Picturing Feynman Diagrams and the Epistemology of Understanding

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In this paper, I take up the following puzzle: If Feynman diagrams represent states of affairs, but do not do so truthfully what can their epistemic value be? I argue that Feynman diagrams have been epistemically powerful (at least in part) because, as pictorial representations, they facilitate an understanding of quantum electrodynamics, and quantum field theories more generally. Drawing on Richard Feynman's own remarks and Catherine Z. Elgin's account of the role of understanding in science, I tease out what it might mean to have an understanding of something that is not factive. Although my approach allows for a thin sense of substantively non-factive epistemic success, it is continuous with a factive sense of understanding that is more familiar in the sciences.

1. Introduction

In "Why Feynman Diagrams Represent" (2008), I argued that Feynman diagrams (FDs) have two distinct functions: they are both calculational devices, developed to keep track of the long mathematical expressions of quantum electrodynamics (QED),[1] and they are pictorial representations.

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1. Of course, FDs have been developed to represent the strong and electroweak forces as well. Although I believe the following epistemological remarks likely apply to these images also, because the sources that I draw from are focussed on Feynman's development of the diagrams and the first decade or so of their subsequent use as well as Feynman's own remarks and general approach, I focus on QED.

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This challenges the common view that FDs are calculational devices alone and that it is misleading, if not an outright error, to think of them as pictorial (Brown 1996, pp. 265–7; von Baeyer 1999, p. 14). Following Kendall Walton's account of representation (1990), I drew out what it means to think of FDs as pictures (or depictions), which in turn explained why FDs represent. However, my defence conceded an important point: not all of the objects represented in FDs denote extant things and not all of the states of affairs represented are thought to happen as depicted. In other words, though they represent, FDs are not factive. This raises a puzzle about what their epistemic value might be.

In this paper, I argue that FDs have been epistemically powerful (at least in part) because, as pictorial representations, they facilitate an understanding of QED, and particle physics more generally. Drawing on Richard Feynman's own remarks and building from Walton's theory of representation, I tease out what it might mean to have an understanding of something that is not factive. Importantly, this depends on clearly distinguishing understanding from knowledge and describing the ways in which picturing is analogous to and supportive of understanding. Taken in this way, we can appreciate that accepting the literally and substantively false can, in some circumstances, be characterized as an epistemically successful strategy because it supports understanding. To help explain and motivate this approach, I consider another seemingly promising account of non-factive epistemic success, proposed by Catherine Z. Elgin in "True Enough" (2004). This approach, though valuable in itself, will be shown to be insufficiently permissive to account for the epistemic success of FDs, especially in their post-QED applications (Kaiser 2005, pp. 195 ff.). I conclude by showing that although my approach to understanding allows for a thin sense of substantively non-factive epistemic success, it is continuous with a factive sense of understanding that is more familiar in the sciences, and shows the extent to which FDs, especially the 1950s meson diagrams that Feynman inspired, are a special case.

2. Why Feynman Diagrams Represent

In "Why Feynman Diagrams Represent," I explained that objections to the idea that FDs are representations tend to assume that for an image to represent at all it must denote and thus it must, in an important sense, be getting things right. FDs include virtual objects that do not in any obvious sense exist, thus they cannot be thought to denote. In a similar vein, as Niels Bohr (as recounted by Schweber [1994]) and James R. Brown have argued, FDs show subatomic particles as having definite paths, but since the peculiarities of QED depend on particles not following definite paths, FDs cannot be denoting them (Schweber 1994, p. 444; Brown 1996, pp. 265–7; Meynell

2008, p. 52). I suggested that this line of argument relies on an equivocation on the term "representation." It confuses an idea of representation as standing for another object and thus depending on an object's existence (see Goodman 1968), with the idea of representation as picturing, which is equally amenable to representing actual or purely fictional objects.[2] This second meaning allows that FDs can in principle picture subatomic particles that do not exist and states of affairs that never do and perhaps (physically or even logically) never could come to pass.

It follows that any attempt to explain the epistemic role of FDs as pictorial representations will need to address the character of pictorial content, as truth and denotation cannot do the epistemic work. Just as Kendall Walton's *Mimesis as Make-Believe* (1990) crucially informed the original project it will again prove useful in the account of understanding proffered below. For Walton, representations function as props in games of make-believe (Walton 1990; Meynell 2008, p. 49 ff.). When we look at a pictorial representation we draw on a set of principles of generation (PGs) to determine their content. PGs include all of the cognitive procedures required to glean the content, such as conventions, habits of mind, background knowledge (perhaps tacit),[3] contextually stipulated rules, and basic perceptual or cognitive capacities. Drawing on these PGs to see the content in the picture, we imagine that we are looking at an event (Walton 1990; Meynell 2008). In fact, when we examine the picture to figure out what is depicted we examine it as if we were trying to figure out what is going on in a real state of affairs (Walton 1990, pp. 292 ff; Meynell 2008, pp. 50–1).

This may seem paradoxical when talking about pictures of events that didn't and perhaps couldn't happen, but there are familiar examples. When examining a picture of Santa Claus, we look to the set of his eyes and his mouth to see if he is happy. We may even be able to infer from this and additional clues whether any children depicted with him have been naughty or nice. That we examine pictures of events that didn't or couldn't happen as if we were looking at the events themselves is obvious when we are considering a picture of Santa Claus, but it's rather more contentious when

2. For brevity when I use the term "object" it should be read as "object or state of affairs." Unlike linguistic content, pictorial content cannot represent objects without also representing states of affairs. This is because depicted objects always are depicted in some scene or some orientation or with some shape or other, and thus one has not only an object depicted but some object in a situation or of a certain character creating a state of affairs (for a more exhaustive explanation see Meynell 2018, pp. 571–5; Meynell 2013, pp. 335–9).

3. Interestingly, David Kaiser in his comprehensive and authoritative volume, *Drawing Theories Apart*, emphasizes the importance of tacit knowledge in the dispersion of Feynman diagrams after their introduction in the late 1940s (Kaiser 2005; Meynell 2008, p. 44).

examining a FD. Nonetheless, there is ample evidence for FDs being depictions in this sense in Feynman's own original presentation of the diagrams, various remarks by commentators that identify them as intuitive or quasi-physical,[4] and the history of their uptake and use in the 1950s for projects for which, mathematically, they were ill-suited (Kaiser 2005; Meynell 2008, pp. 44–5).

Feynman's own original published FD in "Space-Time Approaches to [QED]" (Feynman 1949a, p. 772) is labeled not only with mathematical expressions, but also with nouns—"electrons," "virtual quantum," "time." Also, he clearly provides PGs—guides for how to imagine the states of affairs depicted—which would be pointless were we to suppose that FDs are nothing other than calculational devices. These PGs include figures from the sister paper, "The Theory of Positrons" (Feynman 1949b, p. 751; Meynell 2008, pp. 53–4), his reference to Stückleberg's method of picturing negative energy states (Feynman 1949b, p. 749), and the famous bombardier analogy[5] on how to see in a diagram both the path of charge (through electron-positron production and annihilation) and the development of events through time (1949b, p. 749; Meynell 2008, pp. 51–2). There are also the PGs supplied by other types of pictures in physics that have been remarked upon by commentators. These include the worldlines of Minkowski diagrams (Kaiser 2005, pp. 185–87, 364–6) and visual analogies between FDs and the tracks of subatomic particles in bubble chamber photographs (Harré 1988, p. 64; Kaiser 2005, pp. 372–3). It is the interplay of these familiar visual analogies with other types of representation and various other PGs that give rise to the so-called "intuitive" appeal (Kaiser 2005, pp. 369–70) and "quasi-physical" character (Mattuck 1976, p. 88) of Feynman diagrams.

To the extent that viewers employ the same PGs, they see the same things (Walton 1990, pp. 38–41). Thus, in their representational role FDs allow viewers to engage in coordinated imaginings of subatomic events.

4. Even those commentators who claim such physical interpretations are a mistake make my point as they show that reasonably competent viewers nonetheless treat them as depictions—i.e., as props for imagining subatomic events.

5. To quote the passage in full: "In the approximation of classical relativistic theory the creation of an electron pair (electron A, positron B) might be represented by the start of two world lines from the point of creation 1. The world lines of the positron will then continue until it annihilates another electron, C, at a world point 2. Between the times t1 and t2 there are then three world lines, before and after only one. However, the world lines of C, B, and A together form one continuous line albeit the "positron part" B of this continuous line is directed backwards in time. Following the charge rather than the particles corresponds to considering this continuous world line as a whole rather than breaking it up into its pieces. It is as though a bombardier flying low over a road suddenly sees three roads and it is only when two of them come together and disappear again that he realizes that he has simply passed over a long switchback in a single road" (Feynman 1949b, p. 749).

The PGs that generate these imaginings are generally shared within the particle physics community but, unlike Dyson's rules for their construction in calculational roles, some of them are optional or admit of various alternatives. Moreover, just as with the evolution of style and genre in the fine arts, so the practices of drawing and interpretation evolve (in the case of FDs, very quickly) as people try out new ideas or play with these imaginative tools to deepen their understanding (Meynell 2008, pp. 53–5).

So, while the PGs determine the pictorial content of FDs, there is nonetheless flexibility about what exactly one is to imagine within these constraints. In Feynman's own presentation it is clear that one can think of the depicted electrons as either particles or directions of propagation of a wave or field. Thus, the flexibility in determining the content of FDs, though constrained, can stretch even to basic ontological commitments or assumptions. I suggested that this flexibility of interpretation (which is absent for FDs qua calculational devices) goes some way to explaining the extraordinary proliferation of FDs in areas of particle physics (such as S-matrix theory) where the perturbative expansions that, from a calculational perspective, justify the existence of FDs were ill-suited (Kaiser 2005, pp. 195–207; Meynell 2008, pp. 54–5).

The use of FDs in contexts where they lack any calculational application—what might better be called quasi-Feynman meson diagrams—is particularly suggestive, implying that the representational role did important epistemic work. Here, the idea that the diagrams were only props for the imagination seems particularly plausible. Moreover, these diagrams appear to be even further from reality than their calculational cousins. After all, they have far more tenuous ties to the equations and little empirical evidence in their favor. So, the question of how they could be epistemically efficacious seems even more pressing. Both the propriety of various different interpretations and the non-denoting and non-factive character of FDs and their diagrammatic descendants suggest "knowledge" may be the wrong epistemic success term and, to the extent that they are epistemically efficacious, "understanding" may be better suited to the task. Indeed, as I will show in the next section, some of Feynman's own remarks suggest as much.

3. Some Telling Remarks by Feynman

Philosophers, when interrogating the concept of "understanding," often use the language of "picturing" or "having a picture of" the understood object or phenomena in question (e.g., Salmon 1998; De Regt and Dieks 2005; De Regt 2014) and Feynman is no different. Perhaps, the most revealing remarks on the topic appears in an oft-quoted (Schweber 1994, pp. 407–08; Wüthrich 2010, figs. 4.10–4.18, pp. 83–95; Gross 2012, p. 185) letter to his old undergraduate friend, Ted Welton, written a year or so before Feynman first presented his diagrammatic method. Here he writes:

> The reason I am so slow is not that I do not know what the correct equations, in integral or differential form are (Dirac tells me) but rather that I would like to – understand these equations from as many points of view as possible. (Wüthrich 2010, Fig. 4.15; underline Feynman's)[6]

And a little later:

> I find physics is a wonderful subject. We know so very much and then subsume it into so very few equations that we can say we know very little (except these equations—Eg Dirac, Maxwell, Schrod). Then we think we have the physical picture with which to interpret the equations. But there are so very few equations that I have found that many physical pictures can give the same equations. So, I am spending my time in study—in seeing how many new viewpoints I can take of what is known. (Wüthrich 2010, Fig. 4.16; underline and punctuation Feynman's)

Here we see a clear distinction between knowledge and understanding with knowledge being associated with mathematics and presumably deductive reasoning, and understanding being associated with picturing and taking many viewpoints. With understanding we see a kind of pluralist method that explores possibilities within constraints. It seems each physical picture or viewpoint is a picture of an imagined state of affairs constrained by the mathematics. In Feynman's so-called "physical thinking" multiple pictures, multiple understandings are available. Why would we bother to construct such pictures? In Feynman's words, "the hope is that a slight modification of one of the pictures will straighten out some of the present troubles" (Feynman 1947, p. 11; Wüthrich 2010, Fig. 4.16).

He continues:

> I dislike all this talk of others [of there] not being a picture possible, but we only need know how to go about calculating any phenomenon. True we only need calculate. But a picture is certainly a convenience & one is not doing anything wrong in making one up. It may prove to be entirely haywire while the equations are nearly right—yet for a while it helps. The power of

6. Wüthrich includes pictures of most of the pages of the letter in *The Genesis of Feynman Diagrams* (2010); references are to these images.

> mathematics is terrifying—and too many physicists finding they have correct equations without understanding them have been so terrified they give up trying to understand them. What do I mean by understanding? Nothing deep or accurate ~ just to be able to see some of the qualitative consequences of the equations by some method other than solving them in detail. (Wüthrich 2010, Fig. 4.16; underline Feynman's)

While it is tempting to think that the qualitative consequences that are of interest to scientists are the phenomena of the lab, here Feynman appears to be referring to the physical pictures, the imagined world of QED. He seems to have something akin to Cartwright's notion of "fitting out" in mind, whereby a wholly abstract mathematical expression is brought under an interpretation that makes it in some sense more concrete, moving it a step closer to contact with the world (Cartwright 1999, pp. 40–3). Not only is being able to form these imaginary physical pictures that are drawn from the equations part of what it is to understand QED, but it is clear that for Feynman we can have knowledge without understanding. Solving the equations and confirming them through experiment is one type of epistemic success—knowledge; understanding the world they describe is another. Though clearly such understanding facilitates cognitive progress there is no suggestion that understanding is more important or could take the place of solving the equations—just "for a while it helps." It seems to me that Feynman is suggesting that seeing the consequences, picturing, and understanding work together in the practices of making FDs and "seeing" a quantum world in them.

Another interesting discussion of understanding can be found in Feynman's popular science work, *QED: The Strange Theory of Light and Matter* (1985). After noting some trivial cases of failing to understand—poor expression, unintelligible accents, or the use of technical terms with ordinary names (like "work")—he comes to more philosophically interesting points. The first echoes a discussion familiar in philosophy of science regarding the difference between how and why questions (see for instance, Carnap [1966] 1995, p. 12). He suggests that perhaps "while I am describing to you *how* Nature works, you won't understand *why* Nature works that way. But you see, nobody understands that. I can't explain why Nature behaves in this peculiar way" (Feynman 1985, p. 10, italics his). He continues:

> Finally, there is this possibility: after I tell you something you just can't believe it. You can't accept it. You don't like it. A little screen comes down and you don't listen anymore.... It's a problem that physicists have learned to deal with: They've learned to realize that whether they like a theory or they don't like a theory is *not* the

> essential question. Rather, it is whether or not the theory gives predictions that agree with experiment. It is not a question of whether the theory is philosophically delightful, or easy to understand, or perfectly reasonable from the point of view of common sense. The theory of [QED] describes Nature as absurd from the point of view of common sense. And it agrees fully with experiment. So I hope you can accept Nature as She [sic] is—absurd. (Feynman 1985, p. 10, italics his)

This psychological point is an important one. It reminds us that understanding is not merely an achievement but an attitude toward some content as well as the ways in which it coheres with what we believe and our past experiences. But there is much more going on in this passage, including the role of so-called "common sense" and the idea (contra to his letter to Ted Welton) that in some sense QED is not understandable.

Walton offers a way of elucidating these remarks. If common sense is anything it presumably reflects and is built from the quotidian experience and the numerous expectations that govern our understanding of what happens from one moment to the next in our daily lives. Among other things, it makes our immediate perceptions comprehensible. Walton introduces the Reality Principle, which states that when no other PGs are available for determining the content of a representation we fill it in by relying on what would be true in reality, if the rest of the content were to exist in the actual world (Walton 1990, p. 147). This is why it is reasonable to believe that the *Mona Lisa* does not depict a chimera that is lion from the waist down and that Bilbo Baggins breathes oxygen and has kidneys. Walton then tempers the epistemic arrogance implicit in this principle by amending it to a Mutual Belief Principle, which fills in the content gaps according to "what is mutually believed" (Walton 1990, p. 152)—common sense—in the relevant (typically, the artist's) society. We can take the Mutual Belief Principle as a kind of formula for "common sense," which provides a set of default PGs that have a strong *prima facie* influence on our imaginations; we automatically rely on them when grasping the content of representations when no other PGs are in force. At the same time, common sense, whatever it may be, is hardly universal and what is mutually believed in any group changes over time. Moreover, we are members of many societies and in the sciences different disciplines or schools may vary significantly in terms of what is "mutually believed" within them, so common sense is a shifting target.

At the time of the development of QED and in Feynman's discipline, "common sense" might reasonably be thought to be the causal rules of classical physics (De Regt 2014). In producing his diagrams Feynman made sense of a number of phenomena that defy common sense. So, for instance, we see how a positron can be an electron going backwards in time because we can follow the path of charge (see footnote 5, above). This physical picture may be absurd and defy common sense but it offers an understanding. It gives us a tractable, qualitative way of thinking about the phenomena. By introducing this way of visualizing a causal process, Feynman creates a vision of the quantum world as he employs PGs for imagining the quantum world. Whether this fictional world corresponds to the actual world or not is a separate question from whether it offers us an understanding of it at all.

To summarize, we can find several different aspects of understanding in Feynman's remarks. We see that understanding a physical state of affairs is done by picturing that state of affairs (in the mind but perhaps also on paper), drawn from—but not entirely determined by—what we already know of the relevant domain. A variety of pictures of imaginable worlds may be drawn from the same knowledge set, using the same PGs. We have achieved understanding if we can either make a picture of a certain state of affairs or see a state of affairs in a picture. We can also see within any given picture the qualitative consequences of what is depicted, how the scene might unfold and what it means for other relevant objects that may not be depicted in the scene at all. When we attempt to understand the world we may, mistakenly, look for some deep truth—a reason why—but this is not the kind of understanding that science provides. What science can do is produce insight into how (and perhaps why, in a more mundane sense of identifying the antecedent causal conditions and causal relations more generally), the world works, even when this defies common sense. Of course, when it does defy common sense and the many habits of mind that get us through everyday experience, it becomes very difficult to picture—but not impossible. Such pictures may be haywire but help nonetheless. The feeling of understanding, the sense of grasping a plausible or even correct picture as well as the feeling of not being able to understand—being unable to produce, grasp, or accept a picture that appears before one—is also a necessary component and reminds us that understanding is a cognitive attitude of epistemic subjects. This brings us to the final point that I think is implicit in what Feynman says and, indeed, contributes to his work in popularizing science. We can understand things more or less. While understanding is a success term, there is no absolute gauge of understanding, it admits of degrees and depends on particular contexts.

4. Understanding and Knowledge as a Contrast Class

We have seen that Feynman makes use of a distinction between knowledge and understanding, and I propose to press this a little further in the hope of elucidating understanding through contrasting it with knowledge. Unfortunately, defining knowledge is by no means straightforward, as there are almost as many different theories of knowledge as there are epistemologists. Moreover, until fairly recently "knowledge" was the only epistemic success term that enjoyed careful analysis by epistemologists, which, arguably, has led to the concept being stretched in an effort to cover what might be better thought of as types of understanding. On top of this, our colloquial usage of the terms sometimes treats them as interchangeable. Nonetheless, a fairly standard (if imprecise and incomplete) representative characterization can be given. When philosophers, and especially mainstream epistemologists, talk about knowledge they are typically referring to a three-place relationship between an epistemic subject, some proposition, and a state of affairs. This is the rough form of the justified true belief (JTB) analysis that undergirds most analytic epistemology: *S* knows that *p* iff S *believes* that *p*, *S* is *justified* (or warranted) in believing *p*, and *p* is *true* (Gettier 1963).

This canonical account of knowledge is factive in that both the attitude of the epistemic subject and the external success conditions for knowledge are concerned with true propositions, or facts. If *S* believes that *p* then they believe that *p* is true and to be knowledge *p* must be true. Moreover, although the details on this are controversial, justification, while not reducible to truth, is nonetheless truth-conducive and thus factive (see Zagzebski's [1994] useful discussion). If our account of understanding allows cases with non-factive content, this suggests that the epistemic attitude and any necessary procedural success standards, should not be tied to truth, at least not in so direct a fashion as knowledge.

Happily, Catherine Z. Elgin, following Nelson Goodman's work (esp. 1968, 1978), has proposed an account of understanding that not only clearly distinguishes it from knowledge, but does so, in large part, on the basis of the nonfactivity of understanding. Elgin maintains that, especially in science, we may knowingly and rationally accept falsehoods in our scientific reasoning so long as they are felicitous. These are not the poor cousins of truth; they are unapologetically false, though true enough for the purposes at hand (Elgin 2004). Now, in the sciences these purposes do ultimately serve truth, though this payoff may be some distance down the line. The question is whether Elgin's felicitous falsehoods, which are merely true enough, are still too true for the kinds of nonfactive understanding that Feynman seems to be talking about and that are seen in the uses of quasi-Feynman meson diagrams in applications beyond QED. Ultimately, we will see that her Goodmanian commitment to the centrality of denotation, this time as a key figure of understanding, renders the view insufficient for our task. Nonetheless, there are a number of useful insights in her account that I will put to work in later sections.

5. Elgin's Understanding—True Enough

One of the striking things about Elgin's scientific epistemology is the primacy of place given to understanding. Indeed, building from the standard JTB account, she argues that science is not primarily concerned with knowledge (Elgin 2004, pp. 114–16). In "From Knowledge to Understanding" (Elgin 2006), she suggests that traditional epistemology provides an image of knowledge as a stack of individual facts, each true and justified in its own right, but not inherently related to each other. Science, in contrast, "is not an aggregation of separate, independently secured statements of fact, but an integrated systematically organized account of a domain," which is why theories play such an important role (Elgin 2006, p. 200). Theories are central and effective because they "select, order and regiment the facts" (Elgin 2006, p. 204); by doing so they facilitate understanding. Individual scientific facts—knowledge properly speaking—can be produced from scientific theories as individual claims that are tested and confirmed; however, these observations and conclusions, their significance, and epistemic power rely on the broader theoretical structure through which the domain is being investigated (as Duhem [1962] and later Quine [1951] pointed out) (Elgin 2006, p. 201). In order to bring clarity to complex domains, theories must strategically ignore some facts and idealize others—for instance, stipulating what counts as a signal and what counts as noise (Elgin 2006, pp. 204–08). This requires a certain degree of pluralism and a certain degree of pragmatism, as different theories of the same domain will foreground, ignore, and idealize different facts and features, sometimes only leaving pragmatic ends to choose between them. So, a scientific epistemology that simply extends mainstream epistemic analyses and norms to science is bound for failure because of the centrality of factivity to traditional epistemology and its irrelevance to much of science. There is a role for knowledge, but it is a secondary one that serves understanding.

The method of moving beyond knowledge to understanding—this structuring of general and particular facts so as to render them tractable and fruitful—only becomes possible with the addition of felicitous falsehoods. These include various kinds of idealization and abstraction, like curve smoothing, rejecting outliers and simplifying models. *Ceteris paribus* clauses abound as we recognize that central claims of certain theories are all but never strictly-speaking true (Elgin 2004, pp. 116–19). However, this presents Elgin with a difficulty rather like that which I originally posed and which motivates the current discussion: Once we admit there are epistemically efficacious scientific objects that fail the basic success conditions for knowledge, how do we characterize their epistemic success (Elgin 2004, pp. 113–14)? Elgin's response is, in effect, to loosen the success standard, treating true enough as a threshold concept (in contrast with ordinary disquotational accounts of truth). When we adopt a claim as true enough we are saying that its divergence from the truth is negligible (Elgin 2004, p. 119). Of course, what counts as "negligible" will be a contextual matter but getting as close to the truth as possible is not necessarily desirable. If the primary goal is "an understanding of how things are" and understanding is holistic, requiring the kinds of selection and ordering discussed above, then having overly complicated facts will introduce obfuscating detail (Elgin 2004, p. 120). Even something as seemingly simple as solar system dynamics would become difficult, if not incalculable, were we to demand that the true center of gravity, the barycentre, be used to determine the path of solar system objects orbiting the sun. Determining where the threshold lies requires answering the question "True enough for what?" (Elgin 2004, p. 121). So, for instance, for most if not all purposes of solar system astronomy, treating the center of the sun as the barycentre of solar system orbits will be true enough. Unfortunately, Elgin offers little direction for determining when the threshold is met, pointing only to rather vague considerations: Does the felicitous falsehood add to our understanding of how things are? Does it highlight features that might otherwise be invisible? Does it make manifest patterns in phenomena? If so, it is true enough (2004, p. 128). Clearly, Elgin sees understanding as providing a "springboard for further (sic) the inquiry" (Elgin 1997, p. 79), but she offers only a vague sense of when it is rational to adopt a felicitous falsehood or when we can hope to achieve understanding through it.

Some light is shed through her account of the type of epistemic relation by which understanding is achieved. Felicitous falsehoods direct our attention by exemplifying features that contribute to understanding (Elgin 2004, pp. 124–27). Exemplification is a tricky notion, though simple enough on the face of it: "Any symbol that at once instantiates and refers to a feature exemplifies that feature" (Elgin 1997, p. 64). So, for instance, "A free sample of laundry detergent exemplifies the soap's cleaning power; a blood sample, the presence of antibodies. A theorem exemplifies its logical form, while a sample problem in a textbook exemplifies the reasoning it seeks to inculcate" (Elgin 1997, p. 65). Reference for Elgin comes cheap, by way of convention and stipulation, requiring nothing but an extant object and something to refer to it; but instantiation and thus exemplification requires shared features between the symbol and the referent. A symbol that exemplifies not only refers to its object but displays and draws attention to features of that object by instantiating them. Exemplification may be purely theoretical, as when a theoretical model exemplifies the simplified and idealized relative motion of objects in a real system, but physical processes can also exemplify. Experiments exemplify their results insofar as they refer to and instantiate features underlying ordinary events and so make evident phenomena that are typically obscured by the complex interaction of natural processes (Elgin 2004, pp. 125–6). By foregrounding telling features of a domain both theoretical and physical exemplifications grant us epistemic access to that domain and they can achieve this without being factive.

In sum, for Elgin, an acceptable scientific theory helps us understand reality not because it provides a "mirror of nature" but through presenting us a carefully organized bricolage of fact and felicitous falsehood that points to the relevant features of nature that drive and thus explain various phenomena (Elgin 2004, p. 128). The extent to which we can fruitfully and creatively navigate and exploit this bricolage indicates the extent to which we understand the theory itself and its domain. Nonetheless, this understanding is ultimately constrained and directed toward truth. Elgin is clear that a good scientific theory must accommodate the facts and it must be factually defeasible (Elgin 2004, p. 129). In other words, there must be "some reasonably determinate, epistemically accessible factual arrangement which, if it were found to obtain, would discredit the theory" (Elgin 2004, p. 129). Presumably, this means that with a good theory we can understand how and why our felicitous falsehoods deviate from the facts without falsifying the theory. What is more, insofar as exemplification is a key instrument in producing understanding, non-existent objects are barred from having a role in understanding.

We can now see that, while a number of features of Elgin's account might usefully affirm and elucidate the insights of Feynman's remarks on understanding, true enough is still too true for our purposes, as is exemplification. Certainly, Elgin's view of understanding allows the pluralism suggested in Feynman's remarks—different theories may be found to accommodate the facts of a given domain, just as Feynman found that many physical pictures can be drawn from the same equations. Like Feynman, Elgin finds the value of understanding in that it allows us to move forward in our investigations—"for a while it helps" (Feynman 1947, p. 11; Wüthrich 2010, Fig. 4.16), as a "springboard for inquiry" (Elgin 1997, p. 79). That this is achieved by simplifying and organizing key ideas and relations, while putting others in the background, is a useful addendum to Feynman's remarks. However, the importance of conformity to the facts in Elgin's account is just too strong as is her focus on reference. After all, virtual particles are clearly represented in FDs but they are not thought to exist in any robust sense, so they presumably can't exemplify anything. Even if we were to allow that FDs in their original application in QED were true enough because they contributed to an understanding of the domain that conformed to experimental observations and could be deduced from Tomonaga and Schwinger's more conventional and respectable theory, this would not apply to the quasi-Feynman meson diagrams that proliferated in the 1950s. In part, because they no longer followed the calculational rules and in part because the nuclear interactions of interest were so mysterious, their only firm connection to the truth is as a very distant goal—a hope that eventually there might be good grounds for believing that one or other of these new images in some sense conformed with reality. Considering that there were good reasons at the time for thinking any given one of them was substantively false, they cannot be thought to meet the threshold of being true enough.

6. Getting the Picture

Rather than loosening truth, I propose to take an entirely different approach, by exploring the analogy between picturing and understanding in the hopes of teasing out a more promising success standard. This, of course, picks up a theme in Feynman's remarks, as he identifies being able to make a picture—indeed a variety of pictures—with understanding. So, what I propose to do is spell out what it is about pictures and picturing that makes them good analogues for understanding. I will suggest that there are three features characteristic of pictures and the way they present their content that do this work. Happily, this not only fits with Feynman and Elgin's remarks on understanding, but it also reflects themes that have been noted in philosophical discussions of scientific understanding. First, understanding is a particular kind of active cognitive process (De Regt 2014) that is analogous to the activity of viewing a picture. Second, understanding unifies, bringing a variety of disparate information into "one picture," as it were (Friedman 1974; Kitcher 1981). Third, understanding reflects a kind of appreciation for causal connection and qualitative consequences that is characteristic of pictures (Salmon 1998; Woodward 2003). With these themes in hand we will have a way of cashing out the epistemic efficacy of non-factive images, by treating the characteristic content of understanding as pictorial.[7]

Regarding the analogy between the activity of viewing pictures and the activity of understanding, there are basic formal features of images that require their viewers to engage their content in a far more active way than

7. By "treating the characteristic content of understanding as pictorial" I only mean to suggest that the key cognitive features and success standards of understanding are features characteristic of correctly and completely assessing and appreciating the content of pictures. Nothing is implied about the character of the mental content of understanding. The model here is epistemologists who allow that not all knowledge is propositional but nonetheless focus on "*S* knows that *p*" analyses.

that characteristic of belief or acceptance—the cognitive attitudes associated with knowing. Because pictures are two-dimensional[8] they present their content all at once. This means that images invite individuals to order depicted content in their own way, attending to the relations between parts that are of most interest to them (Tufte 2001, p. 13). The relations aren't only of part to part but also part to whole. Complex images reward multiple viewings, as taking different paths through the content helps a viewer appreciate the multiple interconnected relations that make up the whole. If one really "gets" the picture one can easily draw out individual claims specifying relations between disparate components.

We see the first two features clearly at play here. Whatever the domain to be understood, the epistemic subject takes an active role putting it all together—thinking it through—and will presumably use their interests to guide their attention. This activity of the subject does not render the content subjective. With pictures PGs determine the content despite not determining how one orders it. The same is true of understanding a particular scientific domain, which is constrained by expert knowledge, background beliefs, and the habits of mind gained from one's experience, both disciplinary and otherwise. Just the same way two people can see the same thing in a picture, two people can have a shared understanding of a subject or a domain even if they don't think about it in quite the same way. (This reflects the flexibility within constraints that I discussed previously [Meynell, 2008, p. 50]).[9]

The sense of being able to navigate through the whole domain in a variety of different ways also points to the extent to which understanding unifies—an idea developed by Phillip Kitcher (1981) and Michael Friedman (1974), albeit through very different approaches. "Getting the big picture" or seeing how something "fits into the big picture" are instructive idioms that nicely conform to the intuition that understanding unifies through something like the complex mutual contextualization of content that one gets in a two-dimensional picture. We can also see the importance of unification in Elgin's ideas about making a domain tractable through strategic

8. Of course, some pictures—moving pictures—are three-dimensional with time being added as another dimension and scientists have long made use of three-dimensional models also. I will assume for the sake of simplicity that what I say about two-dimensional images can also be extended to images of more dimensions.

9. De Regt maintains that understanding is an inherently pragmatic notion because it revolves around an epistemic subject and their context. From this starting point, he argues that despite being pragmatic, understanding is epistemic nonetheless (De Regt 2014, pp. 379–80). Although I agree that there are pragmatic aspects to understanding, I hope it is clear that I take it to be un-controversially epistemic, with norms and success conditions that befit the particular character of this cognitive attitude and its content.

simplification and felicitous falsehoods. This is, in effect, unifying through zooming out—knowing that there are more accurate, devilish details that could be attended to, but ignoring them for the moment for the sake of grasping the whole.

The third feature bridging picturing and understanding comes from the spatial resemblance of pictures to the states of affairs that they represent (even if these are fictional or impossible). Such pictures have implicit content derived from our ordinary experiences of states of affairs and their causal relations. Central to our ordinary experience is the expectation that the basic causal processes that we find in our folk physics and biology will follow roughly the patterns that they have in the past and that if they diverge from them there will be something that caused them to do so. Without these expectations being all but invariably fulfilled we would find the world unintelligible. In our experience of reality these are background beliefs and habits of mind (be they tacit, embodied, or explicit); in our comprehension of pictures these are PGs, based on the Mutual Belief Principle, which typically include but are not limited to many of the background beliefs that inform our experiences.

What is important to note here is that our PGs can develop and change so that we find new meaning in pictures, make new pictures, or find that we can make sense of pictures that were unintelligible before. Art history courses presuppose as much, but we can also find more pertinent discussions of more or less the same idea in the philosophy of science. In "Visualization as a Tool for Understanding" (2014), Henk De Regt offers an account of the transformation of standards of intelligibility and tacit rules of visualizability that took place in the transition from classical physics to quantum mechanics and ultimately QED (as well as quantum field theory more generally). Though De Regt does not put it in these terms, the account lends itself to an interpretation that treats this transformation as a change in the accepted PGs for imagining phenomena in the subatomic realm.

De Regt maintains that what was considered intelligible in classical physics was often tied to what was visualizable and, in turn, visualizability was understood in mechanical terms conforming to our everyday expectations of causal interactions. When people like Wolfgang Pauli claimed the new physics defied visualization what they were saying is that it no longer conformed to these familiar mechanical types of interaction (de Regt 2014, p. 385). In Waltonian terms, the PGs governing causal interactions that we derive from ordinary experience no longer could be employed to make an intelligible picture of the domain. However, as De Regt explains, the standards for intelligibility, and indeed visualizability, can change over time and did so within the discipline of 20th century physics, as it transformed from classical to quantum. Schrödinger's wave mechanics marks one important development and Heisenberg's brand of thought experimental empiricism another (De Regt 2014, pp. 386–8). FDs embodied a new set of norms—PGs for us—reflecting and reaffirming new standards for visualization and understanding. If FDs defy common sense, and the sense of understanding associated with it, it is because we can no longer straightforwardly draw on ordinary experiences as default PGs for determining the content. While De Regt locates the reason for the explosive development of various quasi-Feynman meson diagrams in the fact that they were not classical, "realistic" representations, I think we have the means of giving this a more precise expression. As props for imagining the subatomic realm that was unhooked from commonsense PGs, FDs provided visual methods and new PGs that could be further developed and imaginatively deployed. Thus, as pictorial representations, FDs facilitated imagining subatomic phenomena that defied common sense, allowing physicists to "see some of the qualitative consequences" of a theory, mathematical expression, or claim. Such pictures, whether in minds or on paper, though they "may prove to be entirely haywire" or "absurd" may nonetheless "help."

We can see that unification and appreciation for the component causes or qualitative consequences are only part of what is needed to specify success standards for understanding. After all, the norms governing unification and causation vary both over time and between disciplines (De Regt and Dieks 2005; De Regt 2014). A Waltonian lens is helpful for spelling things out. If we think of these norms as PGs we can see that understanding will be achieved when we can put an object, x, into context and make the relation between x and these contextual factors meaningful by drawing on the appropriate disciplinary conventions, habits of mind, background beliefs, and felicitous falsehoods to "get" the "picture." We may have to struggle to do this; it will often not be easy to practice the appropriate habits of mind, learn the correct background beliefs and felicitous falsehoods, and acquire facility with the required conventions in order to really put the picture together. But the application of the correct PGs is part of what constitutes the normative procedure. By applying them one can compare parts and see how the component parts fit together; one can get a sense of how the objects in a domain are causally connected and how they might interact.

We can also see that success in this procedure will come in degrees. If one has only a rudimentary understanding of some domain or object, x, one gets a rough picture of what is going on, with some sense of where x comes from and where it's going. If one has a profound understanding one has a finely tuned picture which one can work through in various ways with a sense of all the possible contingencies leading to and following from *x* as well as a clear sense of which are more likely. Real mastery (or lacking that, sheer audacity) supports a kind of imaginative play, as various PGs are swapped out for new ones. As Walton puts it, "Imagining is a way of toying with, exploring, trying out new and sometimes farfetched ideas. Hence the value of luring our imaginations into unfamiliar territory" (Walton 1990, p. 22).

So, we are now well equipped to bring our focus back to Feynman's remarks and compare them to the account that we've developed from thinking about the analogy between understanding and picturing. We see that understanding a physical state of affairs can be done by picturing that state of affairs (in the mind but perhaps also on paper), drawn from but not entirely determined by what we already know of the relevant domain. A variety of pictures of imaginable states of affairs may be drawn from the same knowledge set. We have achieved understanding if we can either make a picture of a certain state of affairs or see a state of affairs in a picture and appreciate the qualitative consequences of what is depicted, judging how the scene might unfold and what it means for other relevant objects that may not be depicted in the scene at all. When we attempt to understand the world we may, mistakenly, look for some deep truth—a reason why—but this is not the kind of understanding that science provides. What it can do is provide insight into how and why, in a more mundane sense, the world works, even when this defies common sense. Of course, when it does defy common sense and the many habits of mind that get us through everyday experience, it becomes very difficult to picture, but not impossible. Such pictures may be "haywire," but "help" nonetheless. The feeling of understanding, the sense of grasping a plausible or even correct picture as well as the feeling of not being able to understand—either being unable to produce a picture or accept the picture that appears before one—reminds us that understanding is an attitude of epistemic subjects, just as knowledge is. We can understand things more or less. While it is a success term, there is no absolute gauge of understanding; it admits of degrees and depends on particular contexts.

7. Developing an Understanding

With success conditions that are separable from but related to knowledge in hand, we are now equipped to explain non-factive understanding as epistemically successful. As with traditional analyses of knowledge we can think of understanding as basically a three-place relationship between an epistemic subject, some mental content (whether a picture or a proposition), and the world. When understanding fails we can locate the failure in the relation between (i) the subject and content or between (ii) the content and the world. Thus, if someone fails to understand some object or event it may be because of their poor grasp of the content or it may be because the content fails to correspond to relevant states of affairs in the world. "Understanding *x*" and "having an understanding of *x*" can now be seen to treat the relationships between (ii) the content and the world in importantly different ways. To say "I have an understanding of *x*" is to make a tentative claim that I can successfully create a "coherent picture" of *x*: I can identify component parts and relate them to each other, I have some overarching sense of how it all goes together, and I can specify some of the qualitative consequences that follow. What is more, my picture is not obviously and problematically inconsistent with what I already know, nor does it contradict central beliefs in the relevant epistemic community. To say "I understand *x*" is to assert that this picture is also right (to a lesser or greater degree, at least in important respects). To have an understanding is only loosely related to facts or knowledge as it neither asserts some content as true or true enough, nor suggests having justificatory grounds for the same. It may be informed by beliefs or knowledge claims (as, in effect, PGs), but it does not implicitly assert them. In contrast, to claim to understand *x* implies that there are things that we know about *x* and that we assert as much. The success standards of understanding *x* combine those of having an understanding of *x* along with the success standards, such as factivity, that are characteristic of knowledge. If this appears to be a ludicrously high standard, we can make it rather more attainable by adopting accepted fallibility provisos and admitting that some of this "knowledge" need only be true enough. Arguably, reference and exemplification will be sufficient to understand a domain, if only superficially. This is consistent with the idea that understanding is degreed. Indeed, understanding *x* surely allows some false beliefs into the mix; certainly, the fewer false beliefs the better, but understanding *x* can tolerate a number of false beliefs about *x*, so long as they don't have too central a place and so long as there aren't too many of them.

To say FDs offered an understanding of the subatomic realm implies that they enabled physicists to imagine what might be going on in this domain in ways that were consistent with the best theory of the time. Moreover, as a shared representational object they coordinated imaginings among physicists, so they helped a whole community to develop an understanding of the quantum realm. Some might be bolder and claim that the connections to the theory and the evidence supporting that theory—as well as the evidence for some specific PGs, such as the positron being an electron traveling backward in time—merits the claim that physicists understood the interactions of QED through Feynman's diagrams. The same cannot be said for the quasi-Feynman meson diagrams of the 1950s, which didn't enjoy evidentiary support. Nonetheless, each of these images provided an understanding of quantum field theory which, given the peculiarity of the phenomena and the extreme difficulty of developing informative experimental procedures to investigate this realm, is no small thing. Getting an overall picture and having a way of seeing the various possible qualitative consequences of that picture, constrained though not determined by what little was already known, provided assorted understandings and imaginative platforms for moving forward. As such, both FDs and their quasi-FD descendants were fruitful because they helped the science to develop despite the cognitive and experimental inaccessibility of the domain.

In the end, it seems that the basic epistemic value grounding non-factive pictures is one of the five that Kuhn identified as uncontroversial in the *Essential Tension*—fecundity (Kuhn 1977, pp. 323–24). This seems like pretty thin soup and typically, merely getting a picture that may or may not fit the world is not going to count as an epistemic success at all. The only time that having non-factive, non-denoting understanding is really going to count as an achievement is when one is so early in the investigation of a given domain that the facts simply aren't available and the domain itself is so unfamiliar it has defied understanding. If one is so lost that one doesn't even know how to go about trying to get the facts, then being able to form any picture, even one that's "haywire" or "absurd" is a type of epistemic success.

8. Conclusion

It is difficult to avoid self-referential conceits when summarizing an argument like the one I have given above. After all, the task is to leave the reader with the sense that they understand the whole that was presented to them by reviewing key points that exemplify the main thrust of the argument, to show how it all fits together and suggest where one might go with it. I have tried to draw a thread from Feynman's suggestive remarks about understanding and picturing and cash them out through examining the character of pictorial content. Visualization and picturing have often been associated with understanding and I have suggested that the way pictures present their content is not only conducive to understanding but exemplifies features of what it is to understand. The active role of the epistemic subject, the importance of unification, and the capacity to "see" qualitative consequences are features of both viewing pictures and understanding. This analogy thus provides success conditions and norms by which to specify understanding as a robust epistemic achievement. At the same time, leaning on Elgin's work, I have tried to show that nonfactivity is far from rare in the sciences and, indeed, that felicitous falsehoods may be unavoidable. But I have also shown that felicitous falsehoods may still be too true to capture all of the valuable non-factive epistemic objects that we might want to allow in the sciences and, indeed, that FDs (and certainly quasi-Feynman meson diagrams) may be of this kind. Even so, I have argued that FDs facilitated understandings of the subatomic realm and did this by way of their representational role, which unified phenomena, suggested various qualitative consequences, and allowed imaginative play. Thus, as pictorial representations FDs are robustly epistemic in a fashion that is significantly divorced from their calculational role.

It is a dangerous time to be writing about the legitimacy of non-factivity in epistemology, given the current political climate. However, the places where the kind of non-factivity I identify will be epistemically valuable are, instructively, few and far between. It is only in those realms where we have little evidence and where our implicit ontologies, heuristics, explicit methods and rules are failing us that these flights of fancy are not only permissible but necessary if we are to make progress. If we don't have knowledge and we can't gain true understanding, then developing an understanding may be the best we can do.

References

Brown, James R. 1996. "Illustration and Inference." Pp. 250–268 in *Picturing Knowledge: Historical and Philosophical Problems Concerning the Use of Art in Science*. Edited by Brian Baigrie. Toronto: University of Toronto.

Carnap, Rudolf. [1966] 1995. "The Value of Laws: Explanation and Prediction." Pp. 3–18 in *An Introduction to the Philosophy of Science*. Edited by Martin Gardner. New York: Dover.

Cartwright, Nancy. 1999. *The Dappled World: A Study in the Boundaries of Science*. Cambridge: Cambridge University Press.

De Regt, Henk. 2014. "Visualization as a Tool for Understanding." *Perspectives on Science* 22 (3): 377–396.

De Regt, Henk and Dennis Dieks. 2005. "A Contextual Approach to Scientific Understanding." *Synthese* 144 (1): 137–170.

Duhem, Pierre. 1962. *The Aim and Structure of Physical Theory*. Translated by Philip P. Wiener. New York: Atheneum.

Elgin, Catherine Z. 1997. "Relocating Aesthetics: Goodman's Epistemic Turn." Pp. 63–80 in *Between the Absolute and the Arbitrary*. Ithaca: Cornell University Press.

Elgin, Catherine Z. 2004. "True Enough." *Philosophical Issues* 14: 113–121.

Elgin, Catherine Z. 2006. "From Knowledge to Understanding." Pp. 199–215 in *Epistemology Futures*. Edited by Stephen Hetherington. Oxford: Clarendon Press.

Feynman, Richard. 1949a. "Space-Time Approach to Quantum Electrodynamics." *Physical Review* 76 (6): 769–789.

Feynman, Richard. 1949b. "The Theory of Positrons." *Physical Review* 76 (6): 749–759.

Feynman, Richard. 1985. *QED: The Strange Theory of Light and Matter.* Princeton, N.J.: Princeton University Press.

Friedman, Michael. 1974. "Explanation and Scientific Understanding." *Journal of Philosophy* 71 (1): 5–19.

Gettier, Edmund. 1963. "Is Justified, True Belief Knowledge?" *Analysis* 23 (6): 121–123.

Goodman, Nelson. 1968. *Languages of Art: An Approach to a Theory of Symbols*. Indianapolis: Bobbs-Merrill.

Goodman, Nelson. 1978. *Ways of Worldmaking*. Indianapolis: Hackett Publishing.

Gross, Ari. 2012. "Pictures and Pedagogy: The Role of Diagrams in Feynman's Early Lectures." *Studies in History and Philosophy of Modern Physics* 43: 184–194.

Harré, Rom. 1988. "Parsing the Amplitude." Pp. 59–71 in *Philosophical Foundations of Quantum Field Theory*. Edited by Harvey Brown and Rom Harré. Oxford: Clarendon Press.

Kaiser, David. 2005. *Drawing Theories Apart: The Dispersion of Feynman Diagrams in Postwar Physics*. Chicago: University of Chicago.

Kitcher, Phillip. 1981. "Explanatory Unification." *Philosophy of Science* 48: 507–531.

Kuhn, Thomas S. 1977. *The Essential Tension: Selected Studies in Scientific Tradition and Change*. Chicago: University of Chicago Press.

Mattuck, Richard. 1976. *A Guide to Feynman Diagrams in the Many-Body Problem*, 2nd Edn. New York: McGraw-Hill.

Meynell, Letitia. 2008. "Why Feynman Diagrams Represent." *International Studies in the Philosophy of Science* 22 (1): 39–59.

Meynell, Letitia. 2013. "Parsing Pictures: On Analyzing the Content of Images in Science." *Knowledge Engineering Review* 28 (3): 327–345.

Meynell, Letitia. 2018. "Images and Imagination in Thought Experiments." Pp. 498–511 in *The Routledge Companion to Thought Experiments*. Edited by Mike Stuart, Yiftach Fehige, and James R. Brown. London: Routledge.

Quine, Willard V.O. 1951. "Two Dogmas of Empiricism." *Philosophical Review* 60 (1): 20–43.

Salmon, Wesley. 1998. *Causality and Explanation*. Oxford: Oxford University.

Schweber, Silvan. 1994. *QED and the Men Who Made It: Dyson, Feynman, Schwinger, and Tomonaga*. Princeton: Princeton University.

Tufte, Edward. 2001. *The Visual Display of Quantitative Data*, 2nd Edn. Cheshire, CT: The Graphics Press.

Von Baeyer, Hans. 1999. "Note bene." *The Sciences* 39 (1): 12–15.

Walton, Kendall. 1990. *Mimesis as Make-Believe: On the Foundations of the Representational Arts*. Cambridge, MA: Harvard University.

Woodward, James. 2003. *Making Things Happen: A Theory of Causal Explanation*. New York: Oxford University.

Wüthrich, Adrian. 2010. *The Genesis of Feynman Diagrams*. Dordrecht: Springer.

Wüthrich, Adrian. 2012. *The Genesis of Feynman Diagrams*, Kindle edition. Dordrecht: Springer.

Zagzebski, Linda. 1994. The Inescapability of Gettier Problems. *The Philosophical Quarterly* 44 (174): 65–73.