Journal of Social Research Methodology* 22 (1):19–35.

Levy, Arnon. 2015. "Modeling without Models." *Philosophical Studies* 172 (3):781–98.

Levy, Arnon, and Adrian Currie. 2015. "Model Organisms Are Not (Theoretical) Models." *British Journal for the Philosophy of Science* 66 (2):327–48.

Mäki, Uskali. 2005. "Models Are Experiments, Experiments Are Models." *Journal of Economic Methodology* 12 (2):303–15.

Mallapaty, Smriti. 2020. "What the Cruise-Ship Outbreaks Reveal about COVID-19." *Nature* 580:18.

Marshall, William. 2017. "Introduction—Model Organisms for Understanding Biology." *BMC Biology* 15:55.

Morgan, Mary. 2013. "Nature's Experiments and Natural Experiments in the Social Sciences." *Philosophy of the Social Sciences* 43 (3):341–57.

Morgan, Mary, and Margaret Morrison. 1999. *Models as Mediators*. Cambridge: Cambridge University Press.

Ortega, Pedro, and Daniel Braun. 2013. "Thermodynamics as a Theory of Decision-Making with Information-Processing Costs." *Proceedings of the Royal Academy, Series A* 469 (2153):1–18.

Parker, Wendy. 2009. "Does Matter Really Matter? Computer Simulations, Experiments, and Materiality." *Synthese* 169:483–96.

Parkkinen, Veli-Pekka. 2017. "Are Model Organisms Theoretical Models?" *Disputatio* 9 (47):471–98.

Reiss, Julian. 2008. *Error in Economics*. London: Routledge.

Rocklöv, J., H. Sjödin, and A. Wilder-Smith. 2020. "COVID-19 Outbreak on the *Diamond Princess* Cruise Ship: Estimating the Epidemic Potential and Effectiveness of Public Health Countermeasures." *Journal of Travel Medicine* 27 (3):taaa030.

Russell, T., J. Hellewell, C. Jarvis, K. van Zandvoort, S. Abbott, R. Ratnayake, S. Flasche, R. Eggo, W. Edmunds, and A. Kucharski. 2020. "Estimating the Infection and Case Fatality Ratio for Coronavirus Disease (COVID-19) Using Age-Adjusted Data from the Outbreak on the *Diamond Princess* Cruise Ship, February 2020." *Euro Surveillance* 25 (12):2000256.

Schelling, Thomas. 1978. *Micromotives and Macrobehaviour*. New York: W. W. Norton.

Su, Shan, Yiming Shao, and Shibo Jiang. 2021. "Human Challenge Trials to Assess the Efficacy of Currently Approved COVID-19 Vaccines against SARS-CoV-2 Variants." *Emerging Microbes and Infections* 10 (1):439–41.

Suárez, Maurico. 2004. "An Inferential Conception of Scientific Representation." *Philosophy of Science* 71 (5):767–79.

Sullivan, Emily. 2022. "Understanding from Machine Learning Models." *British Journal for the Philosophy of Science* 73 (1):109–33.

Suppes, Patrick. 1960. "A Comparison of the Meaning and Use of Models in Mathematics and the Empirical Sciences." *Synthese* 12:287–300.

Takuya, Y., K. Hajime, K. Kensaku, S. Motoi, and W. Takaji. 2020. "Descriptive Study of COVID-19 Outbreak among Passengers and Crew on *Diamond Princess* Cruise Ship, Yokohama Port, Japan, 20 January to 9 February 2020." *Euro Surveillance* 25 (23):2000272.

Thomson-Jones, Martin. 2012. "Modelling without Mathematics." *Philosophy of Science* 79 (5):761–72.

Toon, Adam. 2011. "Playing with Molecules." *Studies in History and Philosophy of Science, Part A* 42 (4): 580–89.

van Fraasen, Bas. 1980. *The Scientific Image*. Oxford: Oxford University Press.

Weisberg, Michael. 2007. "Who Is a Modeler?" *British Journal of the Philosophy of Science* 58 (2):207–33.

Weisberg, Michael. 2013. *Simulation and Similarity: Using Models to Understand the World*. Oxford: Oxford University Press.

Weisberg, Michael, and Kenneth Reisman. 2008. "The Robust Volterra Principle." *Philosophy of Science* 75 (1):106–31.

Winsberg, Eric. 2010. *Science in the Age of Computer Simulation*. Chicago: University of Chicago Press.

Woodside, Arch. 2010. *Case Study Research: Theory, Methods, Practice*. Bingley, UK: Emerald.

Cite this article: Nefdt, Ryan M. 2023. "Motivating a Scientific Modeling Continuum: The Case of "Natural Models" in the COVID-19 Pandemic." *Philosophy of Science* 90 (4):880–900. https://doi.org/10.1017/psa.2023.72