6. Grasping and explaining – an account of scientific understanding

What is scientific understanding and how is it achieved? In the previous chapters, I argue that understanding requires explanation and that understanding should be conceived as an ability, rather than a type of propositional knowledge, which manifests in the process of grasping relations and articulating these in the form of explanations. Through analyzing the episode of how biologists gained understanding of the genetic regulation of vertebrate development, I show that scientific understanding necessitates propositional knowledge as well as further research skills and appropriate equipment for its manifestation. Now, I bring all these lines of thought together to provide a novel account of scientific understanding. In section 6.1, I present and explain the scope and conditions of the 'Grasping and Explaining-Account of Scientific Understanding', the GE-account in short. In section 6.2, I elaborate the advantages of the GE-account in contrast to the accounts of understanding developed by Henk de Regt, Kareem Khalifa and Finnur Dellsén, which are introduced in chapter two.

Importantly, all the claims I am making here are supposed to hold for understanding of phenomena achieved in science through scientific methods and practices. I stay agnostic about the extent to which the GE-account of scientific understanding developed here may also apply to other types of understanding in other contexts.[1]

6.1 The GE-account of scientific understanding

I argue that scientific understanding is an extensive, complex cognitive ability that individual scientists possess and that is manifested in the process of grasping relations between pieces or bodies of knowledge and investigated phenomena, between

1 Therefore, I will occasionally talk about understanding without the qualifier *scientific*, but this then also refers to scientific understanding. In cases where I discuss other forms of understanding or understanding in general, I will clarify this explicitly.

several phenomena or within parts or aspects of a phenomenon, among its parts, that scientists were not aware of before, and articulating these relations in form of explanations. Explanation is a central and necessary element of understanding, as it makes the recognized relations between knowledge and phenomena or within phenomena comprehensible and revisable for the scientist. In order to manifest this ability, to actually understand some aspect of a phenomenon, the availability and usage of propositional knowledge, research skills, as well as an appropriate equipment are required. If one of these elements is missing, it will not be possible for a scientist to achieve understanding.

The GE-account of scientific understanding that I elaborate and argue for in this chapter entails necessary and sufficient conditions for acquiring scientific understanding and takes the following form:

A scientist *S* has scientific understanding of an empirical phenomenon *P* in a context *C* if and only if

i. *S* grasps (details of) relations that *P* stands in and articulates these relations in the form of new explanations of (aspects of) *P (manifestation condition)*,
ii. *S* possesses and uses (material) equipment, relevant knowledge and research skills provided by *C* and required for understanding *P (resource condition)*, and
iii. *S* is a member of a scientific community that enables *S* to understand *P* and parts of that community approve *S*'s understanding of *P (justification condition)*.

This means that understanding is the ability to make sense of a phenomenon through using knowledge, equipment and research skills that are at a scientist's disposal in a reasoning and research process. A result of this reasoning process is a new explanation. The possession of required resources, covering (background) knowledge, equipment, and specific research skills, is a necessary precondition for scientific understanding. These resources, which are acquired, learned and trained by scientists during their education and practice, allow for the grasping of relations of a phenomenon, which have not been known by the subject before she started to reason about the phenomenon in question. And the relations that have been grasped are then articulated in the form of an explanation, in order to identify and specify the nature and aspects of the relations. Additionally, explanations allow for an assessment of the acquired understanding of an individual scientists by other members of the respective research community. When a scientist has performed this process, when her scientific understanding has become manifest, she will have produced new knowledge. Namely, the knowledge of an explanation that was not known to her before, and possibly not by anyone else. Scientific knowledge is a product of scientific understanding, but it is not identical to understanding.

Understanding is the ability to generate new knowledge, which exceeds the mere possession of knowledge. In what follows, I elaborate the GE-account of scientific understanding, its scope and conditions, in detail.

6.1.1 Clarifying the scope of the GE-account

Let me start with the scope of the GE-account, before I turn to the conditions. First of all, understanding requires a subject and an object: Someone understands something. The subject of understanding I am focussing on is the individual scientist. I will not analyse what some kind of collective understanding amounts to. Although there is already some work on understanding on the level of groups,[2] I focus on the smallest unit of understanding, which is the individual scientist. So, the individual scientist is the subject of understanding, the one who understands, and an empirical phenomenon is the object of understanding, the thing that is understood. Since I want the GE-account of scientific understanding to accommodate as many scientific disciplines as possible, I adopt a very broad notion of what a phenomenon is and follow Hans-Jörg Rheinberger, who takes phenomena to be epistemic things that "embody what one does not yet know."[3] Objects, structures, events, processes, or mechanisms belong to the phenomena that scientists investigate. Hence, the GE-account of scientific understanding does not cover understanding of theories, explanations, models, or other representations used in science. While the GE-account requires the articulation of an explanation for the manifestation of understanding, for which theories may be necessary, neither explanations nor theories are the objects that scientists want to understand. Ultimately, scientists want to understand phenomena in the world, ranging from quantum phenomena, chemical reactions, genetic interactions, to geological or social phenomena, to mention just some examples. Theories, explanations, models and the like are necessary means to reach this goal. Whether the understanding of these representations can be captured by the GE-account as well, or whether and in which ways the understanding of representations differs from understanding empirical phenomena, are questions that I have to leave unanswered.

While the GE-account focusses on the understanding that individual scientists achieve, it does pay attention to the crucial role that the context plays for the understanding that any scientists can possibly achieve. Every scientist is situated in a specific disciplinary, historical, technological, and social context that has an influence on the understanding she may be able to achieve. I illustrate the context-

2 For an analysis of group or collective understanding, see for example Boyd, K. (2019). "Group understanding." *Synthese*, 198 (7), pp. 6837–6858, DOI: 10.1007/s11229-019-02492-3.

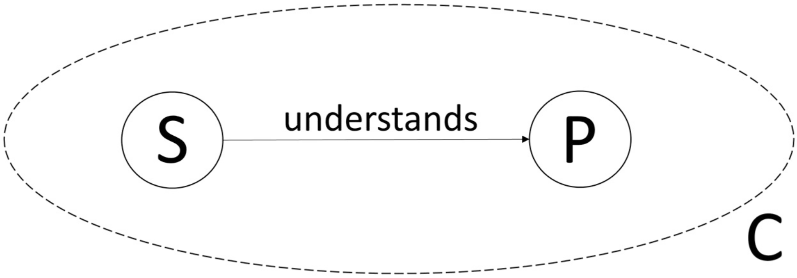
3 Rheinberger, H.-J. (1997), *Toward a history of epistemic things. Synthesizing proteins in the test tube*, Stanford (CA), Stanford University Press, p. 28.

sensitivity of scientific understanding with the episode of the research on zebrafish in chapter five and argue for the context-sensitive nature of understanding in chapter 4.2. In chapter four, I rely on the work from Michael Polanyi on the relation between articulate intelligence (formal or explicit reasoning) and inarticulate intelligence (abilities like understanding). According to Polanyi, scientists need explicit formal frameworks, covering propositional knowledge and theories, in order to understand phenomena, because the respective disciplinary formal framework systematically stores a huge amount of information potentially relevant for the phenomenon in question, without which it would be much more difficult or even impossible to understand the phenomenon. Contemporary scientists do not start from nowhere when initiating a new research project. Instead, they rely on the well-established and confirmed conceptual frameworks that their predecessors established over decades and centuries. While these conceptual frameworks are never immune to revision, they nevertheless function like glasses through which the new phenomenon is viewed in a specific way. This claim is illustrated with the episode from biology in chapter five. Before molecular biologists and developmental biologists joined forces and established the new field of developmental genetics, none of the involved scientists were able to understand the phenomenon in question, that is, the genetic regulation of vertebrate development. This was partially due to insufficient formal conceptual frameworks of both biological disciplines. Molecular biologists lacked the concepts and language to talk and think about developmental phenomena, and vice versa, the conceptual framework that developmental biologists used so far did not cover phenomena at the genetic level. Researchers participating in the study of genetic regulation of vertebrate development had to revise their respective formal frameworks, in this case through an integration of two already existing ones.

So, in general, the community to which an individual scientist belongs significantly affects the understanding of a phenomenon that she may achieve. This is why the GE-account covers cases of scientific understanding of an empirical phenomenon *P* that an individual scientist *S* gains in a context *C*. Figure 1 depicts this basic idea.

The various dimensions in which understanding is affected by the context are captured by the *resource condition* and the *justification condition* of the GE-account, which I spell out in sections 6.1.3 and 6.1.4. Before I do this, let's have a look at the first condition of the GE-account, the *manifestation condition* of scientific understanding.

Figure 1: An individual scientist S understands an empirical phenomenon P in a context C.



6.1.2 The *manifestation condition*

As I just mentioned, the GE-account only captures scientific understanding of empirical phenomena. However, in this first condition I talk about relations that *P* stands in and about aspects of *P*. I explain why it is important to talk about relations and aspects of *P* in the context of the manifestation process of understanding, the process of grasping relations and articulating them in the form of explanations.

6.1.2.1 Grasping relations reviewed

Let me start with relations. The concept of relations, or dependency relations, is central in the debate on understanding in general, not only on scientific understanding. Despite there being many points of contention, there is some basic consensus or some shared intuition that understanding is something like "seeing how things hang together".[4] And things hang together through some kinds of relations. Stephen Grimm, for instance, states that dependency relations are the objects of understanding and illustrates this claim with two examples. If we want to understand why a cup of coffee spilled, we must grasp the relation of the spilling of the cup to the nudging of the table that caused the spilling. If we want to understand the US House of Representatives, we have to grasp various dependency relations among its elements, its composition, its powers, and procedures.[5] Christoph Baumberger argues that dependency relations can be different in kind, ranging from relations that hold between parts or aspects of the phenomenon that is to be understood (such as causal, probabilistic, mereological, supervenience, and teleological relations) to relations among elements of a body of information through which a phenomenon is understood (such as logical, conceptual and explanatory relations).[6] And alterna-

4 See for example Baumberger, Beisbart & Brun (2017), p. 12.
5 See Grimm (2017), pp. 214ff.
6 See Baumberger (2011), p. 79.

tively, according to Kareem Khalifa's model of understanding, scientists grasp the *explanatory nexus* of a phenomenon, where the *explanatory nexus* contains correct explanations of *p* as well as the *relations* between those explanations. Note that Khalifa does not suggest an ontic view of explanation, i.e. that explanations are mind-independent things in the world. Instead, he explicitly states that he is noncommittal about the nature of explanation. Khalifa allows that the notion of explanation can be identified with the notion of explanatory information and he does occasionally talk about explanatory factors or features. Explanations can represent mechanisms, causal structures, but also non-causal, contrastive or probabilistic relations.[7]

In sum, the concept of relation is omnipresent in the debate about understanding. To my knowledge, every scholar involved refers somehow to (dependency or other kinds of) relations, relationships, connections or ties when talking about understanding. However, the agreement does not go much further. Regarding the question what kinds of relations can or must be grasped for understanding, various answers and views can be found. While the disagreement about the nature of relations that need to be grasped for understanding may affect some issues regarding different types of understanding, it does not affect the GE-account of scientific understanding. As the various scientific disciplines understand various different kinds of phenomena, these different and diverse phenomena (probably or reasonably) stand in various different and diverse relations towards various different kinds of other things. These may include relations among the parts of a phenomenon (internal relations), between the phenomenon and its parts (for example mereological or grounding relations), among different phenomena (for instance causal or statistical relations), and theories or bodies of knowledge that are taken to represent phenomena (representational relations). What kinds of relations a specific phenomenon, its parts or aspects stand in can only be analysed in the individual case of understanding that phenomenon. Note that all the kinds of relations I am mentioning here are only meant to be examples. I do not intend to provide any representative or even complete list of kinds of relations that phenomena can stand in. Fortunately, as the GE-account is supposed to cover many (ideally all) scientific disciplines, the precise nature of the grasped relations is irrelevant for the abstract account. As the basic consensus only demands that some kinds of relations must be grasped for understanding, it is not necessary for the GE-account to specify any kind of relation that needs to be grasped for understanding any of the diverse phenomena that are the objects of scientific research. Again, it must be investigated case by case which relations a specific phenomenon stands in. In the episode from the research on zebrafish, for instance, causal relations among

7 See Khalifa (2017b), pp. 6ff.

genes were of interest, and hence had to be grasped.[8] That a phenomenon may stand in various different kinds of relations is also the reason why I do not only talk about phenomena, but also about their parts and aspects. Referring only to phenomena and their parts may lead to the impression that I put an emphasis on mereological relations.[9] While mereological relations may be important for understanding a phenomenon, I want to allow all possible kinds of relations to be grasped if required. Hence, I occasionally refer to the more abstract term 'aspects' of phenomena. I return to the differentiation between phenomenon, part or aspect in section 6.1.2.3, after addressing the two processes that make up the manifestation of understanding. One of these is grasping.

The concept of grasping is almost inseparably tied to the concept of relation, at least in the debate on understanding. Again, almost every scholar in the debate agrees that to understand a phenomenon, scientists have to grasp relations of that phenomenon, that grasping demarcates understanding from knowledge, but there is no consensus what exactly it means to grasp relations. I address and discuss this question what grasping is or what it should be taken to be in section 4.3.1 and conclude that the so called "naturalistic view", according to which grasping a relation amounts to recognizing this relation and being aware of it, is the most plausible option. I identify grasping as having epistemic access to a relation of the phenomenon, that a scientist establishes some connection between her mind and the world through grasping, which is the view that, for example, Michael Strevens and Alexander Reutlinger et al. hold as well.[10] Understanding is a cognitive ability, and if we want to understand some phenomenon that lies outside of our mind, in the world, we somehow have to "connect" our mind to the phenomenon. That is what we do through grasping. When a person grasps a relation, this relation somehow catches her attention, it gets into her focus. She is somehow aware that there is something interesting or relevant about the phenomenon that she wants to understand.

It happens only in the next step, after recognizing or grasping that some relation is there, that the person applies modal, counterfactual, inductive, deductive or analogue reasoning, to make sense of the relation that was just grasped. I take grasping

8 For a basic overview over philosophical discussions concerning relations, see for example MacBride, F., "Relations", *The Stanford Encyclopedia of Philosophy* (Winter 2020 Edition), Edward N. Zalta (ed.), URL = https://plato.stanford.edu/archives/win2020/entries/relations/ (last accessed April 14th, 2022).

9 It should be noted that the term 'part' itself has no ontological restriction in mereology, c.f. Varzi, A., "Mereology", *The Stanford Encyclopedia of Philosophy* (Spring 2019 Edition), Edward N. Zalta (ed.), URL = https://plato.stanford.edu/archives/spr2019/entries/mereology/ (last accessed April 14th, 2022).

10 See Reutlinger, Hangleiter & Hartmann (2018); and Strevens (2013).

to be a process that is distinct from other reasoning abilities. In my view, it is implausible to mix up grasping and other reasoning or inferential abilities, as a subject first needs to identify something to reason about. A subject cannot make modal or other kinds of inferences about something that she is not aware of in the first place. For example, I cannot understand or even reason about global climate change if I do not grasp some (potential) causes or physical laws involved in climate change. Hence, I take grasping a relation to be a process that precedes any thinking about that relation. Grasping a relation is a process that foregoes and also parallels reasoning about that relation. The subject will immediately start to reason about the relation once she grasped it, in order to make sense of how the grasped relation is involved in the phenomenon one wants to understand. That is, once I grasped that energy conservation laws may have something to do with global climate change, I begin to reason about this relation in order to make sense of it. However, merely reasoning about the relation of energy conservation laws and global climate change is no guarantee that I will make sense of that relation. This is why I do not include the notion of reasoning in the *manifestation condition* of understanding, but rather a different process.

6.1.2.2 Articulating new explanations

Namely, the articulation of the grasped relation in form of an explanation is the second step in the manifestation of understanding. The articulation is necessary for clarifying and testing what exactly has been grasped, to make the grasped relation comprehensible and revisable. I argue in section 4.3 that being able to grasp relations is necessary, but not sufficient for understanding, because a scientist cannot make sense of the grasped relations without the articulation of the relations. Through grasping, she will know that something important or interesting is going on that she has not been aware of before, but she will not be able to make sense, to discover aspects, of the grasped relation. As a result, the grasped relation will remain opaque for the scientist. By articulating an explanation, the scientist can sort out and specify the aspects of the grasped relation, which can then be presented, assessed or even corrected by herself or her colleagues. In short, one can say that through the articulation of the grasped relation in the form of an explanation, a scientist combines what she has grasped with further knowledge that she already possesses, her conceptual framework, in a consistent manner. Without articulating the grasped relation in form of an explanation, scientists will not be able to understand (aspects of) the phenomenon that stands in the respective relation, because scientists can only think about any empirical phenomena by using the specialized language and terminology they learned. Only by using and applying the respective terminology, classificatory systems, or nomenclatures can scientists sort out how parts or aspects of the phenomenon are related and what kind of relation holds. Together, grasping relations and articulating these relations in the form of explanations manifests understanding.

Recall that in chapter three, I adopt an epistemic conception of explanation and allow for a plurality of models of explanation to provide understanding. I view an explanation to be a representation of relations of (parts or aspects of) the phenomenon under investigation, which provides reasons (explanans) for characteristics of (parts or aspects of) the phenomenon (explanandum). This notion of explanation is very generic, which is necessary since it is intended to accommodate the various different kinds of phenomena, which can stand in various different relations, that scientists investigate as well as the demand for an explanatory pluralism found in science. Investigations of scientific practice revealed that various forms of scientific explanations exist (e.g., causal, mechanical, unificationist, functional, model-based, contrastive, probabilistic ...), are legitimately used, and that all of them can provide scientific understanding in certain contexts, as no timeless or universal criteria for explanation (and understanding) exist. Varying kinds of explanation are grounded in different perspectives on a phenomenon due to different formal frameworks, present different relations that were grasped, and lead to an increase in knowledge, specifically in terms of its diversity, which could become relevant in diverse contexts. Hence, the GE-account accommodates my argumentation in chapter three, in which I claim that an explanatory account of understanding, an account that conceptualizes explanation as necessary for understanding, is more appropriate to capture scientific understanding in light of scientific practice. According to the GE-account, understanding and explanation are related in the sense that explanation is a necessary product of the manifestation of scientific understanding. This claim is also supported by the episode from the biological research on zebrafish, in which scientists articulated and communicated explanations of the respective (aspects of the) phenomena they were investigating in the various studies.

In this *manifestation condition* of scientific understanding, I require that new explanations are articulated. What do I mean with 'new' explanations, and is this qualification important? Being 'new' in my usage of the term means that the explanation represents a relation that has not been known to the subject that articulated this particular explanation, and hence acquired understanding, before. The explanation must be new *only* to the individual subject, i.e. my use of the term 'new' is very local and relative to the subject. Other scientists may already possess this explanation, but this would not change the fact that a specific individual, or maybe even several individuals in a research group, articulate the explanation, and therefore have gained understanding, without having heard of or read the explanation before. The possibility that other scientists may already possess a specific explanation does not downgrade the achievement of an individual who came up with the same explanation by herself without having known the explanation before. Consider the hypothetical case that two scientists, Amy and Bob, within a very large research community investigate the exact same phenomenon, asking the same research questions and, by coincidence, come to grasp the same relations and articulate identical explanations. However, due to the many members of that community, Amy and Bob did not know each other when they gained understanding, respectively. The fact that someone else on the planet might have or actually has understood a phenomenon in the exact same way does not devalue the understanding achieved by any other subject. Such constellations always appear, for example, in supervisor and student relations in academia. Students are expected to use the knowledge they gain in lectures and the skills they train during their education to solve problems (i.e. construct explanations) of phenomena they did not understand before. That their supervisors already have this understanding of the phenomena does not change anything about the understanding the students acquire by creating solutions or explanations which are new to them. This remains a great cognitive achievement.

An explanation can be new in three different respects:

1) the explanans for a known explanandum can be new,
2) a known explanans is related to a new explanandum, or
3) both the explanans and the explanandum, i.e. the whole explanation, can be new.

In the first case, a known phenomenon is explained differently, e.g. due to additional research. Khalifa provides the example of research on peptic ulcers. First, scientists thought that acid causes peptic ulcers, but it has been discovered that bacteria are the actual cause of peptic ulcers. In this case, the explanans "caused by acidity" has been replaced by "caused by bacteria", while the explanandum "the occurrence of peptic ulcers" stayed the same.[11] Therefore, the understanding of an already known phenomenon changed. In the second case, scientific understanding is acquired by applying an already known explanans to a new explanandum, i.e. a new phenomenon. For example, if one can already explain the motion of the Earth through Kepler's law, one can also explain the motion of other planets in different solar systems which were just discovered by a brand-new high-resolution telescope (new phenomena) with Kepler's law. In these cases, a different and new phenomenon is understood. Both explanans and explanandum are labelled new if a new phenomenon is discovered (e.g. the appearance of a new butterfly species) for which there has not been an explanation before and through conducting research an explanans is generated that did not already apply to any other phenomenon (e.g. this specific butterfly species evolved in this way because of the very specific environmental changes, which affect only this species due to the niche it occupies). In this case, too, a new phenomenon is understood.

11 See Khalifa (2017a) for more information about the research on peptic ulcers.

Still, why is it important to articulate *a new* explanation, and why not simply *an* explanation? This difference is important because the GE-account of scientific understanding is intended to cover understanding that is gained through conducting scientific research or scientific practice. The account is not intended to capture cases in which scientists did not perform research on a specific phenomenon by themselves, but gained understanding through receiving an explanation of a phenomenon by listening to the testimony of colleagues or reading about a new explanation in a journal article published by a different research group. The reason for this is that I do not think that the manifestation of understanding of a phenomenon through receiving an explanation is much different for scientists than for laypeople. Laypeople also want to understand phenomena in the world, this is not an exclusive goal of scientists. And the usual way laypeople go about understanding some phenomenon they are interested in is to read literature about the respective topic or listen to talks or podcasts from specialists, which are often scientists. In such cases, the subject in question, may it be a scientist or a layperson, gets to know an explanation of a phenomenon, but has not articulated the explanation herself. In such situations, when an explanation is explicitly available already and a subject learns or receives this explanation by reading a text or by listening to an expert testimony, two different things can happen. Either, the explanation is just added to the knowledge of a subject, which is not identical to understanding the aspect of the phenomenon that the explanation represents. This is a case of simply knowing an explanation in the sense that the subject accepts, maybe even believes, the explanation, can repeat and possibly even reformulate it. Or she does grasp the relations represented by the received explanation, and through this is getting epistemic access to the phenomenon that she did not have before she received the explanation.

In this second scenario, her understanding of the phenomenon will have changed or improved, in contrast to the first scenario, in which she just gained additional knowledge of the explanation, but no understanding of the phenomenon. I elaborate on the difference between knowing an explanation and understanding the phenomenon that is represented by this explanation, through grasping, in section 4.3. However, the point I want to make here is not about the difference between knowledge and understanding, but instead about the question whether there is a difference in the understanding through receiving an explanation in cases where the subject is a scientist or a layperson. At least *prima facie*, I do not think that there is a difference. Whether one is a scientist or layperson, if one reads or listens to some explanation of some phenomenon, one will have to grasp the relations that are represented by the explanation. In contrast, achieving understanding through conducting scientific research is only possible for scientists who acquired the necessary resources and were trained to use them for the manifestation of understanding. I elaborate on these resources in section 6.2. Laypeople are not trained to be scientists, they lack the resources that scientists have, are not able to conduct scientific research and hence are not able to understand a phenomenon through this procedure. Laypeople as well as scientists are in principle able to acquire understanding of a phenomenon on the basis of an explanation they receive, but only scientists are able to achieve understanding of a phenomenon through scientific methods and an articulation of a new, previously not known or non-existent, explanation grounded in these methods.

6.1.2.3 Aspects of phenomena and details of relations

Again, the objects that scientists ultimately want to understand are empirical phenomena. I already explained in section 6.1.2.1 that relations of phenomena need to be grasped for understanding, as understanding is something like "seeing how things hang together". However, I introduce additional qualifications in the *manifestation condition* of understanding, namely that *details of* relations of *aspects* of *P* should be grasped and explained. Why do I introduce these additional restrictions? Because, at least in the vast majority of cases, phenomena are not fully understood in the course of a single study. In other words, (most) phenomena that are of scientific interest are so complex that it is impossible to grasp and explain all the relations a phenomenon stands in at once, or even to grasp all the details of one relation between only two aspects of a phenomenon at once, as individual relations may also be quite complex. Usually, scientists perform several experiments, compare many samples, and collect a lot of data to discover aspects of a phenomenon. Scientists understand a phenomenon in a piecemeal fashion, through grasping and explaining more and more aspects of the phenomenon, the relations between these different aspects, and also the details of any relation. This process takes time.

Consider the zebrafish episode from chapter five, where this piecemeal understanding of the target phenomenon can be seen on two different levels. On the more general level, the phenomenon that biologists working on zebrafish wanted to understand is the genetic regulation of embryonic development of vertebrates. As this is a very complex phenomenon in which various different genes interact with each other at various stages during the developmental process, the biologists had to split up in several research groups, focusing on specific genes in their respective laboratories. Some groups restricted their research to the development of the cardio-vascular system, others to the nervous system, etc. In other words, the various research groups grasped (and subsequently explained) different relations between some aspects of embryonic development, namely those they were researching. The results gained in the different zebrafish laboratories are shared with the community, for example via the Zebrafish Information Network (ZFIN), an online database, to enable colleagues to use results for their research on a different aspect of embryonic development. On the level of a particular research group, even the understanding of the function of one specific gene takes place step by step. Recall the research on the *oep* gene that I discuss at length in chapter five. The results on the function of *oep* for the Nodal signalling pathway, which were published in one single article, required several experiments, each one focussing on one specific feature of the function of *oep*. For instance, one experiment was required to test whether Oep is necessary for Nodal signalling or whether it has merely an amplifying function, while another experiment was necessary to discover the exact location of Oep in the Nodal signalling pathway. Again, these are just two out of more experiments that one group of scientists conducted on *oep* in zebrafish.[12]

Hence, it is neither necessary nor always the case that a phenomenon is understood in merely one manifestation process of grasping and explaining. On the contrary, it only rarely is the case that a phenomenon is fully understood by a scientist through one manifestation process. Furthermore, various details of a relation or several relations that are relevant for understanding (aspects of) a phenomenon may be grasped successively, especially when the investigated phenomenon or the relations involved get more complex. It happens that first the presence of a relation is grasped, and that further details of this relation are worked out in the course of further investigation. It may even be the case that some details of a relation become epistemically accessible only after other details of the relation or further relations were already grasped and articulated in hypothetical explanation. This feature can be observed in the episode of the research on *oep*, too. The goal of the scientists in this episode was to understand the function of the *oep* gene in embryonic development. When they generated zebrafish mutants that lack the *oep* gene, the process of understanding started by first grasping the similarity relation between the phenotypes of the generated *oep* mutant and the *sqt/cyc* double mutant. This is a relation between the phenotypes of two mutants. Based on the knowledge that the *oep* mutants lack the Oep protein, the *sqt/cyc* mutants lack the protein Nodal, and on the observation that both mutant strains have a similar phenotype, the biologists concluded that the proteins Oep and Nodal must be related somehow. Only due to the grasping of the similarity relation between the *oep*- and the other mutants was it possible for the biologists to grasp, to get epistemic access to, a relation between the proteins Oep and Nodal and, therefore, also between the respective genes. Only now had the biologists *reasons* to assume that there is a connection, but they did not understand this connection, yet. To gain understanding of what is going on and how the genes involved interact, the biologists investigated the observed similarity of the different mutants further and considered reasons for it. They were looking for an explanation of the similarity and had the idea that Oep and Nodal might act in a common pathway. If this is the case, it would explain why the same phenotypic effects can be observed when one of the two components of the same pathway is missing. In both cases, the pathway would not function properly and lead to identical effects.

12 See Gritsman et al. (1999) for information concerning all the experiments in this study.

This was the first step in the manifestation of understanding of the function of *oep* in embryonic development. The biologists understood that *oep* is somehow related to *nodal* (or its orthologs). However, they had no idea what this relation may look like, or how exactly these proteins interact. They had not grasped the details of the relation between *oep* and *nodal*, yet. In a second step, the functioning research infrastructure came into play. After arriving at the idea that Oep and Nodal might somehow act in a common pathway, the biologists referred to the results and knowledge about the proteins, and also the genes coding for the respective proteins, previously gained in other studies, not in their own. Research on Oep as well as on Nodal in zebrafish was already conducted, but independently from each other. A relation between the respective genes had not been assumed before. The integration of additional knowledge "suggested that Oep is required for cells to receive Nodal signals."[13] This is already a much more concrete conception of the relation of *oep* and *nodal*, more concrete than the insight that the two genes are somehow related. The biologists arrived at the hypothetical explanation that *oep* has an important function in vertebrate embryogenesis, because it activates the Nodal signaling pathway by which germ layer formation, organizer development, and the positioning of the anterior-posterior axis are regulated.

However, this was only a hypothesis or a hypothetical explanation. The scientists wanted to have supporting evidence to ensure that they understood the function of *oep* correctly. In a third step, the biologists designed and conducted several experiments to determine whether Oep is indeed necessary for Nodal signaling and where in the pathway Oep is located exactly. For example, through counterfactual reasoning the scientists came up with an experiment to test the counterfactual situation that Oep is *not* necessary for Nodal signaling. This experiment did decisively show that Oep is indeed essential for Nodal signaling, and not merely an amplifier. The biologists could confirm their hypothetical explanation, that they actually grasped a detail of the relation in question. Nonetheless, before conducting the additional experiments to investigate aspects of the function of Oep (the phenomenon) in the third step of the manifestation of understanding, the biologists could not know whether their articulated hypothetical explanation is correct. That is, they could not know whether they already understood the function of *oep*, that they actually grasped a detail of the relation between *oep* and *nodal*, or rather misunderstood it. The experiment in which the biologists tested the need of Oep for Nodal signaling could have falsified the hypothetical explanation and the biologists would have realized that they had misunderstood the function of *oep*, i.e., that their explanation did not match the phenomenon. In this episode, the articulated hypothetical explanation was confirmed, but it does happen that hypothetical explanations are falsified, which indicates that researchers misunderstood the relations of the phenomenon

13 Ibid. p. 125.

in question. When phenomenon and explanation are conflicting with each other, the conflict (usually) motivates scientists to articulate an alternative explanation, to understand the phenomenon in a different way in which the conflict dissolves.

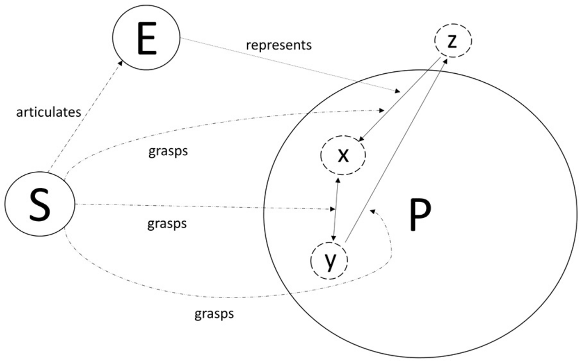
In sum, in order to understand the function of *oep* in embryonic development (the phenomenon), the scientists successively grasped and explained the similarity relation between the *oep*- and other mutants, then the relation between *oep* and *nodal* (or its orthologs), and subsequently the *details of the relation* between *oep* and *nodal*, e.g. that *oep* is necessary for activating the Nodal signaling pathway and not an amplifier, as well as the exact location of Oep in the pathway, i.e., the receptor and transcription factor with which Oep interacts. Hence, the *parts or aspects of the phenomenon* between which these relations hold include the phenotypes of the mutants, the genes and respective proteins. It is not sufficient for understanding to merely grasp the parts or aspects of the phenomenon independently from each other, as this would not allow to "see how things hang together". Rather, one must grasp which aspects or parts are related, and how exactly they are related. Or consider the famous flagpole example. If you want to understand why the shadow of a flagpole has a certain length, it will not be sufficient to grasp or recognize the length of the shadow, the length of the flagpole and the position of the sun (aspects of the phenomenon) without grasping how these aspects are related.

6.1.2.4 The gradual nature of understanding and the iterative nature of its manifestation

So, as scientists understand the phenomena they are investigating step by step, the understanding of the respective phenomena manifests in the successive grasping and explaining of details of relations that hold between different aspects of the phenomena. The manifestation process of scientific understanding is schematically shown in figure 2.

The iterative nature of the *manifestation condition* accords with one feature of understanding that is so far uncontroversial in the philosophical debate on understanding, namely its gradual nature. Understanding comes in degrees, as I already said in section 4.2.2. The GE-account adheres to the procedural nature of understanding and accommodates it by an iterative, stepwise process of grasping and explaining (details of) relations of (aspects of) phenomena or several relations of several aspects one after another. The understanding is complete for a specific scientific episode if all relevant relations and their details are grasped and articulated in explanations. Following every instance of grasping, the scientists reason or reflect about the grasped information, articulate them in a hypothetical explanation and continue to explore the phenomenon if they identify further questions concerning the phenomenon they cannot answer yet.

Figure 2: The manifestation of scientific understanding.



S grasps relations R_1, R_2, and R_3, which hold between the aspects x, y, and z, where z is some external aspect that is related to the internal aspect x, and articulates a new explanation E_{R3} that represents R_3. The details of R_3, which are not depicted here, would include, for instance, what kind of relation it is. If R_3 turns out to be a causal relation, a further detail will be that z causes x.

If scientists find gaps in their newly acquired knowledge of a phenomenon, which they cannot close by referring to available knowledge, they will conclude that their understanding is incomplete. That is, they have not grasped every detail of a relation, or all relations involved, or could not articulate all the grasped information, yet. Importantly, notice that I use the notion of 'complete understanding' in reference to a *specific research episode*. I do not talk about complete understanding as a context-independent, ideal understanding. Rather, I view understanding to be complete if scientists within a specific research episode answer all research question about a phenomenon they wanted to answer in this episode. This does not exclude the possibility of investigating the very same phenomenon again in the future and asking new or possibly even the same research questions in light of new knowledge or evidence again. However, in order to gain any scientific understanding, specific resources are required.

6.1.3 The *resource condition*

Therefore, I call the second condition of the GE-account *resource condition*, as it captures all the resources that scientists need for understanding a phenomenon through scientific research. The analysis of the scientific episode from biology in chapter five revealed the necessity of these resources, which cover (material) equipment, relevant knowledge and research skills. In this section, I argue that these resources are, in an abstract sense, necessary for any kind of scientific research in any scientific discipline, and hence also for scientific understanding.

6.1.3.1 (Material) Equipment

The insight that scientists need adequate equipment to do research at all should not come as a surprise. Neither does the observation that not every phenomenon can be investigated with any equipment. A microscope will not enable anyone to observe stars and other planets. While the awareness that the research on different phenomena requires diverse equipment will probably be seen as trivial for many readers, I think it is important for an account of scientific understanding to mention this insight explicitly. This is so for the mere fact that the existence and availability of equipment has a direct and grave impact on the possible understanding that scientists could acquire of any phenomenon. Leaving this fact unmentioned would not do justice to the fundamental influence of the equipment on understanding.

First and foremost, one cannot try to understand a phenomenon one is not aware of. For instance, in order to understand global climate change, one must first realize that something like global climate change exists or takes place. To achieve this, certain equipment like thermometers are already required in a sufficient quantity. Once some phenomenon is discovered, scientists need to engage further with it in some way to understand it. For this further engagement, additional and potentially divers equipment is necessary. In order to understand the mechanisms involved in or driving climate change, scientists need, for example and among other things, appropriate computer models and computing capacity to run their simulations.

Two remarks are in need. First, throughout chapter five, I used and referred to the term 'tool'. I do not use this term here, as I subsume tools under the notion of equipment. For doing research, scientists need tools as well as the stuff or material to apply the tools to. Thermometers as well as computer simulations can be viewed as tools, and hence belong to the equipment of climate scientists. Second, computer models and the data that are used by scientists, not only in climate science, are not strictly speaking 'material', while computers on which the simulations are run and the data stored definitely are material objects. This is the reason why I bracket the attribute 'material' when talking about the equipment. Without some material equipment like computers or hard drives, at least, no research will be possible, including disciplines like theoretical physics or theoretical chemistry that, at first glance, do not use 'material' equipment in their investigations. Hence, in theoretical disciplines like theoretical physics or chemistry, or even in the humanities, the (material) equipment may play a subordinate role in the acquisition of understanding. However, some minimal (material) equipment like books, writing material or computers will be necessary in such theoretical disciplines. Furthermore, many of the empirical sciences require much more and divers material equipment than theoretical disciplines. In the scientific episode on understanding the genetic regulation of vertebrate development presented in chapter five, the list of necessary equipment includes an appropriate model organism, or even a specific mutant strain of that organism, depending on the research questions asked, adequate aquaria systems, dissection microscopes, devices to induce mutations, for instance through γ-radiation, chemicals or induction of mRNA, and descriptive devices including cellular fate maps, neural wiring diagrams, or staging series. Again, which equipment is required precisely is dependent on and needs to be analyzed for the concrete scientific episode, given the respective research discipline and the phenomenon that is investigated.

In short, (material) equipment is necessary for conducting scientific research on phenomena, and hence for gaining scientific understanding of these phenomena. While this insight may not be very novel, it should be made explicit, as the available equipment determines one contextual dimension that impacts the possibility of understanding. Depending on the available equipment, it is possible to understand some phenomena, but impossible to understand others. The existence and use of specific (material) equipment makes understanding possible in the first place. Biologists would not have been able to acquire understanding of the genetic regulation of vertebrate development if they had not introduced zebrafish as a model organism to work on and created and assembled additional equipment, like the devices to induce mutations and to identify phenotypic effects. Yet, the appropriate (material) equipment does not exhaust the resources needed for understanding. Another resource that scientists need as well is relevant knowledge.

6.1.3.2 Relevant knowledge

I take knowledge to be necessary for scientific understanding, in the sense that a scientist cannot understand a phenomenon if she does not know anything about it. I consider knowledge to be propositional and I subsume concepts like natural laws, theories or empirical data under the term knowledge. If a scientist wants to understand a certain phenomenon, she must start somewhere and must draw on theoretical and empirical background knowledge that has been established and accepted by the scientific community the scientist belongs to. This claim accords with Michael Polanyi's analysis of the interconnectedness of articulate and inarticulate intelligence, which I present in more detail in sections 4.2.3 and 4.3, and his conclusion that humans cannot understand the world without reference to an established articulated conceptual framework. Polanyi argues that humans always rely on the knowledge about the world that previous generations collected and stored in the respective language of a community. This is the case for every human community, not only different scientific communities. Resorting to knowledge about the world already established and stored in language in the past enables new generations to directly approach new problems, questions, or phenomena, instead of starting from the beginning all over again. In the case of science, students acquire the necessary knowledge in lectures and seminars during their studies. For example, physics students learn the basics in mechanics, optics, electromagnetism or solid state physics, together with the respective vocabulary that the physical community developed to represent and store knowledge in these fields. Already established knowledge is taught to junior researchers, in order to enable them to make use of that knowledge when addressing new phenomena and unanswered questions in all scientific disciplines, not only in physics, of course. Without taking some knowledge as an established basis, no new knowledge could ever be gained, no progress in scientific knowledge could be made.

The knowledge that is already established and available in a concrete research episode is another contextual factor that influences the understanding that can possibly be acquired of a phenomenon. Depending on what scientists know and do not know (yet), they may be able to understand some phenomena, but not others. Take again the episode on zebrafish from chapter five. Molecular geneticists wanted to understand the effects of genetic interactions on the development of vertebrates, but the knowledge that they possessed within their discipline was insufficient to understand this particular, though complex, phenomenon. Molecular geneticists had only been concerned with molecular processes within a cell, and their available background knowledge enabled them to address phenomena in this domain, but they could not exceed it. For addressing and understanding developmental phenomena, knowledge about molecular features or processes was not enough. Additionally, knowledge about cell, tissue and organ properties as well as organism as wholes was required. And molecular geneticists acquired this knowledge through cooperating with developmental biologists who possessed it and were interested in the same phenomenon as the molecular geneticists. As I elaborate in section 5.2.1, developmental biologists had the same problem as the molecular geneticists at the beginning of the research episode, namely that they were lacking necessary knowledge. The developmental biologists did not know anything about molecular mechanisms or properties or about genetics. Since the background knowledge from molecular genetics and developmental biology complemented each other, and researcher from both disciplines had a shared interest, the cooperation and, ultimately, integration of the disciplines was fruitful for the understanding of the genetic regulation of vertebrate development.

Notice that I do not claim that an integration of different scientific disciplines is necessary for or always a guarantee for achieving understanding for some phenomenon. It happened that in the episode from scientific practice that I have chosen that an integration of two research disciplines fruitfully enabled understanding, but this may not always be the case. Attempts of integration or even merely cooperation of different disciplines may also fail, and in many cases scientists within one disciplines are able to generate new knowledge that they need on their own, without interacting with any other discipline. In short, I am not making any claims about the role of integration of various scientific disciplines for scientific understanding. Such a form of integration may fruitfully enable or foster understanding of certain phenomena, as in the research on zebrafish, but it does not have to, necessarily. The only claim I am making here is that for understanding a specific phenomenon, specific knowledge is required. One cannot understand the genetic regulation of vertebrate development without having knowledge from molecular genetics as well as from developmental biology, one cannot understand global climate change without some knowledge from physics, one cannot understand potential effects of a high inflation without some knowledge from economics. How scientists acquire the knowledge that they need for understanding a specific phenomenon, whether they generate this knowledge themselves within their own disciplines before addressing the respective phenomenon, cooperate with scientists from another field or establish a new discipline through an integration of several already existing disciplines, varies depending on the episode one looks at.

So, with the term knowledge I am referring to every kind of propositional knowledge that may be relevant for the phenomenon under investigation and already contained in the background knowledge of the scientist or in the informational sources of the research community. All scientists rely on the already established background knowledge of their community when conducting their research, answering new research questions, and generating new knowledge. Knowledge must be explicit or made explicit when necessary.[14] Whether a scientist can understand a specific phenomenon depends on what she already knows or to which knowledge she has access and on the available (material) equipment she could use in her investigations. Yet, another type of resource necessary for understanding is missing.

6.1.3.3 Research skills

In addition to the equipment and knowledge, various research skills play a necessary role for scientific understanding, too. In contrast to my notion of knowledge, I view skills to be non-propositional. The concept of skills or abilities is discussed at length in chapter four, where I develop and apply the following definition of an ability:

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14 Again, I subsume theories under my notion of knowledge and will not address more specific possible functions of theories for (scientific) understanding. In this respect, the GE- account differs from Henk de Regt's account, in which scientific understanding of phenomena can only be acquired on the basis of theories. I discuss the reasons for and the advantages of not giving theories a special status in the GE-account in section 6.2.1, where I compare the GE-account of scientific understanding with the account of Henk de Regt.

x is an ability if and only if *x*

i) is a disposition to perform a cognitive or physical activity successfully with respect to relevant standards,
ii) has been learned and trained in a specific social context, and
iii) manifests in processes that are partially tacit (i.e., that can never be made fully explicit).

Remember that the terms 'ability', 'skill', and 'know-how' are often used interchangeably. I think that there is only a terminological difference between these notions. This is because expressions like 'someone has the ability to x, has the skill to x, or has the know-how to x' all amount to the same thing in the end. They all denote that someone can do something in an appreciated or valued manner. Hence, understanding as well as research skills, which are the topic of this sub-section, fall under my definition of ability. However, understanding is a different ability than the abilities I subsume under the term research skills. Understanding is the ability to make sense of a phenomenon in a scientific way, while research skills are abilities needed for conducting scientific research, e.g. taking measurements with specific devices, collecting samples, or programming computer simulations. I view understanding to be a more holistic ability than the research skills needed to gain understanding. So, for the sake of clarity, I refer to understanding as an ability and to all other kinds of 'know-how' that contribute to understanding in the scientific context, the research skills, as skills.

Research skills enter the scene in the play of understanding by actually using the available equipment and knowledge in order to really do scientific research. Research skills cover all skills that scientists learn and employ in the scientific practice of their discipline. These research skills are required to set up an environment in which new (hitherto unknown) relations can be grasped (i.e. in which a phenomenon can be investigated) and an explanation based on investigating the grasped aspects of the phenomenon and on the available knowledge can be articulated. Scientists have access to information from their background knowledge and also from the current investigation of the phenomenon, for example through observations, measurements, or modelling procedures. This information has to be selected, used, and reasonably connected to grasp relations and articulate an explanation of the phenomenon. There are no fixed rules how exactly this should be done.[15] Depending on the object of understanding, the training of the scientist, which information are

15 De Regt argues for this characteristic of scientific understanding as well, see de Regt (2017), chapter 2.2.

available, how they are (re-) presented and the epistemic goals of the scientist, it varies significantly which relations are grasped by scientists and how the resulting explanation looks like. This is due to the observation that understanding is a multi-track disposition, a feature for which I argue in section 4.2. Depending on their discipline and the historical context, scientists not only have different bodies of information (i.e., knowledge) and varying equipment at their disposal, but they also learn different research skills, e.g., handling a particular measurement device in the laboratory, or using varying modelling or statistical tools. The research skills scientists learn and apply shape the acquired understanding. Research skills, together with the available knowledge and equipment, have an impact on which relations can possibly be grasped and which information are put in the explanandum and in the explanans, that is, which pieces of knowledge are associated with which aspects of the phenomenon and how they are connected (i.e., what kind of relation holds between knowledge and phenomenon or between aspects of phenomenon, i.e., causal, deductive, probabilistic, mechanical, functional,… relations).

The necessity of research skills to understand a particular phenomenon has also been highlighted in the episode on the zebrafish research in chapter five. In order to understand the genetic regulation of embryonic development of complex organisms like vertebrates, sophisticated research skills were as much required as appropriate equipment and relevant knowledge. As for gaining the required knowledge, the integration of molecular biology and developmental biology also provided the possibility for the involved scientists to learn and practice the research skills necessary for the envisioned research. The molecular biologists had the skills to induce and map genetic mutations in zebrafish, but were not able to relate the insights gained through this procedure to any effects that the mutations have on the phenotype of the embryos. In fact, they were neither able to identify any phenotypic effect, nor to actually do research on biological structures that exceed the molecular level. Molecular biologists had the research skills to engage with molecular mechanism, but they never acquired the research skills to work with more complex tissues, organs, or even embryos as a whole. And the developmental biologists, in contrast, had the research skills to identify and work with phenotypic effects, they were able to dissect embryos, but were not able to engage with phenomena on the molecular level through, for example, mutational analysis, because they had never learned to do mutational analysis. Because of the lack of specific research skills necessary for the phenomenon in question on both sides, none of the scientists involved in the early stage of the new research endeavor could investigate the phenomenon they wanted to do research on, and hence no one could have grasped any of the relations involved in the phenomenon or explain anything. Only through the integration and acquisition of research skills from both biological disciplines were the scientists able to do the imagined research, to grasp relations between a mutation and its phenotypic effects in the development of an embryo, and ultimately to draw conclusions on genetic interactions in normal developmental processes. In a nutshell, without the implementation of the respective research skill, the research on zebrafish could not have been conducted, not to be mentioned that biologists would have understood anything.

So, while possessing the required research skills is necessary for grasping relations and articulating explanations, it does not automatically amount to grasping relations and articulating explanations. Therefore, I distinguish between research skills on the one hand and grasping and explaining, alias the manifestation process of understanding, on the other. It can still happen that a research project, despite being conducted properly, does not provide the insights scientists expected. The empirical data that are obtained in a research project may not allow for grasping any hitherto unknown relation, despite the fact that the involved scientists used their research skills appropriately. There is no guaranty that any study, or the data obtained by it, provides new insights into the phenomenon, that it reveals new aspects so that scientists could grasp them. Not every study enables epistemic access to a (so far) hidden aspect of the phenomenon. And even if a scientist is able to grasp a hitherto unknown relation of the phenomenon on the basis of her background knowledge and the appropriate application of research skills, the articulation of the grasped relation in form of an explanation, and hence the understanding of the respective aspect of a phenomenon, may still not be possible. This was the case with James Clerk Maxwell and his attempt to understand the specific heat anomaly of gases like oxygen or nitrogen, an example that I already briefly referred to in section 4.2 and 4.3 and which has been analyzed in detail by Henk de Regt.[16] Maxwell failed to understand the specific heat anomaly, because he could not articulate an explanation of why the anomalous gases have the specific heat ratios that were determined empirically. He got a grasp on the relation between the specific heat ratios and the kinds of molecular motion that these gases exhibit, and introduced the concept of degrees of freedom in his attempt to explain the specific heat ratios based on the kinds of motion of the gas molecules. Still, the explanans he articulated did not accommodate the explanandum, the empirically determined values of the specific heat ratios of the anomalous gases. Hence, Maxwell failed to come up with an explanation of the specific heat anomaly. This phenomenon remained a mystery to Maxwell, he did not understand it, despite the fact that he possessed impressive research skills and was one of the most outstanding physicists in the nineteenth century. It was Ludwig Boltzmann who used the concept degrees of freedom, introduced by Maxwell, to develop his dumbbell model of the anomalous gases, who provided an explanation of the specific heat ratios based on this model, and hence understood this phenomenon.

16 For an in-depth analysis and discussion of this episode from scientific practice, see de Regt (2017), pp. 205–216.

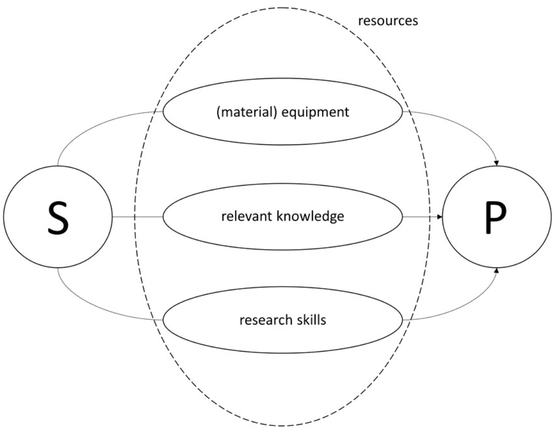
Research skills are intertwined in the manifestation process of understanding, to first grasp and then, subsequently, articulate new discoveries relating to the phenomenon in an explanation. Understanding is the ability to make sense of new discoveries about a phenomenon in the context of already available knowledge. Research skills are required prior to grasping any relations, for setting up experiments, conducting measurements, or for analysing data appropriately so that it becomes possible to grasp, to get epistemic access to, some relation of the phenomenon in the first place. The biologists in the episode on zebrafish would not have been able to grasp a relation between Oep and Nodal if they did not had the research skills to, among other things, generate the Oep-mutants through cloning techniques and identifying phenotypic effects of these mutants. And also after some relation is grasped, research skills are required again to investigate that relation and to arrive at an explanation. For instance, after a relation between Oep and Nodal was grasped, it should be clarified whether Oep has an activating or amplifying function in the Nodal signalling pathway. Hence, the biologists needed the research skills to set up experiments in which they could test precisely these possibilities. If they lacked these research skills, they would not have been able to discover that Oep has an activating function. They would not have been able to explain the function of Oep for Nodal signalling and, therefore, would not have gained understanding of this phenomenon without the research skills to set up and conduct these experimental studies. Understanding manifests in an iterative process, as I argue in section 5.2.3, and for every iterative step of grasping and explaining, scientists need specific resources.

Scientific understanding requires research skills, knowledge, and specific equipment. These three kinds of resources are means that serve the end of understanding. If a scientist is lacking any of these necessary resources, she will not be able to grasp or explain relations of a phenomenon, since she would not be able to research that phenomenon at all. Knowledge, research skills, and also material equipment are necessary for understanding, because their availability and application *enable* scientists to do research, as well as to grasp relations and to articulate them in form of an explanation. In the episode on zebrafish, these were relations between genetic activities and developed phenotypes and also epistatic interactions among genes. It would not have been sufficient if the biologists only had all the propositional knowledge from molecular and developmental biology and all the necessary equipment, including zebrafish mutant strains, aquaria systems, dissection microscopes etc., but would have lacked the research skills. They would not have been able to apply the knowledge and equipment to really carry out an experimental study. Merely possessing theoretical knowledge does not allow for relating this knowledge to phenomena in the world, and thereby understanding them. The same applies for merely possessing the necessary equipment. Simply having the required material and instruments is not identical to having the skills to use them. And being well trained in all the required research skills also only enables understanding if the required equipment and relevant knowledge is available, too. Having the skill to use a dissection microscope, for instance, will not be of any usage for a scientist if she does not also have a dissection microscope and some organism to dissect. And if a scientist can accurately manipulate genes, dissect embryos, and apply statistical tools, if she has the research skills and equipment, she will not be able to recognize any significant effect if she does not know what to look for, or will not be able to make sense of anything that she may recognize if she does not also possess the, in this case, relevant knowledge. Again, this is so because humans cannot understand anything in the world without relying on some already established background knowledge.

6.1.3.4 Having all the resources

So, this second condition of the GE-account, the *resource condition*, explicates which resources need to be available for scientists so that they can possibly understand a phenomenon through research. These resources are (material) equipment, relevant knowledge, and research skills, as figure 3 illustrates.

Figure 3: The resources for scientific understanding.



S needs the resources to do research and scientifically understand P.

What kind of equipment, which knowledge and research skills are needed to understand some specific phenomenon depends on the phenomenon and has to be analyzed in the individual cases. Importantly, the availability of these resources is necessary for understanding a phenomenon, it enables understanding, but it is not sufficient. Even if a scientist has all the resources at her disposal, she still has to manifest the ability to understand the phenomenon. She still has to grasp relations and articulating explanations, and hence to fulfill the *manifestation condition*. Yet, one final condition is still missing, namely the *justification condition*.

6.1.4 The *justification condition*

Scientific understanding of a phenomenon is context-sensitive and hence influenced by historical, disciplinary, and social factors, as I already alluded to in section 6.1.1. In other words, the scientific community in which an individual researcher is embedded impacts the understanding that she can achieve. More precisely, the scientific community serves two functions regarding the understanding of individuals. First, the community has to enable its members to gain scientific understanding of phenomena. And second, parts of the community also have to assess and approve the understanding that its members achieve as scientific. Let's have a look at these two functions, which resemble the famous distinction between the context of discovery and the context of justification.

6.1.4.1 Enabling a scientist to understand a phenomenon

Most basically, every first semester science student joins the scientific community as a whole. Of course, *the* scientific community, referring to the sum of all scientists, is a fairly vague ascription and can be split up into sub-communities along various dimensions. One of these dimensions is the respective discipline, like physics, chemistry, biology, psychology, geology, and so on. Scientific communities belonging to these disciplines can be subdivided even further. Within biology, for instance, we have genetics, physiology, botany, zoology, ecology and many more, and these subdisciplines again cover several sub-communities that are even more specialized in some way. And even within one and the same (sub-) discipline, there is historical variation. Every discipline changes and develops in some way in the course of its history, for example by changing its methods and scientific standards. And it also happens that two or more disciplines merge in order to cope with new phenomena, as it happened in the episode on zebrafish, in which researchers from molecular genetics and developmental biology founded the new discipline of developmental genetics. I do not want to argue for any specific conception or definition of what a scientific community is or may be. Maybe there is no single and strict definition of a scientific community, as communities themselves change in the course of history. Fortunately, this is not a problem for the GE-account of scientific understanding. Every young science student becomes a member of some scientific community, whatever its demarcation to other disciplines or communities may be and whether this demarcation is fluid or not. Throughout their careers, scientists get more and more specialized within their discipline, within their community. To put it differently, scientists specialize in a way that is necessary to gain understanding of the phenomena they are interested in and that are addressed by the specific community they joined. If necessary, this specialization includes a broadening of the discipline, inter- or transdisciplinary research, the collaboration with scientists from other communities or even an integration of several disciplines, as in the zebrafish episode.

Within their scientific community, researchers (ideally) get all the resources they need for doing research on and to understand phenomena. These resources include (material) equipment, already established knowledge, and research skills, as is already explained in section 6.1.3. But furthermore, science students also learn and practice the ability to understand phenomena with which their community is concerned scientifically. Recall that I argue in section 4.2.3 that, in general, understanding is the ability to make sense of an object (a situation, an experience, or a phenomenon) by aligning the object with the language used. In the case of scientific understanding, young scientists acquire the ability to make sense of some phenomenon in a way that is accepted by parts of their community as scientific. They learn to grasp relations that are relevant for the phenomenon in question and articulate these relations in explanation by using adequate background knowledge through exercises or tasks provided by their professors and supervisors. In the course of lectures, seminars, laboratory courses of field trips, supervisors show how open questions or problems concerning some phenomenon are addressed and solved in the respective discipline, how scientists in the discipline understand phenomena they are researching. And then, students or young scientists are confronted with exercises they have to solve themselves. They have to demonstrate that they are able to make sense of, to understand, phenomena on their own. This description of how young scientists acquire the ability to scientifically understand phenomena is backed up by my discussion of how any ability, not only understanding, is learned, which I present in section 4.1.3. There, I argue that any ability can only be learned by practice within a community and guided by a master, teacher, or supervisor, and not from a textbook.

The various crucial functions of the scientific or disciplinary community for scientific understanding and how understanding is contextually influenced becomes apparent in the episode on the research on zebrafish as well. Scientific understand of the genetic regulation of vertebrate development, as in the case of the *oep*-gene, could have been acquired by the involved biologists only because an appropriate context and community were established. Only through the integration of molecular and developmental biology could the researchers on zebrafish acquire the knowledge and train the research skills from both disciplines which they necessarily needed to do the research they wanted to do. Additionally, through conducting *The Big Screen* in the second stage of the episode, the zebrafish community provided itself with the required material resources such as the zebrafish mutant strains and the laboratory equipment, like sophisticated aquaria systems. Having all the necessary knowledge and research skills will not provide understanding if a scientist does not have the material equipment to work with. The availability of all the mutant strains enabled research that would not have been possible prior to *The Big Screen*. And the researches working on *oep* did not only need the respective mutants, but also access to knowledge generated by other research teams to make sense of the similarity they observed, to come up with ways to investigate the relation between the genes in more detail, namely to grasp more aspects of the relation of *oep* and *nodal*, and to understand it at the end. Communication and exchange with other researchers is necessary in order to get all the equipment and pieces of knowledge that are required to understand a specific phenomenon in a certain context. However, the respective scientific community also fulfills a second crucial function for the understanding of individual scientists, to which I now turn.

6.1.4.2 Approving the understanding of a scientist

In addition to providing any individual scientist with all the resources necessary to understand a phenomenon and to teach her how to scientifically understand phenomena, some members of the scientific community also have to assess whether she indeed did understand some phenomenon scientifically. But how can it be assessed whether a scientist has gained scientific understanding, the ability to make sense of phenomena in a scientific manner? This is possible only through an explanation that a scientist articulates and then communicates. Basically, she has to come to new knowledge by herself, not by merely reading a book or listening to someone, and she has to be able to make this new knowledge explicit. Again, the newly produced explanation or knowledge has to be new only for the reasoning subject herself, as I already explained in section 6.1.2. For assessing whether an explanation is in fact a legitimate explanation, that it accords to the existing disciplinary norms, a scientist has to communicate her new insight, the new explanation, and the way through which she arrived at that explanation, to other scientists. Communicating the grasped relation in form of an explanation and the methods and practices through which one arrived at that explanation is the only way for other members of the community to assess whether an individual has in fact understood the phenomenon in question in an appropriate manner.

It is necessary for scientific understanding that scientists articulate explanations, because this is the only way that scientists can make their understanding of a phenomenon explicitly and publicly accessible. Understanding is a cognitive ability and its manifestation, the grasping of relations and articulation of explanation, is a cognitive process. This process is hidden from other members of a research community since scientists have not (yet) found a way to peek into the head of their colleagues and see their thoughts or inferences they make. Only the result or product of the manifestation of understanding, an explanation, can be presented and is, hence, accessible to other members of the community. And scientists should want to make their understanding assessable by making an explanation explicit, because they want to get things right. Ultimately, scientists want to discover, know and understand how the world really is. They aim at having justified beliefs and avoid a reliance on luck, they strive to get the best possible confirmation and justification that their understanding is correct (in terms of the contextual standards of the discipline). To achieve this, scientific understanding has to be made accessible for colleagues.

This idea of seeking confirmation and justification for the individual scientific understanding and thereby increasing its objectivity by appealing to the scientific community is in line with the views of Helen Longino and Heather Douglas, who take objectivity (of hypothesis, explanations, theories) to be a feature of a social community. While both reject a strong notion of objectivity in terms of the value-free ideal, they argue for a conception of objectivity in terms of intersubjectivity reached through social processes like critical discussions.[17] Although neither Longino nor Douglas were explicitly concerned with scientific understanding, de Regt argues that their analyses of objectivity can also be applied to understanding.[18] That is, "whether or not the understanding that is produced may be considered objective depends on whether the individual and social processes conform to the given conditions of objectivity."[19] The notion 'objective' in this quote refers to my usage to the term 'scientific'. That is to say, if the understanding that some scientists achieve is labelled scientific, this understanding will be regarded as objective by parts of the respective community. And Catherine Elgin holds that a scientist, in her role as an epistemic agent within an epistemic community, has to stand "not just in a suitable relation to the phenomenon she seeks to know or understand, but also in a suitable relation to other members of the epistemic community"[20] and elaborates "the obligations that members of the scientific community bear to one another, and [how] these obligations infuse the epistemic goals of science."[21] That is, no scientist can be sure that she did understand a phenomenon scientifically, that her understanding is in line with the epistemic standards of her discipline, without some members of that scientific community accepting the articulated explanation, and hence the ability to understand which was manifested in that instance, as legitimate.

17 See Longino, H. E. (1990), *Science as Social Knowledge: Values and Objectivity in Scientific Inquiry*. Princeton, (NJ), Princeton University Press; and Douglas, H. E. (2004), "The Irreducible Complexity of Objectivity." *Synthese*, 138, pp. 453–473, DOI: 10.1023/B:SYNT.0000016451.18182.91.

18 See de Regt (2017), pp. 41–44. A further discussion of the relations between individual and collective levels of understanding can be found ibid. pp. 88–91.

19 Ibid. p. 43.

20 Elgin (2017), p. 121.

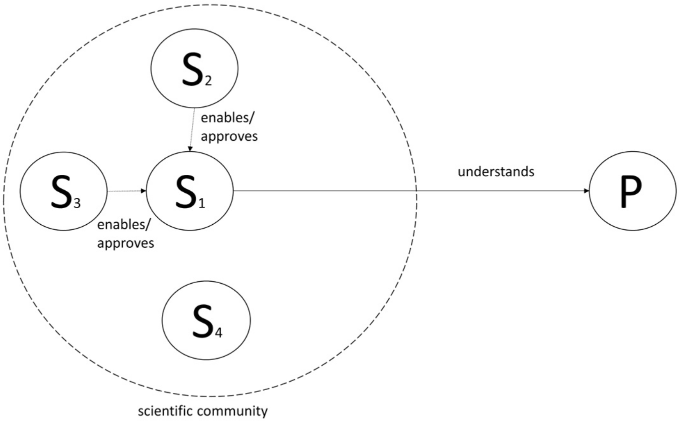
21 Ibid. p. 149. See ibid. chapters 5 and 6 for a full discussion.

In sum, the criteria for assessing whether the understanding of a scientist counts as scientific understanding depends on the scientific community, and are therefore subject to historical and disciplinary variation. Of course, all of this does not ultimately ensure that whole or parts of scientific communities will not be led astray in their understanding of phenomena. There have been cases throughout history in which some scientist understood a phenomenon in a way that was not accepted by (parts of) her community as being legitimate, while some years or decades later it turned out that the scientist in question actually got things right. Any (parts of a) scientific community at any point in time can be wrong in the assessment of the understanding that some of its members gained. As long as (a part of) the community provides good, legitimate reasons why it does not accept some understanding, this is not a flaw, as it may be the case that the understanding really is illegitimate in some specific context. As this context changes during time and along other dimensions, the assessment of someone's understanding may change with the context. So ultimately, this feature fits into the context-sensitive nature of understanding. The context does not only influence whether understanding of some phenomenon is possible at all, but also which understanding of the phenomenon is legitimate or scientific.

6.1.4.3 Being justified in one's understanding of a phenomenon

Every scientific discipline is a community endeavor. Scientists work in groups or teams, they meet and discuss their projects at conferences, workshops or during lunch breaks, they rely on the research and results from their former and current colleagues, and they distribute resources. Science as we know it today is not pursued by an individual in isolation. It would not be possible to conduct science without being a member of a scientific community, because one would not have access to the required resources one needs to perform any kind of research, and to acquire the ability to understand phenomena scientifically, through conducting scientific research. So, the scientific community is important for the individual scientific understanding in two respects: first, by providing the individual with all the available resources (knowledge, research skills, material equipment) and training her understanding, the community makes it possible for an individual to grasp relations of the phenomenon, to get access to a phenomenon, and to articulate explanations in the first place. One may say, the community is crucial in the context of discovery. And second, after an individual gained some understanding of the phenomenon she was researching, she presents the results of her understanding in form of a potential explanation to parts of her community to gain additional justification that her understanding is probably correct in light of the available evidence and the upheld standards. The presented explanation may be accepted immediately, or reviewers might demand more experiments, more data, or a re-articulation of the proposed explanation until it gets accepted. Therefore, the scientific community also plays a crucial function in the context of justification of scientific understanding. Figure 4 illustrates these two functions of the scientific community for the individual's understanding.

Figure 4: The function of the scientific community for the understanding of S.



S_1 understands P, S_2 and S_3 enable as well as approve S_1's understanding, while S_4, who also belongs to the scientific community, might not be aware of S_1.

6.1.5 Understanding – a complex ability

In this section, I presented and argued for the GE-account of scientific understanding, according to which understanding is an ability possessed by individual scientists. It is the ability to make sense of a phenomenon through research, by which new explanatory knowledge is produced. The ability to understand a phenomenon manifests in the processes of grasping relations the phenomenon stands in and articulating these relations in form of explanations. Whether an individual scientist is able to understand a phenomenon, to grasp relations and articulate explanations, depends on the available body of knowledge, trained research skills, and further material equipment, all of which have to be successfully coordinated and applied. These resources are provided by the scientific community. Once a scientists gained understanding, it needs to be judged whether this understanding is legitimate according to the employed disciplinary norms, whether it is scientific at all. Making this judgment requires a scientific community, again.

Understanding a phenomenon requires having knowledge relevant to the phenomenon, having the research skills and equipment to use this knowledge, to apply it to the phenomenon in the relevant aspects according to one's epistemic goals, in order to articulate an adequate explanation. The explanation is the articulation of the grasped relations, but the understanding itself is a cognitive ability manifested in these processes which cannot be entirely articulated propositionally. In contrast, one can simply know an explanation of a phenomenon from a textbook or testimony without grasping anything about the phenomenon and without constructing an explanation. The crucial difference between explanation and understanding, and also between any form of propositional knowledge and understanding, is that scientific understanding requires, in addition to having knowledge or an explanation, the ability to grasp relations and to use various research skills to make these relations comprehensible and articulate them in an explanation. In the context of scientific research, knowledge of an explanation of a phenomenon is not a first stage that is prior to and separated from the stage of understanding that phenomenon. Rather, explanation is an integral part of understanding, it is constitutive for understanding. Scientists understand phenomena by, with, and through the explanations they construct by employing scientific practices.

The GE-account of scientific understanding addresses various issues with which other accounts of understanding, like the ones provided by Henk de Regt, Kareem Khalifa, and Finnur Dellsén are also engaged. What makes the GE-account distinct from these other accounts, and what are its advantages in comparison to them? I elaborate on these questions in the next section.

6.2 Benefits of the GE-account of scientific understanding

What does the GE-account have to say about scientific understanding that has not been sufficiently covered or addressed by other accounts? Does the GE-account provide a more suitable analysis of scientific understanding than other accounts? I argue that it does. In this section, I compare the GE-account of scientific understanding to the accounts developed by Henk de Regt, Kareem Khalifa and Finnur Dellsén. I highlight the weaknesses and problems of these accounts and show how the GE-account is not affected by the issues that the other accounts are facing.

6.2.1 Theories are not always crucial for scientific understanding

I start again with Henk de Regt's account of scientific understanding. While a detailed presentation of de Regt's account is provided in section 2.1, let me summarize its most important features. De Regt differentiates between two kinds of understanding which are crucial in science. The first one is UP (understanding a phenomenon) that he characterizes as having an adequate explanation of the phenomenon. An explanation relates the phenomenon to accepted items of knowledge.

De Regt presents this criterion for understanding a phenomenon, which he calls CUP:

> A phenomenon P is understood scientifically if and only if there is an explanation of P that is based on an intelligible theory T and conforms to the basic epistemic values of empirical adequacy and internal consistency.[22]

The second kind of understanding is the understanding of a theory (UT), which means that scientists are able to use the theory. The understanding of a theory is spelled out in terms of intelligibility.

> [De Regt] define[s] the intelligibility of a theory (for particular scientists) as […] the value that scientists attribute to the cluster of qualities of a theory (in one or more of its representations) that facilitate the use of the theory. It is important to note that intelligibility, thus defined, is not an intrinsic property of a theory but an extrinsic, relational property because it depends not only on the qualities of the theory but also on the skills of the scientists who work with it. Theories are not intrinsically intelligible or unintelligible, but intelligible or unintelligible to a particular scientist or group of scientists. In other words, intelligibility is a context-dependent value.[23]

The thesis that scientists need intelligible theories if they want to gain scientific understanding of phenomena is the basis of de Regt's theory of scientific understanding. If a theory is not intelligible to scientists, they will not be able to use the theory to construct an explanation of a phenomenon on the basis of that theory. Without understanding a theory, understanding a phenomenon is impossible. This implies that de Regt has to determine under which conditions a theory is intelligible. If a theory is intelligible, i.e. if scientists understand the theory, they will have to have some idea of how the theory functions or how it produces certain outputs. Since de Regt allows for a wide variety of theories to provide understanding, he allows for a variety for criteria to assess the intelligibility of a theory. He offers one possible criterion for the intelligibility of theories (CIT):

> **CIT_1:** A scientific theory *T* (in one or more of its representations) is intelligible for scientists (in context *C*) if they can recognize qualitatively characteristic consequences of *T* without performing exact calculations.[24]

22 De Regt (2017), p. 92.

23 Ibid. p. 40.

24 Ibid. p. 102.

By including the individual scientists and the specific context, CIT_1 accommodates the pragmatic and context-dependent nature of the intelligibility of theories, and, hence, also of UT and UP, since both notions depend on the intelligibility of theories. Furthermore, de Regt argues that understanding cannot be achieved by performing a rule-following procedure. Instead, tacit skills, the know-how to make use of a theory or an explanation, are required. Which skills a scientist needs to make a theory intelligible to her depends partially on the qualities of the theory. By applying CIT_1, it is possible to check whether the scientists have developed the appropriate skills for a specific theory. Besides the particular qualities of the theory in question, the combination of established scientific practices in a certain field, the developed abilities or skills of the individual scientists, and the established and available background knowledge determine whether a theory is intelligible for an individual scientist or group of scientists, or not.[25]

The context-dependency of scientific understanding is also crucial for the role of explanation for achieving understanding. De Regt applies a generic conception of explanation, namely that "all explanations are […] arguments […] presenting a systematic line of reasoning that connects [the phenomenon] with other accepted items of knowledge (e.g. theories, background knowledge)."[26] Again, according to de Regt, the construction of explanations on the basis of theories is a matter of skill, of pragmatic decisions which lead to the desired result. He takes understanding to be an epistemic skill. Scientists have to have the know-how to address and solve a new problem. There are no fixed general rules that guide every possible construction process. Various models of scientific explanation, like causal or unificationist explanations, provide different tools for understanding, and all of them may be legitimately used in certain circumstances or contexts. The theory of scientific understanding developed by de Regt accommodates solely explanatory understanding, the understanding that is produced by a scientific explanation.

I agree with de Regt's account in many respects. As I argue throughout this book, I also take understanding to be an ability that includes the articulation, de Regt would say construction, of an explanation of the phenomenon that scientists try to understand. However, I disagree with de Regt in the sense that I do not give theories the central function for scientific understanding that he attributes to them. De Regt uses Ronald Giere's view of scientific theories, according to which scientific theories are "(collections of) principles which provide the basis for the construction of more specific models of parts (or aspects) of the real world."[27] In de Regt's

25 See ibid. p. 103.

26 Ibid. pp. 24f.

27 Ibid. p. 32. For more details concerning Giere's view, see Giere, R. N. (1999), *Science without Laws*. Chicago, University of Chicago Press; and Giere, R. N. (2004), "How models are used to represent reality." *Philosophy of Science*, 71, pp. 742–752, DOI: 10.1086/425063.

view, scientific understanding of phenomena requires intelligible theories. However, he is aware that this centrality of scientific theories for his account of scientific understanding might be problematic and discusses three possible objections. The first one comes from the "new experimentalists", a movement within philosophy of science that started in the 1980s. Key figures of this movement are Ian Hacking, Nancy Cartwright, Deborah Mayo, and also Ronald Giere, among others. New experimentalists claim that a theory-centered perspective on science should be rejected, and that experimentation, instrumentation, and laboratory practices should be analyzed instead, since these activities can be theory-independent. "If this is correct, it would suggest that scientists can achieve understanding without theories: Who would want to deny that scientific experiments provide us with understanding of the phenomenon under investigation?"[28] As a second argument, de Regt considers the claim that philosophical theories of science should not be focused on theories, because theories are comparatively unimportant or not present at all in some scientific disciplines. De Regt considers more descriptive branches of biology, geology, and the social sciences as candidates for scientific disciplines in which theories do not play an important role. "The thesis that theories are essential for achieving scientific understanding seems to entail that these fields and disciplines cannot deliver understanding at all, which obviously would be an unacceptable conclusion."[29] As a third and final argument against the central function of theories for scientific understanding, de Regt considers the claim that the construction of scientific models can be entirely independent from theories, given that models are taken to be autonomous agents. According to this view, scientists would need models, but not theories, to understand phenomena.[30]

De Regt argues that none of the three arguments just presented can accommodate scientific understanding, because "theory is far more pervasive than the objection[s] suggest. Of course, science can be practiced in the absence of full-fledged, explicitly articulated theories, and there is no a priori reason to assume that this cannot lead to (explanatory) understanding."[31] However, if one accepts Giere's liberal conception of theories, which are taken to be (collections of) principles that provide the basis for model construction and experimentation, it is difficult or even impossible to think of science as being theory-independent, so de Regt argues. Scientific experimentation and model-building always take place within a theoretical context and require theoretical interpretation. "Thus, while explicitly articulated theories may be less common in certain areas of geology, biology, psychology, and sociology, scientific activity will still be guided by more loosely circumscribed theoretical princi-

28 De Regt (2017), p. 95.

29 Ibid. p. 95.

30 See ibid. pp. 95f.

31 Ibid. p. 97.

ples."[32] In de Regt's view, theories, low-level or high-level, implicit or explicit ones, are ubiquitous across all scientific disciplines.[33]

It is comprehensible why de Regt insists on the central role of theories for scientific understanding, given the case studies from physics on which he grounds his account of scientific understanding. In these case studies, de Regt investigates the intelligibility of Newton's theory of gravitation from the seventeenth to the nineteenth century, the role of mechanical models in nineteenth century physics, including the effort of understanding the so-called specific heat anomaly on the basis of the kinetic theory of gases and through the dumbbell model provided by Boltzmann, which I discuss in more detail in section 4.2.2, and finally the debates about the intelligibility of matrix mechanics and wave mechanics at the transition from classical physics to quantum physics in the early twentieth century. In all these cases, explicitly articulated theories played a central role for the understanding of physical phenomena. De Regt's notions of UP and UT capture well how physicists achieved understanding in these cases and his analysis provides important insights about the changes of criteria for adequate explanations, intelligible theories, and, therefore, for scientific understanding itself in the course of history. However, de Regt himself states that not only historical, but also disciplinary variation influence the achievement of understanding. And if we look at different disciplines, as I do in chapter five with the episode from biology, it becomes apparent that theories, although not completely absent if Giere's broad notion of theories is adopted, are not always a crucial factor for gaining scientific understanding.

If theories do not play a central role in achieving scientific understanding, they should not be a central concept in any account of scientific understanding. I am not saying that de Regt is completely wrong with his claim that scientists necessarily need theories to understand phenomena. I am saying that he overstates the function of theories for scientific understanding, which is due to his focus on only one discipline that may be viewed as the prime example for a scientific discipline employing explicitly articulated theories: physics. In the episode on the research on zebrafish, Gritsman and her colleagues do not even mention the term 'theory' in the paper in which they present their understanding of the function of the Oep protein. This does not mean that the genetic theory was completely absent in this episode or that the genetic theory was not intelligible for the scientists working with zebrafish. Yet, the importance of the genetic theory to understand the function of the Oep protein was insignificant in comparison to the knowledge of experimental data and results that the scientists obtained. Whatever your favorite philosophical account of a scientific theory may be, the biologists researching the Oep protein did not attribute any crucial function to the genetic theory or other theories that may implicitly have

32 Ibid. p. 97.

33 See ibid. pp. 97ff.

shaped the understanding. Therefore, I do not include any explicit notion of theory in the GE-account of understanding. Instead, I subsume theories under the notion of propositional knowledge, together with laws, principles, axioms, or data. Each of these propositional concepts can play a role for scientific understanding.

The GE-account of scientific understanding can accommodate scientific disciplines in which explicitly articulated theories are less common or not as crucial for scientific understanding as other information better than de Regt's account of scientific understanding. At the same time, the GE-account can also capture those disciplines that employ explicitly articulated theories, like physics. To understand a phenomenon, scientists need knowledge, and this knowledge may comprise knowledge of theories, laws, principles, or empirical data. Which knowledge the scientists need to possess precisely depends on the phenomenon they are trying to understand and on the disciplinary and historical context. By not putting a heavy emphasis on theories, the GE-account has a greater flexibility in accommodating various scientific disciplines. As de Regt highlights himself, "as long as the general characterization and criteria for understanding include elements that allow for historical and disciplinary variation, it is perfectly well possible to formulate an account that transcends the purely local context."[34] By not giving theories a center stage in an account of scientific understanding, the GE-account allows for an additional dimension of variation across historical and disciplinary contexts that de Regt's account cannot offer.

What is more, the GE-account avoids possible criticism that can be raised against de Regt's and Giere's notion of theories as collections of principles. The philosophical debate on theory itself is a huge one, and several conceptions of theories exist. There is not only disagreement between proponents of the Syntactic View (defining theories as axiomatized collections of sentences), the Semantic View (taking theories to be collections of nonlinguistic models) and the Pragmatic View (according to which theories are amorphous entities possibly consisting of sentences and models, and additionally of problems, skills and practices), but also among proponents of one and the same view concerning its details.[35] There is no consensus about how scientific theories should or could be conceptualized. One can argue against Giere, whose conception of a scientific theory falls under the Semantic View, and de Regt that theories are something else than (collections of) principles. The GE-account does not face this issue at all. If scientists in a certain episode understand a phenomenon through or with the help of a theory, which the scientists themselves view as a theory, then this theory will play an important role

34 Ibid. p. 11.

35 For more information about the different views on scientific theories, see Winther, R. G., "The Structure of Scientific Theories", *The Stanford Encyclopedia of Philosophy* (Spring 2021 Edition), Edward N. Zalta (ed.), URL = https://plato.stanford.edu/archives/spr2021/entries/structure-scientific-theories/ (last accessed April 14th, 2022).

in the understanding. However, if scientists in another episode do not refer to or mention a theory at all, then theories will at least not play the most important role for understanding, even if some theory might have influenced the understanding in an indirect way. Again, since the Practice Turn in the philosophy of science, it has been criticized that philosophers of science have put too much emphasis on the concept of theory in the past. Instead of insisting on a central function of theories for scientific understanding and identifying a theory in any episode at any cost, scientists' own views about theory, explanation, and understanding should be taken into account. Whether understanding is approved as scientific should not depend on any theory on which the understanding may be based, but rather on the method by which it is achieved. A method that is governed by the rules and standards implemented in the respective historical and disciplinary context.[36]

I would like to point to a second issue of de Regt's account of scientific understanding. As already mentioned, he distinguishes between UT (understanding a theory) and UP (understanding a phenomenon). Although de Regt claims that he is concerned with UP, he says comparatively little about it. His account rather focusses on UT, "the (pragmatic) understanding of the theory that is used in the explanation"[37], the procedures through which physicists in various historical episodes use theories to construct explanations. In contrast to this demanding and challenging process, UP, characterized as having an adequate explanation of the phenomenon, does not seem to be very impressive. What's more, this characterization of UP causes irritation. De Regt emphasizes again and again that knowing an explanation is not sufficient for or identical to understanding. The question then arises what he means when he says that a scientist *has* UP if she *has* an adequate explanation of the phenomenon. Does 'having an adequate explanation of the phenomenon' not mean that one possesses, or knows, an adequate explanation of the phenomenon? If this is the case, de Regt would contradict his own claims. Granted, this contradiction would only affect UP, not UT. De Regt could defend his account by arguing that UT is an epistemic skill, which he shows convincingly. Still, this would imply that UP is not an epistemic skill. One kind of understanding, UT, is a skill, but another kind, UP, is not? If UT is conceptualized as a skill and UP is not, they are completely different things. Why are both concepts then labelled understanding?

I do not think this interpretation captures de Regt's opinion on understanding. I think he takes UT and UP to be epistemic skills, the former serving the latter. For de Regt, understanding a theory means that scientists have the skills to use the theory to construct explanations. UT is the means to achieve UP, which he takes to be the aim and product of scientific explanations. A scientific explanation provides a

36 How theories might contribute to scientific understanding is discussed, among others, in de Regt (2017) or Baumberger & Brun (2017).

37 De Regt (2017), p. 24.

systematic line of reasoning through which a phenomenon is connected to accepted empirical and theoretical knowledge. When this connection is established, scientists can apply, refine and extend their knowledge further.[38]

> This is the sense in which the explanation provides understanding of the phenomenon. This can be illustrated […] with the example of the kinetic theory of gases. Elementary phenomenological gas laws can be explained on the basis of the kinetic theory by constructing the ideal-gas model […]. The intelligibility of the kinetic theory is a precondition for constructing the model-based explanation of the phenomenological law. But in what sense does this explanation provide understanding? The answer is: by connecting our empirical knowledge of gaseous behavior with accepted theoretical knowledge (in this case, e.g., with Newtonian mechanics) the explanation allows us to make inferences about the behavior of gases in novel situations, and to extend, apply, and refine our knowledge. […] The crucial point is that the skills that are required for constructing and evaluating an explanation are the same as those required for using and extending it. And, as I have argued, it is precisely the possible use and extension of an explanation that embodies the understanding that comes with it. In other words, understanding of the theories on which the explanation is based (UT) corresponds in a fundamental way with the understanding generated by the explanations (UP).[39]

Although de Regt's idea that UP is embodied in the possible use and extension of an explanation is very similar to, and probably compatible with, my idea of articulating new explanations, he does not elaborate this idea very clearly. In the three case studies that de Regt presents, he is primarily concerned with UT, the ability of scientists to use theories. He examines first the intelligibility of Newton's theory of universal gravitation in the seventeenth century, second the use of mechanical models in nineteenth century physics to explain, for example, the specific heat anomaly through the kinetic theory of gases, and third the debate about the intelligibility of matrix mechanics and wave mechanics in early twentieth century quantum mechanics. Since de Regt's account of scientific understanding essentially relies on the thesis that explanatory understanding of phenomena requires intelligible theories, he analyzes in detail the context-sensitive, de Regt says context-dependent, nature of the intelligibility of theories, and which skills and conceptual tools scientists need so that a theory is intelligible to them in different scientific episodes. I do not disagree on any of the points that de Regt presents, but I want to highlight that his analysis is extremely focused on the construction and evaluation of explanation (UT), and not so much on using and extending explanation (UP). In the case studies, de Regt argues at length which theory was intelligible or not to which scientists and who was able to use a

38 See ibid. pp. 44ff.

39 Ibid. p. 46.

theory to construct an explanation of a phenomenon based on the theory in question. His analysis sometimes reads as if UT is a process or procedural ability, while UP is a result, a state, that is reached or not. Other times, de Regt writes that UP is "relating the phenomenon to accepted items of knowledge"[40], but does this framing not overlap with UT as the ability to construct explanations? In short, while de Regt's analyses of how physicists in different historical episodes gained explanatory understanding of phenomena on the basis of intelligible theories are very illuminating, it is not ultimately clear what UT and UP consist in, respectively, and how exactly they relate to each other. The GE-account offers an alternative, and possibly complementary, perspective on scientific understanding of phenomena. By taking the understanding of the available body of knowledge (including theories) for granted, the GE-account concentrates on the understanding of phenomena. This avoids possible irritation as to when UT or UP are the topic of analysis. By focusing on one single concept of scientific understanding defined as one ability, manifesting in the iterative process of grasping relations of the phenomenon and articulating them in form of explanations, it provides a starting point to rethink the notions of UT and UP, and their relation.

In sum, de Regt's account and the GE-account of scientific understanding agree in many respects. However, de Regt's account might face problems when it is used to accommodate episodes from scientific practice in which theories are either not present at all or do not play a central role in the manifestation of understanding in comparison to other pieces of knowledge or information. Additionally, the acceptance of de Regt's account of scientific understanding stands and falls with the conception of scientific theories one accepts. The GE- account avoids these problems completely, since I neither adopt a specific conception of scientific theories, nor do I argue that understanding of phenomena always requires theories. Furthermore, since de Regt differentiates between UT and UP and elaborates a lot on UT, but not so much on UP, it does not become clear in his analysis what exactly UP is, what it consists in, and what it adds to UT. This is a central and pressing issue, since UP is the ultimate aim that scientists want to achieve, as de Regt states himself. As the GE-account only covers understanding of phenomena, it can be seen as complementary to de Regt's theory.

6.2.2 Neither grasping nor understanding simply amount to knowledge

Kareem Khalifa has developed a different model of scientific understanding. As in the previous section, I first provide a summary of Khalifa's account of understand-

40 Ibid. p. 91.

ing, before I address its deficiencies.[41] A more detailed presentation of Khalifa's account can be found in section 2.2.

Khalifa calls his account EKS model of understanding (explanation, knowledge, science model), because these three concepts are crucial for his account of better understanding:

> (EKS_1) S_1 understands why *p* better than S_2 if and only if:
> (A) *Ceteris paribus*, S_1 grasps *p*'s explanatory nexus more completely than S_2; or
> (B) *Ceteris paribus*, S_1's grasp of *p*'s explanatory nexus bears greater resemblance to scientific knowledge than S_2's.[42]

Additionally, the model includes a third principle, EKS_2, which accounts for minimal understanding. EKS_2 answers the question under which conditions someone has any understanding of a phenomenon, which is not equal to understanding achieved through scientific research.

> (EKS_2) *S* has minimal understanding of why *p* if and only if, for some *q*, *S* believes that *q explains why p*, and *q explains why p* is approximately true.[43]

Significantly, Khalifa follows the "received view" of understanding, as he calls it, which states that understanding is a kind of knowledge of explanation. "*S* understands why *p* if and only if there exists some *q* such that *S* knows that *q explains why p*."[44] Therefore, his model, as de Regt's account, is only concerned with explanatory understanding, the understanding-why something is the case.

The first principle labelled (A) in EKS_1 is called Nexus Principle. Khalifa starts with the idea that the subject's understanding of a phenomenon increases if she knows more correct explanatory factors that contribute to the phenomenon and if she knows more of the relations that exist between these factors. On this basis, Khalifa defines the explanatory nexus of a phenomenon *p* as "the set of correct explanations of *p* as well as the relations between those explanations."[45] If the explanatory nexus of *p* only includes correct explanations, then what counts as a correct explanation? Khalifa presents these four conditions:

41 For a further critique of Khalifa's account, see De Regt, Henk W. and Höhl, Anna E. (2020), Review of Khalifa, K., *Understanding, Explanation and Scientific Knowledge*, BJPS Review of Books, https://www.thebsps.org/reviewofbooks/kareem-khalifa-understanding-explanation-and-scientific-knowledge-reviewed-by-de-regt-hohl/ (last accessed April 14th, 2022).

42 Khalifa (2017b), p. 14.

43 Ibid. p. 14.

44 Ibid. p. 18.

45 Ibid. p. 6.

q (correctly) explains why *p* if and only if:
(1) p is (approximately) true
(2) q makes a difference to *p*
(3) q satisfies your ontological commitments (so long as they are reasonable); and
(4) q satisfies the appropriate local constraints.[46]

The fourth condition is important. Like de Regt, Khalifa explicitly allows for an explanatory pluralism. He does not give a strict definition of explanation. In fact, he even allows to identify 'explanation' with 'explanatory information'.[47] With local constraints he refers to the specific interest of the researcher, the established standards of the discipline, and so on. Local constraints are context-dependent. Like de Regt, Khalifa wants to formulate an account of understanding that is universally valid, but allows for contextual variation. Khalifa reaches this goal by formulating three global conditions and one local condition for explanation.

The second principle contained in EKS_1 is the Scientific Knowledge Principle. This principle captures everything Khalifa takes to be necessary for a characterization of grasping. He defines grasping as "a cognitive state bearing some resemblance to scientific knowledge of some part of the explanatory nexus."[48] But what counts as scientific knowledge? Knowledge is scientific if it has been gained through *scientific explanatory evaluation*, SEEing, in short. According to Khalifa, SEEing consists of three components: the consideration of plausible potential explanations of the phenomenon of interest, the comparison of the potential explanations, and finally of the formation of (doxastic) attitudes based on the comparisons. SEEing ensures the safety of one's explanatory commitments and therefore the status of this kind of knowledge as scientific.[49]

I agree with Khalifa's model of understanding in so far as I also think that some knowledge about a certain phenomenon is necessary to understand that phenomenon (how could you ever understand any phenomenon without knowing anything about it, not even that it exists?), that explanations are necessary for scientific understanding and that an explanatory pluralism should be adopted in order to accommodate historical and disciplinary variations in science. Khalifa, de Regt, and I have a common ground in this regard. However, I disagree with Khalifa in his claim that understanding is knowledge of an explanation. The fundamental problem I see in Khalifa's account of understanding is his deflationist conception of grasping. In his view, "talk of grasping can always be replaced by a more specific

46 Ibid. p. 7.
47 See ibid. p. 6.
48 Ibid. p. 11.
49 See ibid. pp. 12f.

epistemic status (e.g., approximately true beliefs, non-scientific knowledge, scientific knowledge). In other words we can always swap out the placeholder – the buzzword "grasping" – with something more pedestrian and informative."[50] The term 'grasping', according to Khalifa, has no meaning. It does not denote anything in the world. But, why should grasping merely be a placeholder or a buzzword for other epistemic statuses? Khalifa cannot answer this question, because he does not give any argument or justification for his deflationist view. Admittedly, I do not have an ultimate proof that Khalifa's deflationist view is wrong. However, it should be noted that, to my knowledge, Khalifa is the only one in the philosophical debate on understanding who holds such a view with respect to grasping. As I explain in section 4.3.1, there is no universal agreement in the debate on understanding about what grasping amounts to. The two main options on the market are either to view grasping as a process of getting epistemic access, to recognize or becoming aware of (aspects of) a phenomenon, which is the view that I endorse as well, or to spell out grasping in terms of other reasoning or inferential abilities. Both views are far more demanding and definitely do not take grasping to be only a placeholder for believe or knowledge states. Having these positions concerning grasping in mind, the burden of proof lies on Khalifa's side. As long as neither he nor anyone else provides convincing arguments or evidence for the deflationist conception of grasping as being merely a placeholder, there is little or no reason to accept it.

A second issue that I have with Khalifa's model of understanding relates to his deflationist conception of grasping. As he takes grasping to be only a placeholder term that denotes other states of believe or knowledge and that does not relate to any capacity or ability, he also denies that understanding requires any "special abilities" that are not required for explanatory knowledge. However, Khalifa does acknowledge the role and importance of skills for achieving scientific knowledge through SEEing.

> Note that each aspect of SEEing involves significant cognitive abilities. For instance, consideration involves highly structured creativity (when generating alternative explanations). Comparison involves insight into different explanatory relationships (e.g. causal structures, dependency relationships, inferential connections within and between explanations), the ability to draw out predictive consequences of each explanation, and various kinds of methodological prowess, such as the ability to design experiments and interpret results. Formation deploys inferential abilities.[51]

50 Ibid. p. 14.

51 Ibid. p. 63. See also ibid. chapter three for more details of Khalifa's view that understanding does not require special abilities.

Khalifa views the product of the process of SEEing to be scientific explanatory knowledge, alias understanding, whereas I take the process of SEEing, the process and activity of creating scientific explanatory knowledge, to be the manifestation of the disposition to understand a phenomenon. The disagreement between Khalifa and me already starts with his definition of minimal understanding.

> (EKS_2) *S* has minimal understanding of why *p* if and only if, for some *q*, *S* believes that *q explains why p*, and *q explains why p* is approximately true.

I disagree that (minimal) understanding is a form of belief. I may believe that the global mean surface temperature on Earth increases because of a higher concentration of greenhouse gases in the atmosphere, but having this belief does not enable me to understand in any sense how or why the rising concentration of greenhouse gases in the atmosphere lead to an increase the global mean surface temperature. Believing this explanation does not entail any abilities to recognize how the global mean surface temperature and the greenhouse gas concentration in the atmosphere are related or how changes in the earth-atmosphere-system may influence the phenomenon of rising mean surface temperatures. Basically, a person may have a lot of knowledge or many beliefs about various aspects of global climate change, but she may never be able to grasp, to recognize or to comprehend, how these various pieces of knowledge relate to each other and how they relate to actual phenomena in the world. A belief or knowledge about a phenomenon is a necessary prerequisite for understanding the phenomenon, and some explanatory knowledge is the product of understanding, but understanding itself is not identical to a belief or knowledge.

As I argue in chapter four, the concepts of propositional knowledge (knowing-that) and understanding (knowing-how) can be easily confused because they both advance only in conjunction with one another. Having understanding denotes the ability to make sense of a certain phenomenon or a specific observation by referring to, using, manipulating and coordinating the newly gained insights or information concerning the phenomenon or observation with already available (background) knowledge through various possible cognitive or material skills. A scientist understands a phenomenon if she is able to align new insights about a phenomenon (new observations or new data obtained in an experiment or study) with the available background knowledge. In the course of this process, the scientist who understands the phenomenon will articulate and provide a new explanation of the respective phenomenon that will be integrated in the existing body of knowledge if parts of the wider scientific community accepts the new explanations as valid. New knowledge of an explanation of a phenomenon is a result of understanding this phenomenon, but it is not identical to understanding. This complex ability exceeds any notion of belief or knowledge by far.

Furthermore, notice that Khalifa may face a different problem here. He argues that understanding is knowledge of an explanation. However, according to his definition of minimal understanding, understanding is having a belief about an explanation. A belief is not identical to knowledge, it is even less in terms of epistemic demands. As I see it, Khalifa has two options. Either he has to say that understanding is believing an explanation, and the understanding improves in terms of better justification of that belief or by approximating truth in some way, or he has to modify his definition of minimal understanding as having a minimally justified belief about an explanation. Otherwise Khalifa identifies knowledge with belief, and I cannot imagine him seriously advocating this claim.

Summing up, Khalifa and I also agree in many respects. Both of us acknowledge the crucial role of demanding abilities in the process of scientific research of a phenomenon and the articulation of scientific explanation in the course of this process. However, we fundamentally disagree in our conceptions of understanding. Whereas *Khalifa views understanding as the product of a research process*, the articulated scientific knowledge of an explanation, *I take the whole process* of grasping relations and articulating an explanation of the phenomenon, for which scientists have to generate and test hypotheses, construct models, using various research methods and evidence, *to be the manifestation of understanding*. My argumentation in this book that understanding is an ability and not a kind of knowledge may not convince Khalifa or any other proponent of the 'understanding is a kind of knowledge'-camp due to incompatible intuitions regarding understanding. Nevertheless, I am convinced that an ability-account of understanding is better suited to do justice to the demanding epistemic activity of gaining understanding, in a scientific as well as non-scientific context.

6.2.3 Why grasping is not enough for understanding

Lastly, I would like to compare the GE-account with the account from Finnur Dellsén. His account differs significantly from the accounts from de Regt and Khalifa, since Dellsén argues for understanding without explanation, for an account of objectual understanding. Again, let me quickly repeat the most important characteristics of Dellsén's account of objectual understanding before I compare it to the GE-account of understanding.

As the previously mentioned two scholars, Dellsén is interested in the understanding of phenomena and assumes that typical cases of this sort of understanding can be found in the sciences. Hence, his account is intended to capture scientific understanding. Moreover, Dellsén is also convinced that understanding is gradual in a way knowledge is not. In his view, scientists have to grasp a model of a phenomenon's dependence relations if they want to understand the phenomenon. Dellsén takes models to consist of two components, namely some kind of information structure and an interpretation, which relates elements of the information structure to elements of the phenomenon. In a nutshell, "understanding consists of grasping a certain kind of model of the understood phenomenon"[52], according to Dellsén. More precisely, scientists must grasp a model that represents the dependence relations that the phenomenon stands in towards other things. That is, scientists must grasp a dependency model. As models are always incomplete representations of their targets, as they are not copies, the quality of a dependency model can vary along two different dimensions, according to Dellsén, which are accuracy (tied to idealization or the misrepresentation of some features) and comprehensiveness (tied to abstraction or the omission of some features). Since both criteria, accuracy and comprehensiveness, are gradable notions, the degree of understanding will depend on the degrees of the accuracy as well as the comprehensiveness and the trade-off between the two regarding any dependency model that is grasped.[53]

In short, Dellsén proposes the following dependency modelling account (DMA) of understanding:

> DMA: *S* understands a phenomenon, *P*, if and only if *S* grasps a sufficiently accurate and comprehensive dependency model of *P* (or its contextually relevant parts); *S*'s degree of understanding of *P* is proportional to the accuracy and comprehensiveness of that dependency model of *P* (or its contextually relevant parts).[54]

DMA does not require explanation, although Dellsén takes dependence relations to usually undergird explanations. He contrasts his DMA with explanatory accounts of understanding, which he summarizes in the following way:

> *U→E*: *S* understands *P* only if *S* grasps enough of an adequate explanation of *P* (or its relevant features); other things being equal, *S* has more understanding of *P* to the extent that *S* grasps more of an adequate explanation of *P* (or its relevant features).[55]

U→E is intended to capture any account of explanatory understanding that takes explanation as a necessary requirement for understanding. Dellsén then discusses three cases in which, according to him, *U→E* fails to accommodate the understanding that scientists achieve, whereas DMA can cope with such types of cases. Before I turn to these cases, I would like to address *U→E* and its relation to the GE-account of understanding.

52 Dellsén (2020), p. 1265.

53 See ibid. pp. 1266ff.

54 Ibid. p. 1268.

55 Ibid. p. 1269.

I do claim in the GE-account that explanation is a necessary requirement for understanding a phenomenon. However, I do not claim that *grasping an explanation* of a phenomenon is a necessary requirement for understanding it. Scientists grasp relations of the phenomenon and articulate what they have grasped in form of an explanation. Therefore, the GE-account is, strictly speaking, not included in *U→E* and may not be affected by Dellsén's criticism of explanatory accounts of understanding. Unfortunately, Dellsén does not clarify what exactly he takes explanations to be, whether he holds an ontic or epistemic conception of explanation. Yet, since he differentiates between explanations and dependence relations that undergird explanation, it seems more plausible to attribute an epistemic conception of explanation to Dellsén. If this is correct, it becomes questionable, though, whether *U→E* does capture most or all accounts of explanatory understanding, as Dellsén wants it to be. Consider two explanatory accounts that he explicitly mentions and takes to be comprised by *U→E*, the accounts of Michael Strevens and Henk de Regt.[56] Both argue for explanatory accounts, but hold completely different conceptions of explanation. Strevens advocates an ontic conception of explanation, de Regt an epistemic conception. Granted, since de Regt characterizes understanding of phenomena as having an adequate explanation, it is comprehensible why Dellsén takes his account to be covered by *U→E* as well. Yet, as I argue in section 6.2.1, this formulation is very unfortunate and does not really capture what de Regt takes scientific understanding to be. Independently of any interpretation of de Regt's account of understanding, the point I want to make here is whether *U→E* succeeds in capturing all explanatory accounts of understanding. Taken for granted that some accounts employ an ontic conception of explanation and others an epistemic conception, what exactly is it that subjects grasp according to these accounts? Do they grasp explanations, because, according to the ontic conception, explanations are out there in the world, or do they grasp (dependence) relations, and then, as maintained by the epistemic conception, articulate or construct explanations of these relations? These are two very different activities, as long as the conception of 'grasping' is not broadened in a way that it also captures the activities of articulating or constructing explanations. Christoph Baumberger, for example, presents such a wider conceptualization of grasping that I address in section 4.3.1.

The upshot of the discussion of *U→E* in the previous paragraph is that it should be made clear what is meant by the term 'explanation' and that, depending on that meaning, any definition or characterization of (explanatory) understanding may fundamentally change. Therefore, it is questionable whether *U→E* does capture most

56 De Regt's account of understanding is discussed at length in sections 2.1 and 6.2.1. For more information on Strevens' account, with which I do not engage in more detail, see Strevens (2013).

or all explanatory accounts of understanding, including the GE-account of understanding. However, as Dellsén compares *U→E* with DMA in terms of three cases, turning to them may shed more light on how *U→E* and DMA might differ in Dellsén's view. On the next pages, I argue that the GE-account can better accommodate the examples that Dellsén presents than his very own DMA.

6.2.3.1 Understanding the values of dimensionless physical constants

The first type of cases concerns 'explanatory bruteness', as Dellsén calls it. 'Explanatorily brute' facts "are phenomena that have no explanation at all – phenomena that are not merely unexplained, but unexplainable."[57] Everyday coincidences or fundamental physical truths, like the values of dimensionless physical constants, are instances of explanatorily brute facts. The fine structure constant or Sommerfeld's constant α=1/137, which describes the strength of electromagnetic interaction between elementary charged particles, is a dimensionless physical constant. These constants cannot be explained by any current physical theory, they can only be measured. Assuming that there are indeed no explanations for the values of dimensionless physical constants, Dellsén argues that DMA can easily accommodate such cases of explanatorily brute facts, "since a dependency model that depicts such a phenomenon or its features as not dependent on anything else would be more accurate than an otherwise identical model that represents them as dependent on something else, and more comprehensive than an otherwise identical model that abstracts away from the issue."[58] Accordingly, a scientific community that discovers and accepts that these values are explanatorily brute is better off than a scientific community that is still wondering whether the values can be explained, according to Dellsén.[59]

Dellsén's claim that DMA is superior to explanatory accounts of understanding, since it can accommodate cases of explanatory bruteness, is not convincing, because, as Dellsén himself admits, "it is very much an unsettled empirical question whether a given fact is explanatorily brute."[60] That is, there is no *a priori* reason to assume that facts which we cannot explain, yet, like the values of dimensionless physical constants, are explanatorily brute. Just because we cannot explain a

57 Ibid. p. 1271.

58 Ibid. p. 1275.

59 See ibid. pp. 1274f. Dellsén also discusses at length Kvanvig's example of the moving electron, as a special type of explanatorily brute facts, and Khalifa's criticism of Kvanvig's interpretation of the case, see ibid. pp. 1271–1274. I do not have the space to go into Dellsén's discussion of this specific case. However, since I argue against his general claim that understanding of explanatorily brute facts is possible, it is not necessary to go into this specific case, too. For a detailed discussion of Kvanvig's example and Khalifa's response, see section 3.3 in this book.

60 Ibid. p. 1274.

phenomenon, yet, does not automatically amount to the conclusion that this phenomenon is not explainable. I am not denying that explanatorily brute facts may exist in the universe, but I claim that we can never know for sure whether any as yet unexplained fact is explanatorily brute. Taking the incredible amount of scientific discoveries of phenomena into account, it is reasonable to assume that future science will be able to explain phenomena that cannot be explained, yet. And it is not possible to know in advance which phenomena we will be able to explain in the future. Dellsén's claim that a scientific community that takes values of dimensionless physical constants to be explanatorily brute has a better understanding as a scientific community who does not is correct just in case these values are indeed explanatorily brute. If this is not the case, it will be the other way around and the first scientific community will never understand these values.

Furthermore, why should we want an account of understanding that covers instances of explanatory brute facts in the first place? Why should this be an advantage? What is so bad about admitting that we can never understand explanatorily brute facts, while we can understand multiple phenomena that are related to these facts? As Khalifa states, "certain information helps to provide (explanatory) understanding of something else, even if it is not itself understood."[61] It is not necessary, and probably also not possible, to understand every dependency model, body of knowledge, or even every single dependence relation within our grasp. Dellsén admits this as well, as in his view "context plausibly determines which parts of a complex phenomenon need to be understood to a significant degree in order for it to be felicitous to say that the phenomenon itself is understood."[62] And even if we consider a context in which some hitherto unexplained fact, like the value of a dimensionless physical constant, needs to be understood for whatever reason, it is possible to make a normative claim of why physicist should strive to find an explanation of this value. Given that there is no proof of the existence of explanatorily brute facts generally, nor of the explanatory brute nature of any one specific fact, scientists should strive for finding an explanation of the respective fact. Maybe no explanation will be found, maybe it will be proven that this fact is explanatorily brute, but the (re)search for an explanation will very likely lead to new discoveries that cannot be imagined, yet. The strive for understanding, but also explanation, of phenomena is the engine of scientific progress. Accepting an unexplained fact as explanatorily brute without having a reason or explanation for this decision may prevent this progress and undermine the very nature of science. In fact, physicists are trying for decades to find explanations for the values of dimensionless constants. In case of the fine structure constant, Arthur Eddington and Wolfgang Pauli were among those who tried to ex-

61 Khalifa (2013), p. 1166.

62 Dellsén (2020), p. 1268.

plain and understand its value.[63] A famous quote that is very often stated in this context comes from Richard Feynman, who wrote in 1985 "immediately you would like to know where this number for a coupling [the value of the fine structure constant] comes from: is it related to pi or perhaps to the base of natural logarithms? Nobody knows. It's one of the greatest damn mysteries of physics: a *magic number* that comes to us with no understanding by man."[64]

This quick excursion into debates in physics clearly shows that even if DMA captures some kind of understanding of hitherto unexplained, or possible unexplainable facts, this will not be a type scientific understanding with which scientists are satisfied or that they aspire. Quite the contrary, the attempts of and struggle for physicists to find explanations for the values of dimensionless constants, even though they were not successful, yet, demonstrate that a type of understanding characterized by DMA should be overcome and replaced by explanatory understanding. The GE-account of understanding comprises the need for explanation that one recognizes if scientific practice is taken into account. Therefore, the GE-account of scientific understanding is better in accommodating scientific practice than DMA. Consequently, scientists do not (scientifically) understand unexplained or unexplainable facts, and there is absolutely no problem in admitting that scientists do not understand everything. If this were the case, no research would be conducted anymore.

6.2.3.2 What does Bohr's model explain?

A second type of cases in which understanding is achieved without explanation is called 'explanatory targetedness' by Dellsén. "In these cases, we come to understand through grasping an explanation, but the explanation helps us understand the explanans rather than the explanandum. Thus, in these cases, the target of one's understanding differs from the target of one's explanation in a way that separates understanding of *P* from grasping an explanation of *P*."[65] The concrete example dis-

63 For more information concerning research and controversies on the fine structure constant, see for example Whittaker, E. (1945), "Eddington's Theory of the Constants of Nature." *The Mathematical Gazette*, 29 (286), pp. 137–144, DOI: 10.2307/3609461; or Kragh, H. (2003), "Magic Number: A Partial History of the Fine-Structure Constant." *Archive for History of Exact Sciences*, 57 (5), pp. 395–431, DOI: 10.1007/s00407-002-0065-7; or Várlaki, P., Nádai, L., Bokor, J. (2008). "Number archetypes and 'background' control theory concerning the fine structure constant". *Acta Polytechnica Hungarica*, 5 (2), pp. 71–104. For a relatively recent suggestion of an anthropic explanation for the value of the fine structure constant, see Barrow, J. D. (2001), "Cosmology, Life, and the Anthropic Principle". *Annals of the New York Academy of Sciences*, 950 (1), pp. 139–153, DOI: 10.1111/j.1749-6632.2001.tb02133.x.

64 Feynman, R. P. (2006 [1985]), *QED: The Strange Theory of Light and Matter*. Princeton, Princeton University Press, p. 129, original emphasis.

65 Dellsén (2020), p. 1275.

cussed by Dellsén is the transition from Rutherford's planetary model of the atom to Bohr's quasi-quantum model. While both models depict the atom as having a positively charged nucleus that is orbited by negatively charged electrons, the Rutherford model does not designate which locations or energy levels could be occupied by electrons. In contrast, Bohr's model does specify the electron orbits with certain fixed radii that correspond to particular energy levels. Although both models are not accurate representations of the atom and deficient in comparison to the contemporary fully quantum mechanical model, it is agreed that Bohr's model is more accurate than the Rutherford model. Hence, Dellsén takes it as intuitive to say that Bohr's model increased understanding of the atom in comparison to the earlier Rutherford model.[66]

One advantage of Bohr's model in comparison to Rutherford's model is its capacity to provide information through which the Rydberg formula for spectral lines of several elements can be explained. Since electrons can only occupy specific radii (energy levels), when they 'jump' between orbitals they gain or lose energy exclusively in fixed discrete quantities that represent the differences between two radii. This information explains why atoms emit radiation with certain fixed wavelengths described by Rydberg's formula. The Rutherford model could not be used to explain the wavelengths of spectral lines, because it does not entail fixed electron radii and cannot account for the observation of discrete wavelength. This example, according to Dellsén, might suggest that explanatory accounts of understanding can capture the increase of understanding achieved by the transition from Rutherford's to Bohr's model.[67] "But this tempting line of thought is mistaken. To see why, note that the spectral patterns described by Rydberg's formula are not a feature of any atom, but a feature of the radiation that is omitted from such atoms. So the phenomenon that is being explained in the above explanation—the explanandum—is not a feature of the atoms as described by Bohr's model at all."[68]

The explanation Dellsén is concerned with here is the following: the radiation from atoms has certain fixed wavelengths described by the Rydberg formula, because electrons within atoms can only occupy specific energy levels. The information from Bohr's model figures into the explanans, but not in the explanandum. While the model enabled explanation of the atom's spectral pattern, it did not enable understanding of the atom itself, since it merely stipulated features like the fixed electron radii. Therefore, Bohr's model did not increase explanatory understanding of the atom in comparison to Rutherford's model, so Dellsén argues. Unsurprisingly, he claims that DMA can better accommodate this case.[69]

66 See ibid. pp. 1275f.
67 See ibid. p. 1276.
68 Ibid. p. 1276.
69 See ibid. pp. 1276f.

> The transition from Rutherford's model to Bohr's provides a more comprehensive model of the dependence relations in which the atom stands towards spectral lines. In this way, DMA validates the judgement that Bohr's model really did increase our understanding of the atom, despite the fact that the model did not provide an explanation of any of the atom's features.[70]

It is true that Bohr wanted to understand the nature and structure of atoms, that his model accurately explains the wavelength of spectral lines emitted by atoms, and that Rutherford's model could not explain this phenomenon. However, Dellsén does not mention another important aspect of this scientific episode. Bohr did not develop his model of the atom because he primarily wanted to explain the wavelength of spectral lines, although this achievement may be viewed as the greatest success of the model, but because Rutherford's model faced other severe problems. Since Rutherford still adhered to the laws of classical mechanics, electrons in his model constantly lose energy in form of electromagnetic radiation (light) while they are orbiting the nucleus. This hypothesis has two problematic consequences. First, as the electrons are constantly losing energy, atoms should emit a continuous stream of electromagnetic radiation as they are spiraling inwards towards the nucleus. Dellsén already described the observation that atoms do not emit a continuous spectrum, but instead light of specific discrete frequencies. Second, and this is presumably the more devastating consequence of Rutherford's model, since electrons are constantly losing energy and spiral towards the nucleus, they will ultimately collapse into the nucleus. This means that no atom is stable! Obviously, this cannot be true, since stable matter exists in various forms. In the publication in which Bohr presents his model for the first time, he wrote in the introduction that in the "attempt to explain some of the properties of matter on the basis of [Rutherford's] atom-model we meet, however, with difficulties of a serious nature arising from the apparent instability of the system of electrons. […] Whatever the alteration in the laws of motion of the electrons may be, it seems necessary to introduce in the laws in question a quantity foreign to the classical electrodynamics, i.e., Planck's constant".[71] Though Bohr mentions the explanation of the hydrogen spectrum through his model as well at the end of the introduction to this paper, this does not seem to be his motivation or driving question for developing his model. That is, the actual explanatory target of Bohr's model is the stability of atoms, and not the emission of spectral lines described by the Rydberg formula, as Dellsén argues.

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70 Ibid. p. 1277.

71 Bohr, N. (1913). "On the Constitution of Atoms and Molecules, Part I". *Philosophical Magazine*, 26 (151), pp. 1–24, pp. 1f. For more details concerning the development of Bohr's model and the historical context, see Robertson, D. S. (1996), "Niels Bohr – Through Hydrogen Towards the Nature of Matter." In Lakhtakia, A. (ed.), *Models and Modelers of Hydrogen*, pp. 49–82, Singapore, World Scientific Publishing.

So, Bohr proposed his model primarily to avoid and solve problems that earlier models of the atom were facing. He had reasons to make the postulations that he did and to introduce a first quantum mechanical interpretation of the atom, since his model presented a stable atom and was in accordance with the early quantum theory of his time. His model can explain spectral lines as well as the stability of atoms. According to Bohr's model, atoms are stable because electrons emit radiation only when they 'jump' between stationary orbits, but not while revolving in one stationary orbit around the nucleus. In his discussion of Rutherford's and Bohr's model, Dellsén is ignoring this fact. Taking the explanation of the stability of atoms provided by Bohr's model into account demonstrates how the transition from Rutherford's model to Bohr's model increased understanding of the atom. Rutherford's model could not explain the stability of atoms, but Bohr's model did. Sure, Bohr's model was not without issues, either. While the atomic structure suggested by the model explained the stability of atoms, the structure and features that Bohr postulated could not be as straightforwardly explained. Yet, these stipulations could at least be justified by referring to other phenomena like the photoelectric effect and early quantum theory that are in accordance with the model, which is exactly what Bohr himself did. Again, as I argued in the case of explanatory brute facts as well, understanding and explaining a phenomenon does not entail the understanding and explanation of all the information that is involved in the understanding and explanation of the phenomenon.

Even if my claim that the stability of the atom was the more important aspect for Bohr than the discrete wavelengths of spectral lines emitted by atoms is wrong, one could still question whether the atom and the emission of spectral lines at certain wavelengths are as distinct phenomena as Dellsén suggests. If scientists want to understand a phenomenon (the atom in this case), they will want to understand every feature of this phenomenon. Since the emission of spectral lines of certain wavelengths is a feature of atoms, to understand the atom in its entirety, the emission of spectral lines must be understood as well. Likely, physicists would not claim that they fully understand the atom if they have no clue why or how atoms emit spectral lines at the wavelength at which they do. Understanding comes in degrees, Dellsén and I agree on this. Therefore, gaining understanding of a phenomenon usually takes time, as its manifestation process is iterative. Grasping and explaining some relations will enable grasping and explaining further relations. Even if one argues that physicists did not explain (or understand) the atom through Bohr's model, yet, but merely the emission of spectral lines, it would be strange to claim that they understood a completely different or unrelated phenomenon. They understood a feature, the emission of spectral line, of the phenomenon, the atom, they ultimately wanted to understand. Bohr's model did not provide an ultimate explanation of the atom, but it enabled new research routes for physicists and pathed the way for the development of the valence shell model which is used today. Understanding the emission of spectral lines can be taken as one step in the process of understanding the target phenomenon, the atom.

6.2.3.3 Galileo's thought experiment, again

The third and last type of cases, which his supposed to be covered by DMA but not by *U→E*, is labelled 'explanatory disconnectedness' by Dellsén. He illustrates this type with Galileo's thought experiment introduced into the debate on understanding by Peter Lipton. I discuss this example and Lipton's view in general in section 3.2. As a memory aid, Dellsén presents this example in the following way.

> The reductio is a thought experiment in which we suppose that a lighter object is fastened to a heavier object. If lighter objects accelerate slower, then the lighter object should slow down the heavier object, so the two objects should accelerate slower than the heavier object would by itself. However, the two objects can also be considered together as one larger object, which is thus heavier than either of the objects that it is composed of, so this composite object should accelerate faster than the heavier object. But since the two objects cannot both accelerate faster and slower than the heavier object would by itself, the idea that heavier objects accelerate faster than lighter objects cannot be correct.[72]

Dellsén agrees with Lipton that the thought experiment provides understanding, but his analysis differs significantly. According to Lipton, the thought experiment, while not providing an explanation, displays a necessity. It shows that gravitational acceleration must be independent of mass.

> However, [Dellsén] fail[s] to see how the necessity of the fact that gravitational acceleration is independent of mass is responsible for our understanding in this case. In [his] view, Galileo's reductio instead shows that understanding can be increased by grasping that two factors are independent, whether by necessity or as a contingent matter. In other words, Galileo's reduction provides understanding not by showing necessity, but by showing a certain kind of independence.[73]

That is, understanding increases when we become aware that two seemingly related factors are actually independent from one another. Dellsén's DMA can nicely capture these cases, since understanding can increase either through improving the accuracy or the comprehensiveness of the dependency model of the phenomenon. In the example of gravitational acceleration, Galileo's thought experiment increases

72 Dellsén (2020), p. 1278.

73 Ibid. p. 1279.

the comprehensiveness of the dependency model by showing that gravitational acceleration and mass are independent.[74]

> Of course, this increase in understanding is by itself rather modest according to DMA, since it does not tell us what factors gravitational acceleration does depend on, only that a particular contextually salient factor, namely, mass, is not one of these. Again, this appears to be a correct prediction, since the understanding of gravitational acceleration provided by Galileo's reductio is indeed rather incomplete.[75]

As in the two previous examples, I disagree that understanding of gravitational acceleration increases, changes or becomes possible at all without explanation. Dellsén argues for the Galileo example that grasping the independence of gravitational acceleration from the mass of falling bodies enables understanding of gravitational acceleration as independent of mass. This is correct, but not the whole story. The crucial question is what is required to realize that two factors are independent. Why should we accept the independence of two factors that so far seem to be dependent? We should accept the independence of two factors if we have reasons for doing so. The Galilean thought experiment did not only show that gravitational acceleration is independent of mass, but additionally provided an explanans, a reason, why this is the case, namely because it is logically impossible that gravitational acceleration is dependent on the mass. Arguing on the basis of the logical impossibility that gravitational acceleration is independent of mass is more than merely finding out that gravitational acceleration is independent of mass and not having any reason or explanans to make sense of that fact. This is the additional component that Dellsén is missing.

In general, why is Dellsén's DMA insufficient for an account of understanding? Because grasping dependence relations of a phenomenon is not sufficient for understanding. For Dellsén, understanding is "roughly the possession of a model of the understood phenomenon's dependence relations."[76] I am sympathetic to that view, since it is compatible with my requirement that relations of a phenomenon need to be grasped if the phenomenon should be understood. I am not claiming that DMA is fundamentally wrong. I am claiming that it is incomplete for understanding. The crucial point is that we need to provide reasons why we think that our dependency model increased in accuracy or comprehensiveness. If we cannot provide reasons for the improved accuracy or comprehensiveness of a dependency model, how could we know that it improved at all? And providing reasons why an aspect of a phenomenon

74 See ibid. p. 1279.

75 Ibid. pp. 1279f.

76 Ibid. p. 1280.

or its dependency model is taken to be like this or that is everything I require from my generic conception of explanation introduced in section 3.1.

The deficiency of Dellsén's account becomes clearer when we apply it to the case of the research on the zebrafish *oep*-mutant, which I present in chapter 5.1. One observation that the biologists wanted to understand was the significant similarity of the *oep*-mutant phenotype and the *cyc/sqt*-mutant phenotype. After observing the similarity, the biologists had the idea that Oep and Nodal, the proteins that are missing in one of the two mutant strains, respectively, may act in a common pathway. This hypothesis would explain why both mutant strains look similar, since in both cases one component of the pathway is missing and therefore, the pathway would not function properly in either of the two mutant strains. In a next step, the biologists tested this hypothesis by injecting mRNA's encoding Nodal in the *oep*-mutants, which should replace the function of Oep. The biologists wanted to test the possibility that their hypothesis is wrong and that Oep and Nodal do not act in a common pathway. Although the experiment confirmed the hypothesis that Oep is indeed essential for Nodal signaling, let us consider the counterfactual case, that the experiment would have shown that Nodal signaling takes place without Oep, that the presence and function of both proteins are or can be independent from each other. If this had been the result of the experiment, the scientists would have known of their independence and could have explained why the proteins are independent on the basis of their experiment and results, but they would not have understood the similarity of the phenotypes of the two mutant strains. They would have had no clue why the two mutants have a similar phenotype. Again, as in the two other cases before, if DMA designates any type of understanding in cases of explanatory disconnectedness, it will not be the type of understanding that scientists want to have. Therefore, Dellsén's account is at least insufficient for scientific understanding.

6.2.3.4 Understanding requires explanation

In sum, Dellsén's DMA and the GE-account of understanding agree in one crucial aspect, while disagreeing fundamentally on another. His DMA is compatible with the GE-account in so far as we both take grasping of (dependence) relations to be crucial for understanding. Although Dellsén speaks of grasping a *dependency model* of the phenomenon while I require grasping *relations* of the phenomenon, I do not think that this conceptual difference is as substantial as it may seem. Since Dellsén argues that models involved in understanding aim to capture the network of dependence relations that a phenomenon stands in, I do not see a disagreement with my claim that a scientist needs to grasp relations of the phenomenon without them being necessarily mediated by a model. In Dellsén's view, models are information structures of some kind that are interpreted so as to represent their targets. Whether models conceptualized in this way are necessary for understanding phenomena or whether it is possible to grasp relations of a phenomenon without such kinds of models or any other kind of mediator remains a question for further research. I am not denying that the GE-account may lack an important aspect here, since I do not analyze the function of models for understanding. Nonetheless, the crucial agreement of DMA and the GE-account is that (dependence) relations of phenomena need to be grasped by a subject.

The decisive disagreement between Dellsén's DMA and the GE-account concerns the role of explanation for understanding. While I take explanation to be necessary for understanding, as de Regt and Khalifa, Dellsén wants to show with his DMA that understanding does not require explanation. As I have shown in the discussion of the three examples provided by Dellsén, he fails to make a convincing point that (scientific) understanding is possible without explanation. In the case of explanatorily brute or not yet explained facts, I do not see in what sense scientists have understanding of these facts. Actually, the attempts of physicists to find explanations of the values of dimensionless physical constants rather suggests that physicists do not understand the values of these constants, yet. In the case of Bohr's model of the atom as an instance of failed explanatory targetedness, Dellsén ignores the successful use of the model to explain the stability of atoms, in addition to explaining the emission of spectral lines at certain wavelengths. For the third type of cases exemplified with Galileo's thought experiment, it is also not clear to me what exactly the understanding consists in. If I come to realize that two factors A and B are not related in the way I thought they are, I may realize that I misunderstood the relation of A and B. But without getting any explanation of why A and B are not related in this way or why they are not related at all, I do not replace my misunderstanding with understanding of the relation. Instead, I replace my misunderstanding of the relation of A and B with no understanding at all.

It is worth noting that Dellsén, although he is arguing for a type of objectual understanding, does take understanding and explanation to be very closely related. He explicitly admits that "explanatory accounts of understanding can seem plausible, perhaps even irresistible, because understanding does tend to bring increased capacities to explain. In that sense, explanation and understanding are indeed closely linked."[77]

> [Furthermore,] although [the DMA] account is not an explanatory account of understanding, it does preserve the kernel of truth in explanatory accounts in so far as a sufficiently accurate and comprehensive dependency model contains the sort of information about a phenomenon that is required to explain it and related phenomena, provided that they can be explained at all. This is so for the simple reason that the dependence relations that these models must correctly represent in or-

77 Ibid. p. 1277.

> der to provide understanding (for example, causal and grounding relations) are precisely the sort of relations that form the basis for correct explanations.[78]

Given these confessions, it is quite surprising that Dellsén writes a whole paper on understanding without explanation. I suspect the crux lies in the standard conception of explanatory accounts of understanding that Dellsén is using, according to which understanding stems from grasping, knowing, or having an explanation. That is, explanation comes first, understanding second. As I argue at length in section 6.1 and in chapter four, I do not consent to this view and turn the order around. The ability to understand comes first and with the help of available knowledge, equipment and further skills, a new explanation comes second through the manifestation of the ability to understand.

6.3 Understanding is an impressive cognitive achievement and a goal of science

What is scientific understanding and how is it achieved? I have presented and elaborated the GE-account of scientific understanding to answer these questions. According to the GE-account, a scientist has scientific understanding if and only if the scientist is able grasp relations a phenomenon stands in and to articulate these relations in form of new explanations of (aspects of) the phenomenon. Understanding is an ability that is manifested through the iterative processes of grasping some relations and articulating (hypothetical) explanations, and improved through grasping more (aspects of) relations and confirming or revising explanations. For grasping relations and articulating them in explanations, the scientist has to possess and use necessary equipment, relevant knowledge and research skills. Additionally, she has to be a member of a scientific community. The community is a decisive contextual factor for understanding, as it provides its members with the necessary resources, including knowledge, skills, and further equipment, that enable scientists to understand a phenomenon. Moreover, young scientists acquire and train the ability to scientifically understand phenomena in the first place through engaging with more experienced members of their community, through guidance by their professors and supervisors. Additionally, to ensure that the understanding gained by an individual scientist counts as scientific understanding and as objective, and not as some form of non-scientific or inappropriate understanding, parts of the scientific community need to assess and approve the understanding gained by individuals. By making the individual understanding publicly accessible, its objectivity increases and its status as scientific can be confirmed.

78 Ibid. pp. 1282f.

I have also compared the GE-account to other accounts of understanding to highlight its merits. Despite the agreements with de Regt's account, Khalifa's EKS model, and Dellsén's DMA, the GE-account does diverge from these views in various respects. In contrast to de Regt, theories do not take a center stage in the GE-account, which makes it possible for the GE-account to accommodate cases from scientific practice in which scientific theories are not (yet) available or do not play a decisive role in the manifestation of understanding. Furthermore, de Regt primarily analyzes understanding of theories, and not understanding of phenomena, although the later one is taken to be the main aim of science. I agree with the basic distinction and that it is necessary to first understand a theory if one wants to understand a phenomenon through that theory. However, my target of analysis is the understanding of phenomena as an ultimate aim of science. In that sense, the GE-account can be seen as an extension of or contemplation to de Regt's account. The disagreement with Khalifa is more fundamental, as he takes understanding to be kind of knowledge and a product of scientific research, while I view the iterative processes of grasping relations and articulating explanations to be the manifestation of understanding through which new knowledge, alias an explanation, is produced. These two basic intuitions may be incompatible and an agreement might never be reached. Still, I take an ability-account of understanding to be more suitable to capture what we want to see if we test one's understanding. In such cases, we do not merely want someone repeating or rephrasing known explanations. Rather, we expect that this person is capable of using and applying available knowledge in a novel way that cannot be prescribed beforehand. And concerning Dellsén's DMA, I disagree that grasping (dependence) relations of a phenomenon is sufficient for understanding that phenomenon. This is so because grasping, conceptualized as having a relation between one's mind and world, as having epistemic access to a worldly phenomenon, which is the conception that Dellsén and I adopt, is not enough for making sense of a phenomenon. Grasping a (dependence) relation is the first necessary step, but merely having access to features of a phenomenon is not identical to figuring out why a phenomenon has precisely these features or how exactly they are related to other features of the phenomenon. Without researching grasped relations further and articulating the acquired insights in form of explanations, scientists will not understand the features of the phenomenon they grasped, as they could not make sense of them. Hence, understanding phenomena scientifically is an ability, manifested in grasping relations and articulating explanations, that exceeds any account of propositional knowledge and that does not necessarily require theories.

Despite all the disputes and conflicting positions concerning the nature, conditions, and various characteristics of understanding, there is also a common ground shared by all scholars engaged with the topic, which should not be forgotten or ignored. Everyone agrees that understanding is an impressive cognitive achievement that comes in degrees and is impacted by the context in which it is achieved. Furthermore, understanding is a goal of every epistemic endeavor, especially but not exclusively for science. Everyone, scientists and non-scientists, strive for understanding something in some domain. Hence, keeping this common ground in mind will enable and empower future research and insights on understanding.