How to study virtual entities historically?

A proposal.

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Abstract

This paper will not present a case study of the historical development of a virtual entity. Rather, I will develop an outlook on virtual entities in the sciences and propose a corresponding method for studying them (historically). In essence, my presentation can be considered a synthesis of different observations from the history and philosophy of science and has its roots in my dissertational research on the development of the virtual particle. Starting with a reflection on the role of presentism for the study of concept formation and development processes, I will show, through the example of the virtual particle, how current debates and interpretations can inform our access to a historical reconstruction. Following these reflections, I will argue for a pragmatist account of concepts as tools for the scientific practitioners. According to the approach presented in my article, concepts perform their functions through representations, and I will lay special focus on verbal representations and their different functions within scientific reasoning. In conclusion, I will frame the outcome of my discussion in terms of a proposal that might, through further research, enrich our understanding of virtual entities in the sciences.

When engaging, either philosophically or historically, with virtuality in the sciences, the first thing to note is that we do not actually have to engage with the abstract notion of virtuality. Most often, we encounter something that carries the epithet virtual, i.e. the notion of a "virtual X." Even one of the most prominent accounts of the term "virtual" by Charles Sanders Peirce, which regularly made its way

into the discussion at the workshop, defines the term in respect to the entity it is connected with:[1]

> "A virtual X (where X is a common noun) is something, not an X, which has the efficiency (virtus) of an X. This is the proper meaning of the word." (Peirce 1902, p. 763)

Whether or not we want to follow Peirce in his definition through efficiency, we certainly have to acknowledge that the notion of a "virtual X" includes, on the one hand, the notion of an X and, on the other, some departure from it.[2]

Since one is often familiar with the "X," attention is immediately drawn to the still puzzling, to me at least, term of the "virtual." What makes the "virtual X" a "virtual" "X"? What are its defining features and in which respects does it depart from "X"? Why did the actors name part of their conceptual framework with this term? What were the resources they drew from: Were they aware of any philosophical connotations or did they invoke an everyday meaning of "virtually," something along the lines "not quite, but close enough"? How did actors who took the notion up interpret the term and why would they still use it?

At the moment, my dissertational research on the historical development of the virtual particle concept is slowly coming to a close. But when I started my investigation some years ago, I posed exactly the questions mentioned above. I tried to reconstruct the connotations the actors had in mind when using the term "virtual"

[1] See also Friedrich Steinle's contribution to this Special Issue.

[2] Alexander Blum mentioned a similar observation in the final discussion, namely that one often invokes negations when giving a definition of a "virtual X."

and tried to make it cohere with notions of virtuality I knew of. In essence, I tried to give meaning to the term “virtual” through characteristics and definition.

Although I deem such an approach still worthy of pursuit and included it in my research, the fact that virtuality comes in the sciences mostly as a concrete instantiation and in connection with a specific concept makes an overarching definition seem spurious. Even when abstracting from the case at hand, for the virtual particle such physical attributes as energy non-conservation or unobservability, to more general definitions, such as Peirce’s, or other connotations like hypothetical, provisional, or “not really, but close enough,” things would not really match up when constructing a historical trajectory for the notion I was interested in. Or at least they did not match up as long as I tried to conceive of the “virtual Xs” I encountered by defining them through necessary and sufficient conditions.

In the course of my research, I slowly shifted focus. Instead of looking at the characteristic features of the “virtual Xs,” instead of trying to understand the notion of the virtual in an overarching definition, I turned towards the function the virtual entities had within their respective theoretical and conceptual frameworks. The shift in perspective is a shift from the question “what did the historical actors have in mind when calling an entity virtual?” to “what did the actors use the virtual entity for? What function did the virtual entity perform for the historical actor?”

Actually, I consider these questions complementary rather than mutually exclusive. Certainly, the characteristics of the virtual entities are important for performing their function. But with the second question in mind, emphasis is put on the concept’s role in the reasoning process, inviting closer investigation.

In the following, my main concern will not be the historical development of the virtual particle concept[3] or of any other virtual entity used in scientific reasoning. Rather, I want to discuss the challenges arising in the historical analysis of concept formation and development and explain how we can approach them with a pragmatist account of concepts. Thereby, I will develop a framework for the historical analysis of concepts, which, in essence, constitutes a synthesis of different observations taken from the history and philosophy of science; the outcome might even be conceived of as a proposal for how to understand the category of a "concept" in a historical investigation in general terms. Yet, as indicated, my own shift in the understanding of concepts originated in my research on a particular virtual entity, the virtual particle, and it helped me to construct a coherent historical trajectory for this concept in my nearly finished PhD thesis. Throughout this paper I will indicate how and why such an approach might be helpful for our comprehension also of other concepts that carried the epithet "virtual."

First, I will turn to the starting point of an investigation of conceptual development, namely to the question guiding the research, i.e., "how did the notion of a '(virtual) X' emerge?", to the person who poses the question, namely the historian of science, and the role of presentism for conceptual studies. Following these more general reflections, I will sketch the pragmatically informed conception of concepts which I used in my historical reconstruction of the virtual particle concept. Shifting the attention as laid out above and following the HPS literature on concept formation and

[3] The interested reader is referred to (Ehberger 2020; 2022) and the contributions to this Special Issue by J.P. Martinez as well as A. Blum and M. Jähnert.

development, I will conceive of concepts as tools that perform specific functions for the historical actors and are accessible to a historical investigation through their public representations. I will indicate how concepts and their representations can be connected to inferential techniques and discern between different kinds of (verbal) representations in terms of their use by historical actors. Finally, I will synthesize the essence of this discussion into a proposal of how to perform a historical analysis of concepts and point out why I deem it particularly fruitful in the historical study of concepts that carry the epithet "virtual".

1. Presentism and Iterations

I think that there is little doubt about the fact that reference to the present is unavoidable when engaging with the history of science[4] and that we should not confound presentism with Whiggism or anachronism. Being aware and making explicit one's own views on (the history and philosophy of) science, is often practiced and part of most historical endeavours. Here, I want to advocate for such an approach.

Certainly, the inclusion of a presentist perspective requires some care, and we definitely should avoid the pitfalls of Whiggism and anachronism.[5] But the idea that the past (and our reconstruction of it) is structured by the present (state of science) has to be acknowledged. As, for example, Hans-Jörg Rheinberger put it, the historian

[4] For very convincing arguments about the necessity of presentism and its possible fruitfulness in the history of science, see for example (Alvargonzález 2013) or (Loison 2016) and the references therein.

[5] For a definition of Whiggism, anachronism and positivism as misuses of in principle acceptable forms of presentism, see (Loison 2016, Section 3).

who is interested in the epistemic process has to take a "position of reflected anachronicity,"[6] and we have to acknowledge that, since at least our conception of the past is (partly) structured by the present (and vice versa), history has to be rewritten from time to time in the "iterative business of the historian."[7]

A presentist perspective and the explication of the historian's own stances towards the history and philosophy of science becomes particularly relevant in studies of concept formation and development processes. To fill this statement with meaning, I want to draw the reader's attention to the short, but very insightful quote by philosopher of science Vasso Kindi:

> "How we understand concepts affects the way we study them historically." (Kindi 2012, p. 37)

In the initial question guiding the historical research, namely "How did the concept X emerge?", the notion of a concept occurs twice: once in the concrete form of "X" and once in the category "concept" itself. Similarly, we can understand the "understanding of concepts" mentioned in the quote in two different ways.

On the one hand, we need to be clear about how we think of the investigated concept X within the practice of science.[8] Although the historian's job is to unravel the

[6] "Position einer reflektieren Annachronizität," (Rheinberger 2002, p. 202).

[7] "iterativen Geschäft des Historikers," (Rheinberger 2002, p. 194). I do not consider it a coincidence that the work of some of the historian-philosophers Rheinberger builds his insights on was concerned with the history of concepts (Canguilhem) and a representational format (the written word and the connected notion of a trace of Derrida).

[8] I consider this stance particularly important for a notion that is still used in the respective field, as for example the virtual particle. But also for concepts which are no longer part of scientific practice there is some end point of the formation and development process, set by the historian. Most

understanding and use of the studied notion by the historical actors as well as its trajectory, having an own understanding is inescapable. Instead of sweeping such personal conceptions under the rug, making them explicit helps the audience of the historian to understand his or her choices. In addition, we might actually use them as the understanding of the notion, its features and applications can give indications on the relevant lines of the concept's historical development as well as on a suitable understanding of the category of a "concept."

This understanding, on the other hand, of the category "concept" itself has high relevance for the story to be told. This is the sense which Vasso Kindi (Kindi 2012, pp. 37-42) intended. For example, if an author understood concepts as elastic things, formed through their use by historical actors, he or she will most probably arrive at a different historical reconstruction than an author who is convinced that a concept needs some hard core, some sort of stable meaning throughout its development. Although the two authors might use the same historical resources, the emphasis put, in the example on either change or continuity, will always be implicit in the work growing out of the historical investigation.

Although the above two paragraphs may suggest a one-way street from the modern day understanding of the author to the historical reconstruction, it is important to note that this is far too simplistic. My own work on the notion of the virtual particle rather suggests to me a strong interrelation between the historian's (in this case my) understanding of

- the modern version of the concept under study,

probably the historian has an understanding of the concept in the respective conceptual framework at this moment. If not, I propose to reflect on it.

- historical versions or what we construct as concepts connected to its historical development,
- the historical development with all its intricacies and
- the category "concept" itself.

As already described, I am convinced that our modern understanding of the concept under study and the category of a concept we initially have in mind will unavoidably inform our historical analysis. But also the historical versions of the concept under study, their genesis, their place in scientific discussions and practices unravelled in our historical investigation will reflect on our modern day understanding of the (category of a) concept. I consider it necessary for a historian to pay great attention to finding some kind of balance between these aspects of the history to be written. In essence, this balance is constructed iteratively by the author in revisiting and questioning all of these aspects in the course of his or her investigation.[9]

When I will present the following, this iteration should be kept in mind: What I propose in the end had neither been my starting point in doing my historical work nor was it a simple outcome of a purported "objective" historical investigation. What I came up with, is a way to study concepts that proved to be suitable for a coherent reconstruction of the development of the virtual particle concept by (iterative) construction. During my historical research that led me to the conception of concepts spelled out in the following, I tried to avoid any kind of dogmatic stance towards the modern notion or towards the understanding of the category of a concept. Rather, I

[9] Here, I have something in mind like the relation between history and philosophy as it was proposed by Hasok Chang (Chang 2012, especially Section 8.4). When put to work several times and by the same person, this can be conceived of as coming close to the iteration process mentioned above.

tried to keep my own stances flexible while keeping in mind that my historical reconstruction is informed thereby.

2. Using current debates in historical reconstructions: the example of the virtual particle

At first, I considered it a hindrance for a historical study that the notion of the virtual particle is still in use and actually discussed in the philosophy of physics. Yet, I realized that I can make use of this literature to create a conception of concepts that might be applicable for the given case study. I want to briefly exemplify how such a perspective can inform the historical reconstruction.

First of all, and quite basically, the virtual particle is, in our days, a concept of theoretical physics, and it is closely connected to a calculational technique: It is a theoretical or, more adequately, a physical-mathematical concept. Furthermore, the virtual particle is an unobservable entity, not merely a hidden one: What we can observe are, by definition, real particles and not virtual ones. A possible future detection of virtual particles, as it is included in the notion of a hidden entity, is ruled out from the start. In addition, virtual particles are never conceived of in isolation but are always embedded in larger complexes (as for example in Feynman diagrams). Connecting these lines of thought, the virtual particle is often considered not to be a fundamental concept of quantum field theory but one of practice.[10]

[10] Just to give one example of such reasoning, consider the following quote by Josef Jauch: "The pragmatic tendency of modern research has often obscured the difference between *knowing the usage of a language* and *understanding the meaning of its concepts*. There are many students everywhere who passed their examinations in quantum mechanics with top grades without really

Even though the philosophical literature is divided between realistic and non-realistic readings of the virtual particle (with a strong tendency towards the latter), there is essentially a consensus that the virtual particle is useful; it has a tool-like character. In his defence of a model-like interpretation of Feynman diagrams, Adrian Wüthrich (Wüthrich 2012) showed how one can draw qualitative conclusion on cross-sections by reasoning with one of the features of virtual particles, namely their off-shellness. Mario Baccelar Valente (Valente 2011) titled his pragmatist response to non-realistic interpretations of the virtual particle by the question: "Are Virtual Quanta Nothing but Formal Tools?" Philosophers who denied the virtual particle any kind of reality or even representational function still hold that virtual particles are "pure instruments" that "give an intuition of mathematical rules" (Fox 2008, p. 36, p. 48) or "formal tools in the calculation of the interactions of quantum fields" (Falkenburg 2007, p. 237). The recognition of the fruitfulness and the application of the virtual particle concept is to some degree independent of an ontological commitment.[11] In this manner, the centrality of the virtual particle in the everyday

understanding what it all means. Often it is even worse than that. Instead of learning quantum mechanics in a parrot-like fashion, they may learn in this fashion only particular approximation technique (such as perturbation theory, Feynman diagrams or dispersion relations), which then lead them to believe that these useful techniques are identical with the conceptual basis of the theory." (Jauch 1968), as cited in (Brown 2018, p. 440).

[11] To be clear, this does not mean that the explanatory power ascribed to or the realm of effects assumed to be explained by the concept is independent of any ontological commitment. For example, a philosopher or physicist might be convinced that only existing entities should be involved in physical explanations, and that the virtual particle does not exist. Nevertheless, he might use the notion in

work of a large part of the quantum field theorists' community as well its utility therein is mostly unquestioned.[12]

Consequently, the virtual particle is (1) a *physical-mathematical concept* and is (2) often *not considered fundamental* but rather showing up in *particular practices* and only *within larger theoretical structures*. Although the stances towards the reality of the virtual particle diverge, the ontological commitment mostly does not interfere with (3) the recognition of the virtual particle's *tool character* and its *fruitful application*.

From this perspective, an approach to concept formation processes that highlights the use of the concept in scientific reasoning of historical actors seems best-fitting. Therefore, in deriving an understanding of concepts and their development, I turned to historical studies on concept formation which are connected to the *practice turn*.

3. Studying concepts after the practice turn

3.1 Concepts as tools

constructing the terms of the perturbative expansion to be calculated and thereby fruitfully apply the notion (this is what the quotes by Fox in the above paragraph allude to).

[12] For full disclosure, there are philosophers who argued that the non-realistic interpretation of virtual particles should entail an exclusion of the notion from physical theory (Bunge 1970; Shrader-Frechette 1977; Arthur 2012). But such stances are rather rare and seem not to have made a big impact on teaching and reasoning in physics.

A focus on the practices of scientists, on how science is and was actually performed, was advocated by historians and philosophers of science[13] even before the advent of what is today called the *practice turn*. But since the early 1980s, this particular way of looking at the history, sociology and philosophy of science has gathered force. Although initially the focus was placed most prominently on experimental practices, in more recent years both theoretical practices and historical studies on concept formation and development have attracted more attention by researchers who highlight the various aspects of the production of knowledge and its social characteristics.[14]

When we try to conceive of concepts as embodied in the practices of a historical community, we have to conceive of them as fundamental actors' categories. In studying concepts and their development, they and the actors who use them have to be embedded in the proper historical and epistemological situation. I emphasize

[13] Notable examples would be Ludwik Fleck (1896-1961), Gaston Bachelard (1884-1962), Stephen Toulmin (1922-2009), or Georges Canguilhem (1904-1995). The practical side of Thomas Kuhn's (1922-1996) theoretical framework has also been expounded by focusing on the idea of a paradigm as an exemplar.

[14] For sketches of the historical development of the practice turn and an attempt at arriving at its defining features, see e.g., (Soler et al. 2014); for a short introduction of possible modes of conceptual analysis, see e.g., (Feest and Steinle 2012); for an introduction to the historical development of studies on concept formation in the history of science, see (Borrelli 2017, Section 1.2). The proposed conception of concepts has a strong overlap with but is not equivalent to Borrelli's views and has profited largely from her work. A very accessible account of how a scientific concept can be understood was recently given by (Arabatzis 2019). The following sections will draw heavily from these accounts.

this point here as concepts have the peculiar feature that, once they are established and accepted, "they disappear as possible objects of revision, and tend to appear as unproblematic or even 'natural'." (Steinle 2002, p. 423)

The pitfalls of anachronism must be kept in mind when we enter the historical development through our modern-day lenses. Specifically so, since not only are the actors embedded in a historically situated epistemic constellation, the concepts they use are also always connected to the then current and developing conceptual framework. As Ian Hacking expressed it: "a concept is no more than a word or words in their sites in which it is used." (Hacking 2004, p. 35; see also Kindi 2012) A concept gathers meaning (only) through its connection to other concepts. And this connection is established in the practice of science. Every time a concept is used, it is used within a specific explanation, derivation, classification, etc. A concept, or a modification of it, has to fit into, extend or even limit the conceptual and methodological framework in a way so that the scientific community is able to acknowledge its fruitfulness[15] for current and future research, for the goals the historical actors had in mind.[16]

The above points and the turn to practice within conceptual studies go hand in hand with a specific conception of concepts, namely as tools for scientific research.[17]

[15] As was regularly stressed by Friedrich Steinle (see e.g., Steinle 2009, pp. 309-310; or Steinle 2012, pp. 106-107) concepts are neither explanatory as such nor do they have a truth-value on their own. Yet, they can (and must) be usefully and appropriately applied in explanations.

[16] Especially Ingo Brigandt (2010, 2012) and Friedrich Steinle (2009, 2012) have highlighted the role of the goals of the historical actors and communities for a coherent historical reconstruction.

[17] For explicit denotations of concepts as tools see e.g., (Feest 2010; Steinle 2010; or MacLeod 2012).

The analogy, like any other, certainly has its limits,[18] yet it carries with it the important insight that concepts are used deliberately by scientists for a specific purpose. Similar to tools we know from everyday experience, concepts may be appropriate or not in a specific situation, for particular research questions. Within their conceptual and methodological environment, they have functions: They perform work for the scientists e.g., in creating new accounts of otherwise not, or hardly, solvable or even expressible problems. At the least, they facilitate the tasks a historical actor is faced with.[19]

But concepts are not only used as tools. Their formation and their usage structure the way we think of the world as well as the way problems are perceived and may be approached. Concepts, nearly by definition, govern what is conceivable, both in terms of questions to be asked and answers to be given. As, for example, Friedrich Steinle put it:

> "Once formulated and stabilized, they [concepts, classifications and laws] shape all subsequent research at a fundamental level. [...] The formation, establishment, and stabilization of concepts and conceptual schemes establish the framework within which the direction of future research may range." (Steinle 2016, p. 319)

[18] For a discussion of the analogy with specific focus on experimental research in psychology, see (Feest 2010, Section IV).

[19] The list of what a concept might do for a researcher is long and I refrain from a delineation of specific epistemic functions since it may unnecessarily narrow down the role of concepts within research practices. For a possible list of in total seven different functions of concepts, see (Arabatzis 2019, p. 86).

Concepts have an active role in the research process, they have "agency" but also "recalcitrance." (See Arabatzis 2006, Chapter 2) They can be manipulated, but not at will. They propose new research questions and are formed thereby.

3.2 Concepts and their (public) representations

All the above observations could be argued for on the basis of a conception of concepts as "elements of thought" or "mental representations", although necessarily shaped by the historical situation. But as such, they would be inaccessible to a historical reconstruction. Hence, the question arises: How to gain access to concepts in a historical study? To some extent, I suppressed this question so far. For instance, Theodore Arabatzis did not locate the agency of the electron in the entity itself or some disembodied "element of thought" but he explicitly located it in the *representations* of the electron.[20]

The notion of representations, the investigation of their functions and their connection to scientific practice have been primary themes of the practical and the social turn in the history and philosophy of science right from its beginning. For example, in Ian Hacking's *Representing and Intervening the* distinctive feature of humans was framed as their capability and their need for creating representations.[21] In most general terms, within this line of research representations, whatever form

[20] The complicated interrelations between the electron as (theoretical) entity, its concept, and its representation have been discussed in (Borrelli 2017, Section 1.3). I want to point out that I do not consider Arabatzis' use of biographical terms suitable for a historical reconstruction of concept formation processes. See my critique in (Ehberger 2020).

[21] "Not *homo faber*, I say, but *homo depictor*. People make representations." (Hacking 1983, p. 132).

they might take, are no longer conceived of as epistemologically innocent depictions of the world. Rather, they are studied under the premise that they take an active role in the research process:

> "The move is from representations as descriptions of the world to representations as means for doing things, tools for intervening, and material artifacts for transforming the world." (Soler et al. 2014, p. 23)

Recent notable examples of historical studies that focus on the practice of theory and what we might call modes of representations are Ursula Klein's framing of Berzelian formulas in the research in organic chemistry roughly from 1820 to 1840 as "paper tools" (Klein 2001), David Kaiser's study on the dispersion of Feynman diagrams as "calculational techniques" (Kaiser 2005) and Adrian Wüthrich's investigation of the genesis of Feynman diagrams (Wüthrich 2010).[22] Although conceptual issues are at stake in each of these studies, the unit of analysis is not a single concept but a mode of representation, its genesis, the action it allows for, its modifications, and its active role when embedded in different cultures of theory.

The inclusion of the notion of representation in the historical study of theoretical or physical-mathematical concepts has most notably been argued for by Theodore Arabatzis, Arianna Borrelli and Emily Grosholz. In the first place, there is a simple methodological motivation behind this. Instead of engaging with "hidden psychological entities" (Arabatzis 2019, p. 86), the historical study of concepts should be assessed through the concepts' (public) representations, may they be verbal,

[22] For a comprehensive account of representations in science studies, the interested reader is referred to (Borrelli 2017, Sections 1.4-1.6).

mathematical (within the realm of mathematics there are again diverse possibilities of representation), diagrammatic, or otherwise:

> "Like experimental practices, physical-mathematical concepts, too, are accessible to historical and philosophical analysis only insofar as they are expressed and communicated in specific ways in situated contexts, and as such possess a material and performative component which can only be neglected at the risk of analysing not science as it is practiced, but its idealized, disembodied reconstruction." (Borrelli 2017, p. 6)

Grosholz (Grosholz 2007) and Borrelli are specifically concerned with seemingly abstract representations of concepts such as the mathematical formalism. Both, coming from different perspectives and using different historical case studies, argue convincingly for the hands-on, performative dimension of the mathematical apparatus and its representations. Drawing on Ursula Klein's work on Berzelian formulas, they argue that the mathematical formalism should be considered one amongst many representational formats and that it functions as a "paper tool."

Specifically for virtual entities, we should be aware that the abstract formalism and diagrammatical techniques are not the only forms of representations, but verbal expositions and the terminology used to refer to a concept function as representations as well. Terminology can carry a lot of information about the actors' understanding of the concept, about its role in the conceptual framework and even about the involved practices. Arianna Borrelli noted "the extreme, at times obsessive, care taken by mathematicians to develop and employ a very exact terminology" (Borrelli 2017, p. 55). Mauricio Suárez similarly stated that "emblems and names are not merely denoting arbitrary signs but also play a connotative function and can exhibit the

objectivity of cognitive representations." (Suárez 2004, 772, Footnote 6)[23] In this sense, we can conceive of the naming of a concept by historical actors as an active and careful abstraction process.

Although the stabilization of a notion often comes with an appropriately chosen name, this is not necessarily the case. The stable reference point for the identification of a concept by historical actors might as well be another representational format, while the terminology used is still in flux (if any exist at all). Terminology, like any other representational format, is a historical object. It changes over the course of time.

For the historical analysis of a "virtual X", an investigation of the different terminological variants and their relation to practice and the conceptual framework is advisable, especially since we encounter a composite structure ("virtual" and "X"). Other terms than "virtual" might have been used to refer to the notion and the "X" might interchange during the historical development while other representations remain stable. When analysing such terminological variants, one often provides a snapshot of the meaning in a given instance by providing definitions through characteristics. Although this is at odds with a purely pragmatic account, as indicated above, I believe that such an analysis can complement this mode of historical investigation.

At this point, one might actually worry that the above described conception of concepts would result in a historical study not of the concepts in question but of

[23] Suárez uses the word "objective" as equivalent to informative regarding the target of the representation.

different representational formats as the concept is not defined by other means.[24] But we know that over the course of the development, the different representations acquired a stable meaning for the historical actors and were understood to refer to one and the same object (Borrelli 2017, pp. 54-55). Retrospectively, we know that such an identification will take place as it formed the original motivation for the historical investigation.

3.3 Concepts, their role in the reasoning process and their embedding in the conceptual framework

Besides the dissolution of the object under study, namely the concept, another worry might have occurred to the reader who is interested in treating the history of a "virtual" entity: How can we speak about representations in a sensible manner when the concept we are interested in might not have a real referent[25] and how can we account for its use in inferential techniques? Luckily, the philosophy of science provides us with diverse possibilities. A first step towards the solution of this problem is to distinguish between denotation and representation, as was proposed by Letitia

[24] Borrelli actually uses this concern and the conception of a concept as a "network of representations" for taking into account the "productive ambiguity" (Borrelli 2017, p. 53) of concepts in scientific practices. When it comes to the usefulness and productivity of concepts, I digress from Borrelli at this point and tend to locate them not in the "ambiguity" of the abstract concept but in the concrete features of the specific and often sharply defined representations and the thinking possibilities they allow for.

[25] At least, this is one of the connotations the term "virtual" can have. For the notion of the virtual particle in particular, the philosophical literature points towards the non-existence of these entities.

Meynell (Meynell 2008), following Kendall Walton's theory of representation, in her discussion of the representational features of Feynman diagrams. This is certainly necessary, but on its own it does not enable us to connect the representation of possibly non-existent entities to epistemic practices.

We might associate the investigation of virtual entities in the sciences with the line of philosophical research that (re-)evaluates the deliberate use of fictions in what scientists themselves consider to be explanations.[26] Alisa Bokulich's notion of "explanatory fictions" rests on this idea (Bokulich 2009; 2012). Letitia Meynell's recent account of the epistemic success of Feynman diagrams (Meynell 2018) heads, through the work of Catherine Elgin, in a similar direction by distinguishing between the non-factive category of understanding and the factive category of knowledge. But virtual entities are not necessarily fictitious, although they might be. I personally favour approaches, such as the deflationary or inferential account of scientific representation by Mauricio Suárez (Suárez 2004; 2015), which remain agnostic about the reality of the represented system by construction and invoke the capacity "of competent and informed agents to draw specific inferences" (Suárez 2004, p. 773) as a prime characteristic of a scientific representation.

Whatever stance one might favour, at this point, we must be careful not to confound the two different notions of "representation" that have been used so far. The first one denotes the representational features of a scientific model in reference to a real-world system. The second one, which underlies the discussion in Section 3.2,

[26] The introduction to (Suárez 2009) can form a good start for the interested reader. This research constitutes a re-evaluation as its historical backdrop is the philosophy of the "as if" [Die Philosophie des Als Ob] of Hans Vaihinger (Vaihinger 1911).

denotes the concrete and manifest representations, be they verbal diagrammatical, mathematical, tabularic or else, in reference to a scientific model. This distinction is not only important in order to avoid the possible confusion arising due to the doubling of the term "representation," but it is important in order to historically and philosophically study the scientific techniques which are used in inferential accounts to connect the model and the real-world system.

Historians encounter models, just like concepts, always in a concrete form, written down or represented in a specific format. Following the authors referenced in Section 3.2 and Marion Vorms (e.g., Vorms 2012), this is not only the sole material we can base our reconstruction on. The concrete instantiations are also the things scientists reason with, which they manipulate, put into different contexts, or, to use a term by David Kaiser, improvise with to draw conclusions. Within these larger representational structures, we encounter the representations of the concepts we try to write the history of. And thereby, not only is the already invoked connection of concepts to the surrounding conceptual framework made concrete by the connection of their representations, but their tool character becomes manifest as well by the reasoning processes and the manipulations they allow for through and in the concrete representation.

In actual scientific practice many different representational formats of particular models are used side-by-side. Mathematical, diagrammatical, tabular or verbal representations structure, facilitate or, as an often overlooked possibility, restrict the inferential possibilities of the practitioners. But all of these representations are thought of by the actors to refer to one and the same model (and, often, real-world system). The different representations thereby mutually interact. This process

thus (trans-)forms not only the conception of the model but also of the concepts figuring in it.

The above points focused on the inferential techniques connected to a concept and the connection thereby established to its conceptual surrounding. But scientists do not only argue for a specific model on the grounds of empirical adequacy and fruitfulness in respect to the research process. Scientists also try to motivate specific models and concepts by embedding them into the conceptual framework, by connecting them to general principles of theory. They argue for the plausibility of the model in a given instance or in connection to the more general principles.

Although I know that the notion of a narrative has been further developed and applied,[27] also in the evaluation of the physical sciences,[28] I want to point the reader to one of the first occurrences of the notion of a narrative in the history and philosophy of physics given by Stephen Hartmann (Hartmann 1999). According to Hartmann, the story or narrative told around a model "is not a deductive consequence of the model nor of the underlying theory. It is, however, *inspired* by the underlying theory (if there is one). [It] takes advantage of the vocabulary of the theory [...] and refers to some of its features [...]. Using more general terms, the narrative fits the

[27] See, for example, the recently published special issue of *Studies in History and Philosophy of Science. Part A* on *Narrative in Science* (Morgan and Wise 2017).

[28] See, for example, (Stöltzner 2017; or Borrelli 2019). Although I would agree with Stöltzner and Borrelli in including other representational formats than verbal ones in the narrative, I use it differently than they do. Especially Borrelli shows how single concepts can be understood as accessible through narrative knowing. I myself do not structure a concept through this kind of reasoning. Rather, I want to highlight the concept's role within such an argumentative structure and the ways in which such arguments were used by historical actors.

model in a larger framework (a 'world picture') in a non-deductive way." (Hartmann 1999, p. 344)

Although a narrative as defined by Hartmann might have a calculational merit, I consider it advisable for historical and philosophical analysis to further differentiate in terms of the use the historical actors made of such storylines, mostly comprising verbal statements but also including mathematical, diagrammatical, or other formats. On the one hand, verbal representations of models are often used in derivations and serve in quantitative analysis of a specific model.[29] On the other hand, narratives, in my narrower definition, motivate a model or a concept. And they do so not by pointing to the inferential fruitfulness of the concepts or models, but through their explicit connection to the conceptual and theoretical framework, by showing how the concepts and models fit into and can be explained within in this larger conceptual surrounding.[30]

I deem such narratives especially important for the history of virtual entities. A "virtual X" shows some digression from the regular "X" and might not even be real or an "X". Due to the virtual character of the "X", the question of how its use might be argued for and how it can be connected to the broader conceptual and theoretical

[29] See my account of the genesis and initial reception of the verbal model of quantum electrodynamics and its use in the quantitative analysis of scattering process during the late 1920s and early 1930s, (Ehberger 2022).

[30] During the 1930s a narrative connecting virtual transitions and virtual particles with the basic principles of the interpretation of quantum mechanics emerged. Specifically in meson physics, the connection between virtual transitions, the time-energy uncertainty relation and the measurement process through counterfactual reasoning gathered prominence. See for example (Wick 1938; Heitler 1941).

framework, to the "world picture", as Hartmann has framed it, takes on specific relevance. If the X is not actual, the questions "why should we use it in and how can we connect it to our description of the world?" and "why and how can we still identify the 'virtual X' as an 'X'?"[31] becomes pressing. If the actors provided more arguments than mere fruitfulness and empirical adequacy (which I personally deem most important), then these argumentative structures (and possibly their negation) might help us in deciphering the notion of "virtuality" in the sciences.

4. Conclusion

Having laid done my discussion of a pragmatist conception of concepts, let me recap and frame the essence of it as a proposal of how to access the historical development of virtual entities. I argued for conceiving of concepts as tools embedded in historically situated constellations and practices, which in turn means that their application, fruitfulness, and epistemic power depends on the framework in which they are put to use. Concepts should further not be understood as some disembodied (and in fact inaccessible) ideas located in the brains of the historical actors, but as manifested through their manifold representations, the terminology being a particularly interesting one for the history of "virtual" entities. As an upshot of this conception, breaks and continuities in the conceptual development can be thought of simultaneously as they are manifested in the historical development of the diverse specific representations.

[31] I want to thank Friedrich Steinle for pointing out that the question used in the introduction of this article is as well put to the forefront.

We should understand the manipulations these representations allow for and their diverse possible combinations as the things with which scientists think and work. They are the things scientists use to draw conclusions on possible real-world systems. Since often more than one concept is actually represented in one representation, e.g. in the concrete representation of a model, the connection between the concept under study and its conceptual surrounding becomes manifest and accessible to a historical reconstruction. Shifts in the conceptual framework can thereby be traced and will possibly reflect back on the concept we are interested in. Yet, scientists not only use concepts for drawing quantitative conclusions, but they might motivate the concepts and models they use by connecting them to the principles of the respective theory or its interpretation. These motivational structures, which I called narratives, might become particularly fruitful in respect to the question what makes the "virtual X" a "virtual" "X" in comparison to the "regular X".

Although the above discussion was mostly concerned with making the abstract notion of a concept accessible to a historical reconstruction, the particular conception of concepts I propose brings to the fore two historical entities which were nearly absent in the discussion so far: the actor and the scientific community. To understand the introduction of any concept, or better a representation, we need to know the background of the practitioners quite well: we have to be aware of the resources they draw from, their epistemic (and possibly ontological) commitments, and their preferred scientific methods. The community of the practitioners regulates which questions are deemed worthy to ask and sets the standards against which a possible solution to a problem or the introduction of new concept have to be measured. The focus on representations further brings the community into the focal point: after all,

representations are not only a means of reasoning but also of communication. And whether or not the communication is successful also depends on the recipients of the message, i.e. the fellow scientists. Without a close investigation of the background of the community of practitioners we will not be able to answer our prime questions when studying virtual entities historically: “Why was the virtual entity, or better, a representation of it introduced in the first place?” and “why would the community accept this virtual entity in its conceptual framework?”

Whether or not the proposed conception of concepts, its environment, and its connection to scientific practice can be fruitfully applied to the historical development of other virtual entities is an empirical question. I can even imagine that the iterative procedure for constructing a suitable understanding for a given concept, which I described in section 1, might lead to a different outcome then in the case of the virtual particle. All I can say is, that the laid-out proposal allowed me to create a coherent reconstruction of the concept I was interested in my dissertational research. Focus on the stability and change in specific representational formats and conceptual frameworks as well as on the application and the function of the relevant (representations of the) concepts, allowed me to draw a trajectory from virtual oscillators over virtual transitions to virtual particles, although the meaning of the term “virtual” surely changed in the course of time. Whether these concepts were conceived of as obvious fictions or whether they were understood (nearly) realistically, they always had specific functionalities for the historical actors, for example as serving as *bridging elements* in calculational practices.

I certainly believe that there are many other functions virtual entities can perform. But shifting attention from the characteristics of virtual entities to their

functions and the way in which the representations of concepts are put to use might prove fruitful in any case. Looking at virtual entities through the lenses of practice and representations, we might find conceptual overlaps of different virtual entities in the sciences through the role they perform in the reasoning process. Whether these will cohere or we will end up with a plethora of functionalities is, again, an empirical question. Whatever we might come up with, it will certainly enhance our understanding of the class of virtual entities in science.

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