# Scientific understanding as dependency-grasping

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### Abstract

Dellsén (2018) has proposed an account of scientific understanding that extends the well-established dependence-grasping account of objectual understanding. This proposal is attractive because it bridges traditional epistemology and the epistemology of science, combining a central philosophical insight about understanding with sensitivity to the scientific context.

In this paper, we raise two objections that challenge the adequacy of this account for scientific practice. First, it fails to ensure that the dependencies one must grasp in order to achieve scientific understanding are appropriately related to scientific models. Second, it overlooks the fact that scientific understanding often involves an awareness of the epistemic limitations of such models.

We then propose modifications to Dellsén's account that address both concerns while preserving its central insights. As a result, we obtain a genuine dependency-grasping account of *scientific* understanding.

## 1 Introduction

To understand a subject matter, one has to grasp relevant connections within that subject matter. This insight has played an important role in the philosophy of understanding starting with Plato and Aristotle. (See Trinkhaus Zagzebski [2020], §3.2.) Can we also rely on it to account for what understanding in the context of contemporary scientific practice, i.e. scientific understanding, amounts to? Dellsén has recently proposed an account of scientific understanding *of a domain* which exactly aspires to do so. His core tenet is that scientific understanding amounts to grasping what he

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calls dependency models, models which track the causal and non-causal dependence relations within a scientific subject matter.[1]

Dellsén's proposal is prima facie attractive: (i) it draws on an important insight from traditional epistemology to illuminate an aspect of scientific practice; and (ii) it ties in with the view that scientific progress is not a mere accumulation of knowledge, but rather consists in a gain of understanding (see Dellsén's very own "noetic account" of scientific progress—[Dellsén, 2022]). As we will argue, it, however, falls short and requires amelioration regarding characteristic respects of *scientific* understanding. To already mention the fundamental problem we will raise, it does not properly demarcate scientific understanding proper from 'layperson' understanding of scientific subject matters. More specifically, it fails to appreciate the important role scientific models, as well as the awareness of their limitations play in gaining scientific understanding.[2]

In this paper, we point out and illustrate these two flaws while at the same time proposing a naturally elaborated version of Dellsén's proposal which addresses them. We first briefly rehearse important background on understanding (§2) as well as on Dellsén's original dependency-modelling account (§3). We then argue that this account as-is effectively equivocates between scientific understanding and 'layperson' understanding of a scientific subject matter—but also show how this can be fixed. More precisely, we propose an enhanced account of degrees of understanding which permits one to distinguish between dependency models which are suitably related to scientific models and those which are not (§4.1). Second, we argue that Dellsén's original account fully ignores salient information about the relation of scientific models to the modelled subject matter which, however, crucially contribute to a *scientific* understanding of that subject matter (as opposed to that of the layperson). We argue that this problem can be addressed by integrating this meta-information into dependency models and by, again, assigning this additional factor suitable roles in

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[1] One might take Dellsén [2018] to have provided an account of objectual understanding, with understanding in science only serving as one possible paradigmatic instance. As he writes: "I will assume that paradigmatic cases of understanding are to be found in the natural sciences — thus, what follows can be viewed as a discussion of scientific understanding. Importantly, this means that a central adequacy condition for an account of understanding is that it makes sense of how understanding is in fact achieved in the empirical sciences. (p. 1264)" If that is one's preferred reading of Dellsén, take our overall point to be that scientific objectual understanding is simply not just another instance of objectual understanding (just with a specific subject matter) but requires important additional qualifications.

[2] Note that, we, like Dellsén himself, only focus on representational understanding. As argued for by Pincock and Poznic [2024], one might very well also want to see an augmentation of an account of scientific understanding so that it accounts for non-representational modelling (such as design modelling, common to in particular engineering contexts, say on how to synthesise methane, or how to build a bridge). This is a further task which we leave aside in this paper.

determining degrees of scientific understanding (§4.2). A brief conclusion wraps up the discussion and highlights an important feature of scientific understanding, namely the context-dependence of degrees of understanding (§5).

## 2 Understanding

Understanding has recently attracted much attention in both epistemology and the philosophy of science.[3] Understanding is typically differentiated into at least three different kinds of understanding: understanding-that (understanding of a proposition), understanding-why (understanding of why a proposition holds), and objectual understanding ('understanding $X$', where $X$ is a topic [Dellsén, 2021], body of information, or subject matter [Gordon, 2017][4] Our focus in this paper will be on the latter notion.

Much has been said about objectual understanding in the recent literature. We cannot provide an exhaustive overview in this context, so we will instead limit our introduction to four key points which have emerged from this literature. i) (Objectual) Understanding is epistemically valuable, i.e. an epistemic achievement worth striving for, to a degree similar to knowledge or explanation,[5] ii) understanding is distinct from explanation,[6] iii) understanding is a matter of degree, i.e. things can be better or worse understood,[7] and iv) understanding requires the grasp[8] of certain systematic connections, which are *intrinsic* to the subject matter $X$ that one understands, or to a more comprehensive subject matter which contains the subject matter which is the relevant target of understanding.

This last assumption is a central motif in the literature on understanding. As Trinkaus Zagzebski puts it, 'understanding is not directed toward a discrete object, but involves seeing the relation of parts to other parts and perhaps even the relation of part to a whole.'[9] Dellsén [2018, 2021] has recently elaborated this idea and adapted it

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[3]See, for instance, the edited volumes by Lawler et al. [2022], and De Regt et al. [2009]. Good overviews on the field of understanding are de Regt and Baumberger [2019], Grimm [2021], Gordon [2017].

[4]In Dellsén [2018], Dellsén chooses to talk of 'phenomena'. Given the heavy associations of this term, we prefer to use the more neutral term 'subject matter'.

[5]A number of philosophers, e.g. Kvanvig [2003], have argued that understanding is epistemically more valuable than knowledge. We here only assume the weaker claim that understanding is epistemically valuable to a degree comparable to knowledge.

[6]See e.g. Lipton [2008].

[7]See e.g. Kelp [2021], §2.1. Some authors argue that this distinguishes understanding from knowledge, since the latter does not come in degrees. See e.g. Dellsén [2018], p. 1264.

[8]There are several different proposals for what "grasping" means in this context (See e.g. de Regt and Baumberger [2019], Gordon [2017], §3). Since nothing in our arguments depends on this, we will remain neutral regarding this issue.

[9]See also e.g. Kelp [2021], p. 101, two of Khalifa's (2017) local constraints on understanding, and

to scientific contexts. We will in the following rely on a common interpretation of the notion of a systematic connection involved in assumption iv) which is clearly brought out in his account: namely that the systematic connections relevant for understanding can include dependency-relations of both a *causal*, as well as a *non-causal* kind.[10]

## 3   Dellsén's account of scientific understanding

In a nutshell, Dellsén's implementation of the idea that understanding consists in the grasp of dependence relations can be summarized as saying that "one understands a phenomenon, $P$, just in case one grasps a sufficiently accurate and comprehensive model of the network of dependence relations in which $P$, or its contextually relevant parts, is situated; and one's degree of understanding of $P$ is proportional to the comprehensiveness and accuracy of such a model." (Dellsén [2018], p. 1262)

Dellsén considers dependency models as interpreted, i.e., as being already linked up with their subject matter (just as is often practice when we talk about models, which are typically also interpreted). However, a dependency model exclusively tracks causal and non-causal dependency relations and may in certain cases not only track their presence, but also their absence. Such a model can be more or less comprehensive, in the sense of representing a larger or smaller amount of the actual dependence-relations which either hold or fail to hold both within the modelled phenomenon, as well as between parts or aspects of it and relevant encompassing or distinct related phenomena.

An accessible example from biology which Dellsén relies on are the Lotka-Volterra equations, which describe the dynamic change in a population consisting of a predator (e.g. lynx, population density represented by $y$) and a prey species (e.g. hare, population density represented by $x$):

$$\frac{dx}{dt} = \alpha x - \beta x y$$

$$\frac{dy}{dt} = \delta x y - \gamma y$$

Here, $\frac{dx}{dt}$ and $\frac{dy}{dt}$ are the growth-rates of the prey and predator species over time, $\alpha$ and $\beta$, respectively capture the natural (i.e. undisturbed by predation) growth rate of the prey population and the predation rate, i.e. the impact of the predator

Pritchard [2009], p. 12, who, in fact, even talks of 'holistic understanding'.

[10]See Dellsén [2018], p. 1266; see also Trinkhaus Zagzebski [2020], p. 66.

population on the death rate of the prey. $\delta$ is the growth of the predator population per eaten prey and $\gamma$ the natural death rate of the predator species.

Taking the Lotka-Volterra equations as a starting point, what could a dependency-model of the same subject matter, i.e. the dynamics of a predator-prey population, look like? For the sake of illustration, let us focus only on intrinsic dependencies and let us assume that the model indeed tracks causal relations. If we do that we could take the equations to indicate a causal dependence between the growth-rates of prey and predator species, such that the growth-rate of the prey species causally depends on both the species' natural growth rate and the predation rate, and the growth rate of the predator species causally depends on both its natural death rate and its growth-rate increase through eating prey. The equations do not carry explicit information about the absence of causal dependencies and they also do not seem to imply anything about the obtaining or absence of non-causal dependencies.

Now, understanding always comes in degrees and according to Dellsén, the degree of one's understanding of a phenomenon derives from two properties of a dependency model of the same phenomenon, namely its accuracy and its comprehensiveness. If someone grasped not the mentioned dependency model, but instead another such model which only tracked the causal dependence between the growth of the predator population per eaten prey and its natural death rate, then that model would be less comprehensive, since it encompasses less of the obtaining causal dependencies and grasping it would therefore convey a lower degree of understanding. Similarly for a less accurate dependency model, for example one in which the growth rates of both populations are causally independent of the natural death rate of the predator species.

According to Dellsén, an advantage of the objectual dependence-based approach to scientific understanding is that it can also account for cases in which a gain in understanding results from the grasp of the obtaining or of the absence of *non-causal* dependencies. For example, while a purely causal view of scientific understanding may be argued to struggle with explaining the gain in understanding brought about by Gallileo's famous refutation of the idea that the gravitational acceleration of objects depend on their mass, the objectual dependence-based approach can easily accommodate such cases: The refutation allows us to better understand gravitation, since it permits us to grasp that two relevant factors are independent of each other, after all. (See Dellsén [2018], §7.) There is a sense in which the dependency model adds to the original model providing the context of Gallileo's argument: it contains explicit

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non-dependencies which are only implicit in the original model.[11]

A further strength of Dellsén's account is that it can make sense of the apparent fact that an increase in scientific understanding can be gained based on considerations involving multiple scientific models and their interrelations. Scientific models are often complementary with respect to a single phenomenon of interest and dependency models can span across different models.[12] This is where the dependency model approach can add insight into expert understanding: it offers an account of how understanding does not always derive from a single scientific model, but can instead span multiple scientific models. The dependence-based approach does not merely track model- or theory-intrinsic relations; it explicitly includes relations between different models, as well as the absence of such relations (i.e. what is independent of what, as in the Galileo example mentioned above), as factors that may further scientific understanding.

# 4   Two limits of the dependency model and how they can be overcome

According to the dependence-based account of scientific understanding which we have just introduced, scientific understanding consists in grasping which dependence relations obtain or fail to obtain within a subject matter. In this section, we will point out two shortcomings of the account which in our view prevent it from delivering an adequate account of *scientific* understanding (as opposed to that of a layperson)—but also propose natural fixes later on.

## 4.1   Dependency models as models of scientific models

Let us now raise the first sense in which Dellsén's account runs the risk of conflating scientific understanding with lay-understanding of a scientific subject matter. To get to this point, one has to take a closer look at Dellsén's dependency models and contrast them with scientific models.

Let us reconsider the example of population dynamics of a predator and an as-

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[11]A strong underlying assumption of Dellsén's is that understanding of a subject matter cannot be gained directly by grasping the (often mathematical) content of a scientific model, but is rather always mediated through a dependency model. This aspect of his account can be taken issue with and we will do so in §§4.1-4.2.

[12]Some even maintain that strictly inconsistent yet partly adequate models can exist [Morrison, 2011].

sociated prey species. As stated before, we could take a dependency model of this subject matter to indicate that the growth-rate of the prey species causally depends on both the species' natural growth rate and the predation rate, and that the growth rate of the predator species causally depends on both its natural death rate and its growth-rate increase through eating prey. This dependency model is of course modelled on a scientific model of the same subject matter, namely the Lotka-Volterra equations. However, while the dependency model coheres with, and is actually modelled on, the scientific model, the latter carries information which the former does not. The Lotka-Volterra equations for example describe a cyclic relation between the two populations in which an increase in the prey population is always followed by an increase in the predator population. This is not captured by the dependency model, since the latter only specifies *that* the relevant factors causally depend on each other, but does not capturethe dynamics of the relationship of these factors which the equations capture, i.e. it fails to represent *how* these factors interact over time. Arguably, this means that grasping this dependency model may not be sufficient for someone to attain genuine scientific understanding of the population growth of predator-prey species pairings.[13]

The example illustrates that certain dependency models may fall short of representing certain aspects of a subject matter which are represented by a scientific model, and which are, importantly, relevant to the scientific understanding of that subject matter. This problem arises due to a strong epistemic assumption which is built into Dellsén's account, namely that dependency models are in a specific sense more important than scientific models regarding scientific understanding: scientific understanding can never be gained directly from a scientific model, but only via the mediation of a dependency model of the same subject matter. This is unavoidable given that the account is built on the basic idea that understanding is generated, or heightened, by grasping dependence relations.

This epistemic prioritization of dependency models might be seen as problematic. After all, one might think that it would be both theoretically more parsimonious and more naturalistic to cut out the middle man and assume that scientific models themselves are the vehicle of scientific understanding.[14] There is room for discussion

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[13]To be more precise: grasping this model may not allow one to attain scientific understanding to a degree necessary to cross a reasonable minimal threshold for 'genuine' scientific understanding. But more on that soon.

[14]Relatedly, one might agree with Wallace [2022] that, at least in highly mathematised contexts (such as that of theoretical physics, say general relativity), the well-initiated scientist in the field

here regarding certain important general questions, but we take it that the apparent problem can be addressed by acknowledging that, while epistemically posterior *with respect to scientific understanding*, scientific models enjoy another kind of priority over dependency models: dependency models are, at least partly, themselves modelled on scientific models—but not vice versa. What enables them to be vehicles of scientific, as opposed to lay-, understanding is that they capture and distil relevant features of scientific models into a medium which, in the broader context of dependence-grasping accounts of objectual understanding, is (or, rather, models what is) apt to allow one to gain, or to increase one's scientific understanding.´

The more nuanced view of the relation between scientific and dependency models does, however, still not allow us to address the conflation problem we mentioned. In fact, the problem only arises in its most succinct form once this view is integrated into Dellsén's account. Let us now look at the example from this new, more refined perspective.

The dependency model proposed here is in line with how Dellsén, drawing on Thórisson et al. [2016], envisages such models, namely as abstract structures which represent the obtaining or absence of dependence relations of different kinds. However, the model clearly carries less information than its scientific reference model. We can do better by adopting a broader view of dependency models which allows us to, both in this case, as well as generally, get closer to the sort of mathematical model which practitioners in the natural sciences work with. The problem with the suggested dependency model is that it merely captures which dependencies obtain between which factors, but does not (and cannot) further 'fine-grain' these relations as done in a mathematical scientific model. At least with respect to causal relations, this shortcoming can be addressed by adopting a more sophisticated view of these relations. In particular, we can re-conceptualize dependency models in terms of contemporary theories of causation which trade the traditional 'on-off'-notion of causation for the more fine-grained notion of causal relevance or influence (cf. e.g. Woodward [2003]). A model which tracks causal dependencies in this more fine-grained manner may be able to track the specifics of the dynamics mathematically described by the Lotka-

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*represents* the target through the mathematics immediately (maths-first)—and not via a collection of sentences "that attempt to make true claims about those systems" (language-first). While Dellsén's presentation of dependency models may suggest that they take this form, we grant him that his account can remain neutral with respect to the metaphysical nature of models. Our following response to the general form of the objection also goes a considerable way towards addressing a more specific version drawing on Wallace.

Volterra equations in terms of the co-variance of values of causal variables.[15] But once we move to such an understanding of dependency models, the problem of causal coarse-graining, which is usually posed in the context of causal explanation (see e.g. Woodward [2007], §4.5), rears its head: There is no one-to-one correspondence between causal models and scientific models. Rather, one always faces a choice of how to set up the causal variables in the causal model to capture the information carried in a scientific model of the subject matter one wants to explain. Causal models furthermore allow for additional fine-graining regarding the causal relationships themselves, as opposed to the connected causal variables, through the notion of invariance under interventions, which reflect the functional relationship between causal variables. (See Woodward [2003], p. 256.) This then leads to a multiplicity of dependency models, ranging from ones involving only binary variables (causal variables only taking two possible values such as *the glass breaks, the glass does not break*), to ones able to represent the full scale of possible values of quantities represented in a scientific model by involving more complex causal variables (e.g. a causal variable representing the yearly natural growth rate of a species as a percentage), where those which contain the fine-grained-enough causal variables of course respect the functional relations from the scientific model.

Given this broad class of different dependency models, ranging, we assume, from extremely simple ones up to models which carry the full information contained in a scientific model, the characterization of scientific understanding of a subject matter in terms of grasping a dependency model as described in Dellsén [2018] is no longer sufficient. There is a marked difference between grasping a model on the positive end of the spectrum and grasping one on the other end, namely that between genuine scientific understanding and 'mere' lay-understanding of a scientific subject matter. This difference is important, but not accounted for by Dellsén's account as it stands.

Dellsén's account can be augmented to overcome this problem. First, consider his original account again to see why it by itself is affected by the problem. Dellsén accommodates the fact that dependency models can vary in how well they represent the

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[15]Since dependency models also capture non-causal dependencies, a natural question is whether similar 'fine-graining' for such relations is required. This may be an interesting question to explore, but we will put it aside here. Relevant examples of dependency models which carry information about non-causal dependencies, e.g. dependency models of explanatorily brute matters, such as dimensionless fundamental physical constants (see Dellsén [2018], §5), do not seem to call for a fineness of grain which goes beyond the binary distinction between factors either being or not being related. In general, it seems that the fine-grained information that mathematical scientific models capture, i.e. the sort of models which play a crucial role in the augmented version of Dellsén's account which we develop in this section, concerns causal relations.

dependence relations which obtain or fail to obtain within a particular scientific subject matter in terms of two relevant factors, namely accuracy and comprehensiveness (Dellsén here draws on Thórisson et al. [2016]), both of which feed into the overall quality of the dependency model, giving us an overall quality-degree for a dependency model. This quality-degree not only serves to underpin comparisons between different dependency models of the same subject matter, but furthermore can be used to define a context-dependent threshold for when a dependency model is good enough to convey genuine scientific understanding to a person who grasps it within that context. Grasping a dependency model which is not accurate and/or comprehensive enough will then, with respect to the relevant context, not suffice to attain genuine, i.e. a high enough degree of, scientific understanding. (See Dellsén [2018], §3.)

Dellsén's purely accuracy and comprehensiveness-based notion of quality does, however, not suffice to rule out the problem we just raised. To see this, let's take a closer look at these two factors. Comprehensiveness is understood in terms of how many of the relevant items and dependency relations in a subject matter a dependency model represents, accuracy in terms of whether the dependency model correctly represents the actual network created by these relations and items. Both comprehensiveness and accuracy are hence measures of the representational correctness of a dependency model, capturing whether the model leaves out relevant elements (items plus dependence relations) of the subject matter (making it less than maximally comprehensive) and whether it misrepresents the relations between these elements (making it less than maximally accurate), respectively. Representational correctness is, however, not the root of the problem we raised. The overly simplistic dependency model of predator-prey population growths is arguably both maximally comprehensive (if we take the Lotka-Volterra equations as our guide to this subject matter, then it covers all the relevant factors which are related by dependency relations implicit in the equations), and maximally accurate (it does not misrepresent the subject matter by including an obtaining causal dependence which, taking again the Lotka-Volterra equations as our guide, actually is absent, or vice versa). Comprehensiveness and accuracy simply do not latch onto the particular aspects which that model fails to represent. The general point is that a dependency model may cover all relevant dependent factors and represent them and the dependence-relations obtaining between them correctly (in the sense of being both sufficiently comprehensive and accurate), but still fall short of capturing aspects of a subject matter which are crucial for

scientific understanding, at least in certain contexts.

To address this shortcoming, we suggest to make the quality-degree of a dependency model sensitive to further factors. Which factors these are depend on the context in which the quality-degree is used to judge whether a given dependency model is apt to allow one to gain scientific understanding. Here, we want to in particular focus on one such factor which we take to be particularly important to scientific understanding, which we will call *scientific model embeddedness.*[16] Our proposal is that the degree of scientific model embeddedness of a dependency model is always determined relative to its closeness to one or more scientific reference models covering the relevant subject matter.

To illustrate this idea, let us first consider a dependency model of a scientific subject matter in which we have a well-established scientific standard model. In this simple case, a dependency model has the maximal degree of scientific model embeddedness only if it completely represents all (non-artefactual) information carried by the reference scientific models. Let us once more consider the Lotka-Volterra equations. The simplistic dependency model we considered will fall short of being maximally scientifically embedded with respect to the equations, since it fails to capture the dynamics between predator and prey species encoded mathematically in them. In contrast, a dependency model which, in addition to being sufficiently comprehensive and accurate, also fully accounts for the dynamics, i.e. is maximally scientifically embedded, may also be of a sufficient overall quality to provide someone who grasps it with *genuine* scientific understanding. It is important to stress that it is not always necessary to grasp a maximally scientifically embedded dependency model to attain genuine scientific understanding, but that depending on the context, dependency models with a less than maximal degrees of scientific embedding may suffice. This is the consequence of working with a context-dependent quality-threshold for genuine scientific understanding. We take this consequence to be a good one, reflecting the different standards for scientific understanding which one finds in scientific practice.

One of the advantages of Dellsén's account we mentioned is that it allows one to

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[16]Note that instead of considering this as an additional quality-relevant factor, one could perhaps adopt a broader notion of accuracy which takes what we here assume is relevant to scientific embedding into account, the idea being that a dependency model which conserves more of the information carried by a relevant scientific model is more accurate. We prefer our approach of singling this factor out for reasons related to the complexity of dependency models of subject matters relative to which there are multiple complementary or conflicting scientific models. This is borne out in the following discussion.

account for the apparent fact that one may gain scientific understanding of a subject matter by appreciating the relations between different, perhaps even conflicting, scientific models of the same subject matter. E.g. a dependency model may contain dependence relations deriving from a classical, as well as from a statistical thermodynamical model of the same kind of physical system. In such cases, what we call scientific model embeddedness is obviously not any longer just a matter of closeness to *one* scientific model; after all, the dependency model represents, and integrates, information captured by more than one scientific model. To develop a proper theory of scientific embedding, such cases would have to be accounted for by providing a measure of scientific model embedding which takes the contributions of different aspects of a dependency model, which may reflect aspects of distinct scientific models of the same subject matter, towards scientific understanding into account. In the context of this paper, we will not attempt to develop such a theory, but we do want to mention three constraints on measures of quality for dependency models which such a measure should plausibly meet.

First, a too coarse-grained dependency model of the sort introduced at the beginning of this subsection, or to generalize to dependency models encompassing several scientific models, a dependency model which is too coarse-grained with respect to all of them, should always convey a lower degree of scientific understanding than one which accurately captures the full (or rather representationally relevant) information of a commonly accepted standard scientific model, or the relevant range of scientific models, of a subject matter. This constraint ensures that the augmented account avoids conflating layperson with genuine scientific understanding.

The second constraint concerns the positive contribution which relatively coarse-grained dependency models can make to scientific understanding. We know from the literature on coarse graining in causal explanation that a more coarse grained model may sometime give us a better explanation than a more fine-grained one (see e.g. Yablo [1992], Woodward [2010], §4). Understanding a subject seems to benefit from coarse-grained perspectives too (as reductionists about understanding in terms of explanation would immediately admit in light of the point above — but as it has just as well been argued for independently, see e.g. Potochnik [2017] or Elgin [2017]). An important characteristic of understanding is the ability to identify an abstract structure in a subject matter and to recognize the same structure in other subject matters. This is where the 'bare' dependence-relations captured by a stand-alone

coarse-grained dependency model can still play an important role. As pointed out before, a coarse-grained dependency model which is very far from any actual scientific model *alone* will not enable one to attain a high degree of scientific understanding. However, a complex dependency model which represents the information carried by such a dependency model *in addition*[17] to the information carried by a suitable scientific model can allow someone to attain a *higher* degree of scientific understanding than a dependency model which represents only the information carried by either of the models on its own. This then is the second adequacy constraint on a general measure of scientific model embeddedness which we think has to be observed.

Note that we take it to be plausible that scientific understanding of a subject matter does not simply grow linearly relative to an increase in complexity within a dependency model. The third constraint then is that a dependency model which already covers a scientific model and adds dependencies that are coarse, can allow one to attain a higher degree of scientific understanding compared to a different complex dependency model which instead covers in addition a further, more fine-grained, i.e. complex, scientific model. The former dependency model may represent (in virtue of the coarse-grained dependence structure it covers) very general connection which are central to the subject matter, the addition leading to a higher increase of scientific understanding than the addition of further fine-grained dependencies with yet little significance. Note that these kind of claims about comparative loss or gain in scientific understanding may depend heavily on the context, e.g. on relevant scientific goals and related factors. This context-dependence should accordingly be reflected by any proposed measure of dependency model quality.

With the third factor of scientific model embeddedness in place, the problem raised at the beginning of the section can be addressed in a straight-forward manner: The three constraints on adequate measures of scientific model embeddedness we introduced ensure that the maximal degree of scientific understanding which a dependency model which only captures a very coarse grained version of a scientific model allows someone grasping it to attain will always be comparatively lower than that of a dependency model which conveys a more fine-grained dependency model which conserves more, or perhaps all of the information carried by an established scientific model. In other words, the account now gives us a means to distinguish, via including sci-

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[17]These coarse-grained dependencies may in particular also involve epistemic dependencies. We will discuss this in more detail in the next subsection.

entific model embeddedness as a further quality-determining factor for dependency models, 'lay'-understanding of a scientific subject matter (relatively lower degree of scientific understanding due to low degree of scientific model embeddedness of the dependency model) from genuine scientific understanding of the same subject matter (relatively higher degree of scientific understanding due to higher degree of scientific model embeddedness of a dependency model which captures more of, or ideally the full, nuanced picture of the subject matter present in a scientific standard model plus in some cases also further coarse grained information). The second and third constraints then ensure that course-grained dependencies can still make substantial positive contributions to scientific understanding, if they occur as parts of a suitable dependency model which also covers the fine-grained dependencies deriving from an established scientific model.

## 4.2   Meta-information about scientific models

Dependency models are meant to track dependencies within a subject matter, or rather, according to our augmented version of the account, within the subject matter as *represented by established scientific models.* What is then missing, however, is a more explicit account of *how* and *to what extent* a scientific model is an adequate surrogate for its target (the original subject matter). Scientific models represent selectively and with limited accuracy: they foreground some features, idealize others, include explicitly false artefacts, etc.—and thereby all-together succeed (or fail) relative to particular purposes. In other words, they have certain epistemic limitations. Awareness of such limitation is an important distinguishing mark of scientific, as opposed to layperson understanding (even if not fully absent from the latter either). Scientific experts do not only understand the subject matter through scientific models, but also, to the extent that this is possible, are aware of how these means by which they gain epistemic access to the subject matter relate to the subject matter itself. This is, we submit, a crucial aspect which Dellsén's original proposal fails to account for.

Indeed, it is surprising that Dellsén's original account does not account for the role which the grasp of epistemic limitations plays with respect to scientific understanding. Tracking (and ideally controlling) dependencies between a model and its target seems central to scientific practice.If a scientific model has a limited range of applicability, then the scientist relying on the model has to be aware of this limitation.

Otherwise, they may for example be misled into making false predictions based on the model. Awareness of such limitations of a model also allows scientists to discard, improve or replace them by new models which are more adapted to their purposes. Furthermore, standard approaches to demarcating science from non-science operate through epistemic factors (take issues of confirmation such as falsifiability, ad hocness, etc.), and not—at least not primarily—through dependencies within the target. Just think about how hollow earth theories, say, concern the interior of the earth just as our standard geophysical model does; and that the difference between those and the standard geophysical model instead lies in refutability or rather how proponents of the model position themselves with respect to refutability—i.e. with respect to questions of how the model relates to the world (and empirical measurements drawn from it). According to Dellsén's original account, then, one can seemingly have scientific understanding of a pseudo-scientific model in the same sense as of a scientific one: the grasping condition is framed in terms of dependency models of an interpreted model, not in terms of the model's epistemic standing.

We can in fact give various kinds of characteristic cases that illustrate how Dellsén's account fails to capture what is clearly part of scientific understanding by not accounting for the role of different kinds of meta-information about scientific models—contra Dellsén's promise in the abstract to 'do justice to the full range of cases of scientific understanding, including cases in which one does not have an explanation of the understood phenomenon'.

**Regime of validity.** Suppose you model a basketball throw as the motion of a point mass with no spin. Scientific understanding here includes knowing *where* the idealization is accurate enough (e.g., estimating basic shooting angles) and *where* it breaks down (e.g., advice that depends on spin or air resistance). Unlike a hobbyist who sees the equation in their first undergraduate physics class, the scientific modeller characteristically understands the model's regime of validity. Dependency models do not account for this, since information about the regime of validity of a scientific model does not concern causal or non-causal dependencies within what it models.

**Structural correspondence.** Consider modelling the behavior of a surfaced submarine using a scaled-down physical model in a water tank. The tank model can serve as a surrogate only given specific correspondence conditions linking model

and target. In this case, the same wave pattern arises only if the ratio of velocities matches the ratio of the square roots of their lengths [Nguyen and Frigg, 2022]. Scientific understanding includes grasping these adequacy conditions—something not required of, say, a casual user of RC vehicles. Again, dependency models fall short since they do not track relations between scientific models and their target.

**Selection effects.** You model statistically the population of fish in a lake. Given the method by which you collect fish data (namely, using a net of a certain mesh size), you note that the statistics you obtain cannot, in principle, reflect the presence of fish too small to be caught by the net. Dependency models do not represent features of the construction of a scientific model, in this case of the sampling method, which are relevant for interpreting and applying it.

**Observer selection effect.** You model the universe through a mathematical model in the spirit of modern cosmology. Given that you qua observer exist in the universe, you can directly restrict the possible models compatible with that existence. The scientific modeller has a precise sense of how possible observations are affected by the presence of the observer. Dependency models do not offer the means to track general constraints on the range of possible scientific models of this sort.

In sum, if dependency modelling is to capture scientific understanding, it cannot be confined to worldly phenomena alone. It must also in some way incorporate that scientific understanding also concerns how those phenomena are represented by scientific models and account for the epistemic limitations which arise as a result.

Before we introduce our solution to this problem, we want to point out that, once again, we cannot simply rely on model quality, as conceived so far, to address the problem. Comprehensiveness and accuracy are factors which track intrinsic properties of a dependency model. Dependency models themselves are, according to our augmented approach to dependency modelling, models of, perhaps several, scientific models which in turn do not themselves carry information about their epistemic limitations. Information about the epistemic limitations of a scientific model is model-extrinsic; it does not enter into the representational content of the model. The added factor of scientific embeddedness captures some extrinsic information, but this information is extrinsic to the dependency model; what needs to be tracked is information which is extrinsic

to the *scientific* model or models a dependency model is modelled on. Accordingly, we cannot rely on comprehensiveness, accuracy, or even scientific embeddedness to give us a means to account for the relevance of awareness of the epistemic limitations of a scientific model to scientific understanding.[18]

Our proposal is to integrate the scientifically relevant meta-information about the limitations and epistemic peculiarities of a scientific model into the corresponding dependency models as a second component besides the tracked network of dependencies. In a complex dependency model which e.g. contains several dependency networks representing either different scientific models of the same or of different subject matters, or dependency networks of different grain modelled on the same scientific model, this information is associated with the relevant part of the dependency model which tracks the scientific model. In a nutshell, dependency models represent meta-information about scientific models they cover in the form of a property of a the dependency networks which track these models.

Given this further augmented view of dependency models, the meta-information carried by a model gives us another factor which influences the model's quality and with it the degree of scientific understanding one can attain by grasping the model. We will once again focus on formulating constraints on a measure of model quality which we take to be necessary to accommodate the role meta-information about models plays with respect to scientific understanding. In doing so, we will treat meta-information as an additional quality-determining factor.[19]

First, the overall quality of a dependency model should positively correlate with the relative amount of meta-information about the relevant scientific model(s) it captures. With respect to scientific understanding, it is always better to be aware of more of the limitations of a scientific model. This constraint reflects the positive influence of one's awareness of a scientific model's limitations on one's degree of scientific understanding of a subject matter. There is of course the question of how exactly the

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[18]Note that one might be tempted to think that the problem could be solved by letting dependency models track the relevant epistemic limitations in the form of networks of epistemic dependence relations encoding them, in effect making comprehensiveness and accuracy and therefore also general model quality sensitive to the limitations and peculiarities of how a scientific model applies to the world. The problem with this suggestion is that these limitations do not lend themselves to being captured by a network of (fine- or coarse-grained) dependence relations between items of the same sort as causal or other worldly dependence relations. An epistemic dependency would plausibly have to have the complete part of a dependency model which represents a scientific model as one of its relata. However, it is quite unclear what the second relatum could be. The most natural answer would be 'the world', but integrating e.g. relevant facts, or whatever the other worldly relatum may be, into dependency models would seem to substantially complicate their structure and raise difficult (meta-)epistemological questions about what it means to grasp such a model.

[19]One could instead work with suitably modified notions of comprehensiveness and accuracy which is sensitive to the presence and amount of meta-information carried by a model.

growth of scientific understanding scales monotonically, as suggested here, with the number of epistemic constraints and the weights they have relative to a particular context. One might in particular find diminishing returns in gaining more and more scientific understanding from a dependency model tracking a scientific model which has an extremely large number of limitations by grasping more and more of these limitations.

Second, the meta-information furthermore plays an enforcing role with respect to the context in which a dependency model is grasped. To illustrate what we mean by this, let us focus on the first of our four examples for understanding-relevant meta-information about a scientific model.

**Enforcing regime of validity** The meta information in a (part of a) dependency model that tracks a scientific model encodes in which contexts the scientific model is applicable and in which it isn't. This tracked information gives us a constraint on the threshold for genuine scientific understanding of the following sort: In a context in which a particular scientific model is not applicable, no dependency model based on that scientific model is permitted to reach or surpass the quality-threshold the model would have to reach so that someone who grasps it is thereby able to gain genuine scientific understanding of the modelled subject matter in that context.

The meta-information hence not only positively influences the degree of scientific understanding one may gain by grasping a dependency model within a particular context, but it also encodes in which kinds of contexts it can even effectively play this role. In case of *Structural correspondence*, these are contexts in which the dependence structure captured by the model satisfies the relevant conditions on its correspondence with the relevant facts. Similarly for *Observer selection effects* and *Selection effects*, in case of which the meta-information respectively rules out contexts in which the conditions for the observation are not met and in which general limitations of the sampling method used to construct the scientific model are ignored. Schematically, the meta-information present in a dependency model hence consists of a set of contexts and a characteristic function which maps each of these contexts to particular conditions on the quality of the model. In 'good' contexts, this condition is empty, i.e. does not interfere with the contribution the meta-information makes to the overall quality of the dependency model. In 'bad' ones, it may, as discussed with respect

to our examples, enforce a limit on the maximal quality of the dependency model or even nullify its quality, thus even preventing the model from conveying what counts as genuine scientific understanding in such contexts.

## 5   Conclusion

We exposed and addressed two shortcomings of Dellsén's original account of scientific understanding related to the role scientific models play in practice with respect to scientific understanding. The augmentations we proposed are conservative in the sense that they kept the original philosophical insight driving Dellsén's proposal, namely that understanding consists in the grasp of dependencies. The resulting improved dependency-grasping account of scientific understanding strengthens Dellsén's account in two central respects. First, it conceives of dependency models as models of scientific models, reflecting the crucial importance of the latter kind of models with respect to the pursuit of genuine scientific understanding. Secondly, it provides a more nuanced view of the overall quality of dependency models, taking into account how much information a dependency model conserves when compared to the corresponding scientific model and how well the dependency model represents salient limitations and peculiarities of the scientific model. As a result, we obtain a genuine dependence-grasping account of scientific understanding, in line with scientific practice.

We want to single out one aspect of the resulting, improved account of scientific understanding, namely that it crucially involves a trade-off between four (as compared to two in Dellsén's original proposal) factors which together determine the overall quality of a dependency model and thereby also the degree of scientific understanding a particular dependency model amounts to for someone who grasps it. Trade-offs by their very nature leave room for variance, be it in how the factors entering into the trade-off are set-up in the first-place, or, perhaps even more importantly, in how results of the trade-off are generated. This gives the account a decidedly pragmatic-contextual flavour. According to it, degrees of scientific understanding are highly contextual and the same holds for comparative or absolute judgments drawing on them. We take this to be a welcome feature of the account which accords well with common intuitions about scientific understanding. There are different standards for attributing scientific understanding in the context of a first-year lecture in the sciences,

in the context of theory-development in scientific research, and the standards may again change in a context where a first-year student meets an experienced scientist. It is a testament to the power of the idea that we gain understanding by grasping systematic connections that these differences can be accommodated by a theory of scientific understanding based on this idea.

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