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Feynman diagrams: visualization of phenomena and diagrammatic representation

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Abstract

I will argue that the development of Feynman diagrams came from the physicist's capacity of visualizing phenomena and that such visualization-skill contributed to the forming of a narrative explanation in the sense of Wise (2011) and Morgan (2001). The second part of the paper explores the extent to which Feynman diagrams can be considered as weak representations of quantum phenomena. I will review some of the most common arguments in support of the instrumentalist view and I will suggest that a form of weak representation that does not imply ontological commitment can be applied to the diagrams. Such a form of weak representation will be characterized as non-denotative, intentional, and as conveying a physical interpretation through narrative explanations.

Keywords Feynman diagrams · Scientific understanding · Narrative explanation · Quantum mechanics · Weak representation

1 Introduction

The present paper aims at providing evidence that the development of Feynman diagrams (Feynman, 1949a) was driven by an attempt to understand quantum phenomena, and that such understanding came from Feynman's capacity for graphical representations.[1] In the second part of the paper I explore the possibility of conceiving such graphical representations as narrative explanations in the sense of Wise (2011) and Morgan (2001). More specifically, I will suggest that Feynman diagrams are neu-

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[1] A caveat: in this contribution I will refer to some of the works that led Feynman to the development of his famous diagrams. A brief look at the absorber theory of radiation, path integrals, and the quivering electron, will provide evidences that Feynman's work was driven by at attempt to understand the phenomena, rather than the theory. A more precise and thorough reconstruction of the history of Feynman diagrams (and of his scientific contributions) can be found in: Schweber (1986); Mehra (1994); Gross (2012); Darrigol (2019); Galison (1998); Wüthrich (2010) and others.

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tral with respect to the ontology of quantum electrodynamics and that they are to be considered as models (in the sense of Morgan & Morrison, 1999 and Stöltzner, 2018) that offer a weak representation of scattering phenomena. I clarify the notion of weak representation as: non-denotative, intentional (see: Van Fraassen, 2010), and as providing a narrative explanation via specific principles of generation (see: Walton, 1990 and Meynell, 2018). I then emphasize how the diagrams are associated with measured cross-sections, thereby providing a concrete connection with experimental physics (see: Harlander, 2021).

As a starting point for discussing Feynman's theorizing, I will rely on the recent work by De Regt (2017) which provides a general account of scientific understanding that applies also to Feynman diagrams and that emphasizes the relation between visualizability and intelligibility. The onset of De Regt's approach is that: "Scientists seek explanations that fit the phenomenon to be explained into a theoretical framework and connect it with relevant background knowledge" (De Regt 2017, p. 36). The connection between the theoretical knowledge, the background knowledge, and the phenomenon is based on the construction of appropriate models which ultimately provide the explanation to that phenomenon. What are the characteristics that the theories should have to be able to facilitate the construction of such model-based explanations? The suggestion is that: "scientists prefer theories with properties that facilitate the construction of models for explaining phenomena, and that is the case if their skills are attuned to these properties" (De Regt 2017, p. 39). This means that scientists search for theoretical virtues (for example: simplicity and visualizability) also in relation to their own scientific skills. When such a combination between theoretical virtues and scientific skills is met, we have a pragmatic understanding.

It is at this point that De Regt introduces his newly forged definition of intelligibility, to be intended as the value assigned by a scientist (or group of scientists) to the qualities of a scientific theory that make that theory more usable.[2] For example, the different formulations of classical mechanics, although equivalent, have different explicit qualities that can be preferred in different model-building contexts. Or, alternatively, visualizability is a property of some theories that, argues De Regt, can make the theory intelligible to some scientists. In this sense, some scientists might find a theory that is visualizable easier to use for building explanatory models. At the same time, other scientists might find that other properties, such as axiomatic structure, elegance, etc, are more useful than visualizability for the same model-building. De Regt (2017, p. 40) specifies that: "if scientists understand a theory, the theory is intelligible to them".

In sum, in De Regt's view: (i) the understanding of a phenomenon comes from an explanation which is provided by a model. Then, (ii) the model is constructed starting from the pragmatic understanding of a theory and (iii) the pragmatic understanding of a theory is to be understood in terms of intelligibility.

With respect to Feynman diagrams, De Regt (2017, p. 252) maintains that they "[…] functioned as conceptual tools that made quantum field theory more intelligible for most theoretical physicists". While I can agree on the sociological effect that the diagrams had in the scientific community (cf: Kaiser, 2009), the claim seems at odds

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[2] The usability of a theory is then referred to as the capacity of scientists to build explanatory models for a given phenomenon starting from that theory.

with how Feynman developed the diagrams, especially in light of the recent works by Wüthrich (2018) and Forgione (2022).

In Section 2, I will suggest a different reading than the one proposed by De Regt: I will maintain that Feynman did not develop the diagrams from an intelligible theory, nor did he develop them to make quantum electrodynamics more intelligible.[3] Rather, I will argue, Feynman's theorizing was fundamental to the development of his quantum electrodynamics, and I will use a number of historical examples to show that the physicist relied on 'physical intuition' and 'visualization' of physical phenomena before turning to the more formal aspects of a theory. Since these 'visualizations' and 'intuitions' are not well defined by the physicist, I will show how they can be characterized in relation to the concept of narrative, that is: parts of a model (or theory) that help us understand what is represented by that theory (see: Wise, 2011; Morgan, 2001).

In Section 3, I will describe Feynman diagrams as explanatory models that weakly represent quantum phenomena. The term 'weakly' stands for a representation that is intentional but non-denotative, where 'non-denotative' indicates that it is not possible to give a one-to-one correspondence between elements of the diagrams and elements of physical reality. For example, as we shall see below, it is not possible to map the lines and arrows of the diagrams to trajectories traversed by particles. In addition, I will further discuss the concept of 'narratives' as products of games of make-belief (see: Walton, 1990), where the 'rules of the game' (or alternatively, the principles of generation) are provided by Feynman's rules.[4] To emphasize the connection between the diagrams and physical reality (measurements), I will refer to Harlander (2021) as a case in point, and I will associate what I have defined as the narratives expressed by the diagrams (and their components) to corresponding (measured) cross-sections. Finally, I will consider a number of possible objections and possible responses.

2 Feynman's look at the phenomena

2.1 De Regt's account of scientific understanding

In this section I briefly introduce De Regts's account of scientific understanding as applied to Feynman diagrams and I emphasize the difference between understanding phenomena and understanding a theory. I will maintain that Feynman's scientific theorizing sought an understanding of quantum phenomena characterized by visualization and narrative explanation.

We shall begin with the pivotal (and new) concept of De Regt's view, which is the concept of intelligibility defined as:

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[3] When discussing Feynman diagrams, I do not only intend the graphic depictions, but also the rules of correspondence that allow for the calculation of the scattering amplitude.

[4] As I will also specify below, the 'rules of the game' ought to be contextualized with respect to the background theory. That is, the principles of generation tell us how to draw and interpret the elements of the diagrams, but quantum mechanics remains the background theoretical framework.

> **Intelligibility**: Value that scientists attribute to the cluster of qualities that facilitate the use of the theory. (De Regt 2017, p. 12)

The definition implies that, among the different qualities a theory might have, there are some that concern the usability of such theory for building explanatory models, and that intelligibility is a value attributed to a theory and assigned by one (or more) group of scientists. Consequently, insofar as different scientists are members of different research contexts, and different values can be attributed to the same qualities, intelligibility will be a contextual concept. Because the concept of intelligibility directly refers to the attribution of a qualitative value by some scientists, it suggests (at least in its definition) a component of subjectivism. If intelligibility is fundamental to De Regt's view of scientific understanding, and the concept implies subjectivism, then scientific understanding will also be subjective. However, De Regt replies that there is more to scientific understanding than the division between objective understanding (i.e., explanation) and subjective components deriving from (for example) psychological factors.

Similar discussions about objective understanding (and consequently, intelligibility) are oftentimes traced back to the nomological-deductive (DN) account of scientific explanation by Hempel, wherein the objective account should avoid pragmatic and psychological components. De Regt, on the other hand, individuates as his philosophical basis the view offered in Friedman (1974), where the pragmatic component of scientific explanation is not necessarily associated with subjectivism, since it can be shared by a class of scientists. The pragmatic component of scientific understanding, argues De Regt, comes from the necessity of adding some extra ingredients to the relation between explanans and explanandum —especially in contrast to the DN view, which derives the explanandum from a broader theoretical framework. These extra ingredients are the models that make the derivation possible, thereby acting as mediators between the theory and the phenomenon.[5] In addition, by acting as mediators, the models remain partly independent from both the theory and the data, and their construction will depend on skills involving approximations and idealizations that are proper of the individual scientist (or research group). Therefore, since scientific explanation requires models, and model-building requires pragmatic skills that are not contained in the theory (e.g., approximations and idealizations), scientific understanding involves a pragmatic component.

To clarify the distinction between the psychological component, the pragmatic component, and the adequate explanation of a phenomenon, (De Regt 2017, p. 23) defines:

- Phenomenology of Understanding (PU): It is the feeling of understanding that may accompany an explanation (e.g., an *aha!* or *eureka* experience).
- Understanding a Theory (UT): Corresponds to being able to use the theory. It is a pragmatic understanding that depends on the scientist or on the scientific community.

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[5] Such a characterization of models as mediators is not new, and it has been famously defended by Morgan and Morrison (1999).

- Understanding a Phenomenon (UP): Corresponds to having an adequate explanation of the phenomenon. It is associated with Hempel's account of scientific understanding and with his Deductive Nomological (DN) model.[6]

Intelligibility pertains to UT since it is concerned with the practical skills of the individual scientists (or the scientific community) and with the capacity of producing effective explanatory models. These practical skills, argues De Regt, are in general a tacit knowledge that can be acquired in social contexts.

In what sense an explanation provides an understanding of a given phenomenon? By taking as an example the kinetic theory of gases, (De Regt 2017, p. 46) maintains that "by connecting our empirical knowledge of gaseous behavior with accepted theoretical knowledge (in this case, e.g., with Newtonian mechanics) the explanation allows us to make inferences about the behavior of gases in novel situations, and to extend, apply, and refine our knowledge". Since the kinetic theory of gases is intelligible, scientists can build models to explain gaseous behaviors, thereby obtaining an understanding of such phenomena.[7]

Having provided a brief overview of De Regt's account, I will now move to comment of what I believe are the most evident differences with Feynman's theorizing. Most succinctly, I will argue that Feynman directed his inquiring enterprises toward the phenomena directly, and did not try to formulate explanatory models starting from a specific scientific context or established theories.[8]

2.2 Feynman's theorizing

It is the relation between UT and UP that marks the main difference between the view that De Regt is proposing about scientific understanding, and what I think characterizes the construction of Feynman diagrams. Indeed, the diagrams did not originate from the established theoretical framework commonly accepted by the scientific community, nor did they emerge from the implicit knowledge held by specific research groups. Perhaps, the strongest evidence in favor of this reading can be found in the reports of the Pocono conference (Pennsylvania) in 1948 in which Feynman presented his new approach to quantum electrodynamics:

> At each step he was asked to justify his procedure; instead he offered to work out a physical example to demonstrate the correct results it produced. But the audience objected to the time this would require and the hair [sic] involved, even though these had been drastically reduced by his methods. The culmination of his

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[6] De Regt specifies that in his account every explanation is an argument and that the DN model is thus one specific articulation.

[7] De Regt (2017) discusses the example in greater detail and shows how the phenomenological gas law $PV/T = const$, which describes particular gases phenomena, can be explained with the kinetic theory and representational models. The theory provides the general principles (for example: gases are composed of some particles subject to Newton's law of motion) and the representational model specifies some of the properties of the gas particles (e.g.: smooth, small elastic spheres).

[8] A word of caution: it would be naive to think that Feynman was entirely impermeable to the scientific context of his time, and that theories such as classical electrodynamics and Dirac's theory did not play a role as foundations and basis of his theorizing.

> audience's feeling that Feynman was running amok without being rigorous came when Niels Bohr stood up, objected to Feynman's use of trajectories for small particles, and started reminding him about Heisenberg's uncertainty principle. Here Feynman gave up in despair, realizing that he couldn't communicate the fact that his analysis was justified by its correct results (Schweber 1986, p. 495).

What the quote emphasizes is that the quantum mechanics community originally rejected Feynman's new approach, and part of the reason is that Feynman's presentation was too physical and lacked mathematical rigor:

> Feynman was prepared to present "this whole thing backward …not formally …with all physical ideas starting from path integrals" (Schweber 1986, p. 491)[9]

It is only in the subsequent years that the diagrams became accepted and started to be employed by different scientific communities (see: Kaiser, 2009), though their propagation was far from uniform. Indeed the diagrams did not come with a clear and unambiguous 'user's manual' and different scientists applied them to different sets of problems and under different assumptions —a further indication of the contextual aspects of scientific understanding advocated by De Regt.[10]

In addition, to witness a larger acceptance of the diagrams we have to wait for Dyson (1949a), who proved the equivalence between the method suggested by Feynman and that of Schwinger and Tomonaga. Then, (Dyson 1949b) formalized the diagrams in the form of rules (Feynman's rules), a step-by-step guide for calculating scattering amplitudes. As remarked by (Kaiser 2009, p. 76):

> [...] Dyson's pair of articles became a "how-to" guide, enumerating carefully the step-by-step rules for drawing Feynman's new diagrams and explaining how their bare lines were to be translated uniquely into the mathematical elements of scattering amplitudes. It was thus Dyson, and not Feynman, who first codified the rules for the diagrams' use —precisely what Feynman's frustrated audience had hoped to hear at the Pocono meeting a few months earlier.

However, Feynman and Dyson soon bestowed different meanings to the diagrams. On the one hand, Feynman believed that the diagrams could convey a representation (in spacetime) of quantum processes (more specifically: quantum scattering processes). On the other hand, Dyson considered the diagrams as a set of calculation tools and graphical representations of combinatorial possibilities —a view that is now considered as the received view.[11] It is again (Kaiser 2009) that remarks the history of the split between the two physicists:

> From the very beginning, Feynman and Dyson held different ideas about how the diagrams should be drawn, interpreted, and used [...] To Feynman, his new

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[9] Quoted from Feynman's interview with Schweber in 1980 Nov. 1st.

[10] During the 1940s and 1950s, different scientific communities attempted to use the diagrams to solve problems outside of the range of QED; a famous example is the use of the diagrams for calculating meson interactions and in general nuclear interactions.

[11] In this sense, Dyson seemed to value the diagrams because they made calculations easier, that is, they facilitated the use of the theory.

> diagrams provided pictures of actual physical processes, and hence added an intuitive dimension beyond furnishing a simple mnemonic calculational device. To Dyson, the line drawings were never more than "graphs on paper" handy for manipulating long strings of equations but not to be confused with the stuff of the real world (Kaiser 2009, p. 176).[12]

But, the peculiarity of Feynman's theorizing —the importance (and oftentimes priority) he assigned to finding representations of physical processes over the more mathematical and formal aspects of the results— was evident before the development of quantum electrodynamics. For example, the last section of Feynman (1948b) offers a tentative generalization of the quantum mechanics path integrals to relativistic moving particles. In that section, Feynman expresses his dissatisfaction with the derivation of the action functional for the Dirac equation because the results were purely formal:

> These results for spin and relativity are purely formal and add nothing to the understanding of these equations. There are other ways of obtaining the Dirac equation which offer some promises of giving a clearer physical interpretation to that important and beautiful equation (Feynman 1948b, p. 387).

Along these lines, (Wüthrich 2018, pp. 507-508) characterizes the search for 'clearer physical interpretation' as a dissatisfaction toward formal solutions, and an attitude that is: "after something like a model or mechanism of the processes that the formal apparatus was supposed to describe". Shortly after, Feynman will derive an action functional for the Dirac equation via the so-called quivering electron: an initially one-dimensional model of an electron moving either to the left or to the right on a lattice —where the probability amplitude was calculated based on the counting of those turns.[13] He will not be able to generalize his results to higher dimensions, but it remains that his attempts focused on a representation (quivering motion) of the processes described by the Dirac equation. Similarly, the absorber theory of radiation by Wheeler and Feynman (1945, 1949) offered a different interpretation of the radiation emitted by a charged particle in classical electrodynamics. There, Feynman imagined, and then developed, an action-at-a-distance theory in which charged particles act on other particles only, and the resulting interactions are half-advanced and half-retarded.[14] Finally, Feynman's interview reported in (Schweber 1986, p. 504) and (Schweber 1994, p. 465) further confirms the peculiarity of his theorizing:

> But visualization in some form or other is a vital part of my thinking and it isn't necessary I make a diagram like that. The diagram is really, in a certain sense, the picture that comes from trying to clarify visualization, which is a half-assed kind of vague, mixed with symbols. It is very difficult to explain, because it is not clear. […] It is hard to believe it, but I see these things not as

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[12] Arguably, Feynman's view on his diagrams changed over the years, see: (Mehra, 1994).

[13] That an electron as described by the Dirac equation oscillates around a mean trajectory was already suggested by Breit (1928) and Schrodinger (1930). Also, a thorough analysis of Feynman's quivering electron can be found in: Wüthrich (2010).

[14] The derivation of the theory and some of its philosophical implications are described in Forgione (2020a).

> mathematical expressions but a mixture of a mathematical expression wrapped into and around, in a vague way, around the object. […] Ordinarily I try to get the pictures clearer but in the end, the mathematics can take over and can be more efficient in communicating the idea than the picture. In certain particular problems that I have done it was necessary to continue the development of the picture as the method before the mathematics could really be found.

These historical examples show that Feynman mixed theoretical thinking with physical intuition, but they do not specify what this ‘physical intuition’ and ‘visualization’ amount to. The quote above indicates that the same Feynman struggled with giving a clear definition of his theorizing, he simply described ‘visualization’ as a fundamental part of it: one that is mixed with mathematical symbols, wrapped around objects. Yet, there is a common factor between all such examples: the use and production of what can be defined as a narrative of the physical processes that are being described. The term ‘narrative’, here, indicates those parts of a given model (or theory) that help us understand what is represented by that model (or theory). In this specific sense, narratives provide explanations by telling phenomenological stories that are warranted by the structure of the model (or theory), and by formulating a physical interpretation of the equations of the given model (or theory). For example, Morgan (2001) discusses the explanatory role of stories in economic models:[15]

> [...] the way models help us to understand the economic world in which we live in is by telling stories about the world. That story might be a story about the real world (past, present and future), or it may be a story about the hypothetical world portrayed in the model: the relationship of the story to the model structure is the same (Morgan 2001, p. 361).

We can thus characterize Feynman’s theorizing in the sense of first focusing on narrative explanations: on the production of phenomenological stories that are then turned into more formal theories.[16] Under this interpretation, De Regt’s view is almost reversed. Intelligibility pertains to those qualities of a theory that make the theory more usable. But, Feynman’s theorizing does not focus on qualities of a given theory, but on the search for narrative explanations starting from which a new theory can be developed. For example, with respect to the absorber theory of radiation: the phenomenological story describes how the radiative reaction of an accelerated charge is determined by the advanced and retarded radiation of the surrounding absorbers. It is starting from that ‘story’ that Feynman searched for an appropriate action functional and the ratios between the advanced and retarded radiation.[17] Similarly, the phenomenological story behind the quivering electron is that the motion of the electrons can be approximated by sharp turns on a lattice (a rapid oscillatory motion: quivering). Finally, most quantum processes can be described in terms of phenomeno-

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[15] The concept is introduced in, among others, Morgan (2001), Wise (2011) and Hartmann (1999)

[16] I should distinguish between ‘narrative explanation’ and ‘physical interpretation’ in that the latter applies to the terms of the former. For example, while a narrative explanation tells a story about scattering processes, the physical interpretation identifies wiggled lines as photons.

[17] Schweber (1994, p. 379) introduces the main tenets of the absorber theory of radiation as an idea that Feynman ‘fell deeply in love with’ in his undergraduate studies at MIT.

logical stories about collisions between 'microscopic particles' (see also: Valente, 2011 and Schweber, 1994).

Surely, one could maintain, perhaps in line with De Regt, that the diagrams, path integrals, or the quivering electron, were more intelligible than the more conventional theories. Then, because of the higher degree of intelligibility, they were more suitable for building explanatory models for certain phenomena. For example, one could maintain that the path integrals were conducive to formulate an explanatory model such as the photon exchange mechanism for the calculation of the Lamb Shift. However, such a reading disconnects the formulation of the path integrals method from Feynman's way of doing science, as remarked in the interview with Schweber.[18] Feynman did not develop the path integrals because quantum mechanics was unintelligible, nor did he focus on narrative explanations to facilitate the use of a given theory. Path integrals were obtained from the (failed) attempt to quantize the absorber theory of radiation, which was born from the intuition of representing a charged particle as both absorber and emitter of advanced and retarded radiations.

Let's take stock. Thus far, I have presented some historical examples of how the starting point of Feynman's theorizing was a vague idea of visualization and search for a physical interpretation. I suggested that these aspects can be all included in the idea of narrative explanations and production of phenomenological stories. But, these aspects inevitably raise a relevant question: what is the relationship between these forms of representation and the physical reality? For example, if the quivering electron is a model of the relativistic behavior of the electron, what does the 'quivering' represent in the physical system?[19] Similarly, Feynman's reinterpretation of Dirac's hole theory posits that positrons are electrons moving backward in time and that the phenomenon of pair-production is to be interpreted as the scattering forward and backward in time of the electron(s).[20] Is the moving back and forth in time a faithful representation of the motion of electrons? In other words, all these considerations naturally raise questions about the purchase on reality of Feynman's visual thinking and theorizing, and since positrons are not anymore considered as electrons moving backward in time, and since Feynman was ultimately dissatisfied with the quivering electron, in the second part of this paper I will focus on Feynman diagrams (Feynman, 1949a).

Notably, what follows is not intended as a definite word on a long lasting debate. Rather, I wish to open the possibility of interpreting the diagrams as weak forms of representation that convey a narrative explanation. My account will be only provi-

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[18] The calculation of the Lamb shift became relevant at the time because the difference in the $2p_{1/2}$ and $2s_{1/2}$ spectral lines of the hydrogen atom was experimentally detected, but a finite calculation starting from the theory was still missing. A more detailed historical reconstruction of those years is offered in: Mehra (1994), Schweber (1986), Wüthrich (2010), Valente (2020), and others.

[19] Originally, (Schrodinger 1930) distinguished between the macroscopic movement of the electron associated to its center of mass and interpreted the microscopic movement of the electron (the quivering motion) in analogy with spin —with the problem that such microscopic zig-zag motions would be faster than light. As argued in (Stöltzner 2018, pp. 488-489) : "Schrödinger was willing to consider a suitably modeled fluctuation as a genuine physical phenomenon even without possessing a 'mechanical' model of the microlevel from which such fluctuations would emerge".

[20] The idea that positrons move backward in time was suggested already by Wheeler, (see: Feynman, 1948a and by Stückelberg, 1941).

sional, for more work ought to be done in polishing the notions of weak representation and narrative explanations, and by comparing it to other possible accounts.[21]

3 Representations or not representations

With respect to Feynman diagrams, De Regt (2017, pp. 251-252) maintains that they provide: "a visualization of interaction processes, albeit one that cannot be taken as one-to-one representation of actual occurrences in nature. […] The visual Feynman diagrams functioned as conceptual tools that made quantum field theory more intelligible for most theoretical physicists. […] Rather than realistic representations of physical processes, Feynman diagrams are tools for solving problems and making calculations". The quote above remarks that diagrams do not have a relation with physical reality and that they are tools we use to calculate scattering amplitudes. While the instrumentalist attitude is not new in the literature (see, for example: Brown, 2018 and Dorato & Rossanese 2018), I argue that it might be too much of a cut-and-dried view. In what follows, I will suggest that Feynman diagrams can be taken to weakly represent some quantum phenomena.

We can divide the debate on the representational character of Feynman diagrams between two opposing positions: (1) the *naive*-realist view maintains that the diagrams are a faithful representation of the quantum phenomena they describe; (2) the instrumentalist view maintains that the diagrams are but a calculation tool with no representational properties —this view is also addressed as the *received view*. Notably, no one in the literature is openly supporting the former, while many seem to adhere to the latter (see: Brown, 2018; Dorato & Rossanese 2018; Baeyer, 1999 and others).

Even though the *naive* realist position is untenable, it is still worth asking whether Feynman diagrams represent at all. To answer the question we shall first consider two of the most common arguments supporting the instrumentalist view. The first of these arguments was also raised against Feynman at the Pocono conference and it caused the lackluster reception of his presentation. While the diagrams depict well-defined trajectories for the quantum objects, such trajectories are not possible in quantum mechanics due to Heisenberg's uncertainty principle. The argument is also mentioned in Brown (2018) and it rules out the possibility of a one-to-one representation of physical quantum processes:

> Feynman diagrams look like cloud chamber pictures, and they are often called space-time diagrams. This leads to the confusion. In fact, the diagrams do not picture physical processes at all. Instead, they represent probabilities (actually, probability amplitudes). The argument for this is very simple. In quantum mechanics (as normally understood) the Heisenberg uncertainty relations imply that no particle could have a position and a momentum simultaneously, which means there are no such things as trajectories, paths through space-time. So the lines in a Feynman diagram cannot be representations of particles and their actual path through space-time (Brown 2018, p. 430).

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[21] For a most recent survey on many such accounts, see: Lawler et al. (2022).

However, it is unlikely that Feynman was unaware of Heisenberg's uncertainty principle since, for example, he already discussed it in his dissertation with respect to the non-differentiable trajectories and path integrals. In addition, classical trajectories, analyzed at the quantum scale (in the order of $\hbar$), can be conceived of as bundles of possible paths in the neighborhood of a least action trajectory. As argued in Forgione (2020a), the representation of classical trajectories as single continuous differentiable paths is a consequence of the simplification warranted by scale-differences. Something similar happens when we use statistical mechanics to study the properties of macroscopic systems, rather than accounting for the motion of all microscopic component parts.

The main gist of the second argument against the realist view is that Feynman diagrams depict physical processes that are inaccessible to us. For example, Brown (2018) defends a dis-analogy between Feynman diagrams and free body diagrams: "[w]e start with the actual physical situation, which might be visible, or a fairly realistic diagram or photo. Then we draw a free body diagram. Usually this is a separate diagram, but it might be superimposed on the realistic picture. Finally, guided by the diagram, we attach numbers and use them in the appropriate equations to solve some problems of interest" (Brown 2018, p. 432). It is the superposition of the diagram to the photo that differentiates free-body diagrams from those representing inaccessible systems. Brown (2018) relates this difference to two different reasoning-patterns: one, that goes from the system (or its photo) to the diagram, and finally to the mathematics; the other one connects the diagrams to the mathematics without correspondence to physical reality. Clearly, since it is not possible to have a realistic picture of quantum mechanical processes, Brown (2018, p. 433) concludes that:"[t]he Feynman rules tell us how to link FDs [Feynman diagrams] to mathematics, but there is no guidance from the physical system". In other words, since the quantum physical systems are inaccessible, we can not draw a picture and pretend it is a representation of reality. At best, we can associate the elements of the diagrams to mathematical equations and use the former as calculation aids. It is then concluded that the role played by the diagrams is that of prescriptive flowcharts, namely, they are lists of instructions to calculate the scattering amplitude.

However, against the dis-analogy between free-body and Feynman diagrams, Wüthrich (2010, p. 14) maintains that: "the abstract drawing serves to articulate the relevant aspects of the physical situation and, at the same time, to derive relationships between the vector of forces acting on the sliding object. As far as their principal functions are concerned, Feynman diagrams are no different". Even though the function of these types of diagrams might be, if not the same, at least similar, it remains that quantum phenomena are not accessible in the same way as classical ones are. If the notion of representation of the free-body diagrams rests on their direct relation with accessible physical reality, perhaps Feynman diagrams are different in the degree of 'abstractedness' and on the selection of the represented qualities.

In this last part of the paper I will offer a tentative argument against the instrumentalist view, and I will make a case for the representational character of Feynman diagrams.

3.1 Weak representation

As a starting point for characterizing how Feynman diagrams represent, I shall consider a weak condition for representation as set forth in Van Fraassen (2010, p. 23):

> There is no representation except in the sense that some things are used, made, or taken, to represent some things as thus or so.[22]

The condition remarks the pragmatic aspect of representation and the consequent intention of a subject to use something to represent something else. However, unless we concede that everything can represent everything else insofar as there is an intention behind it, we need to introduce some condition of resemblance between the content of the representation and the object (or system being represented). For example, we take the free-body diagrams to be representative of classical systems in that they help us calculate the relevant forces applied to our system, even though we know from general relativity that gravity is not simply a force that pulls downward. Nonetheless, we still use such an approximation since it resembles the actual system well-enough to help us calculate relevant quantities. We know that the resemblance is acceptable because the quantities calculated by the theory are consistent with the measurements.[23] One could point out that the representational character of free-body diagrams is also susceptible to the objection raised against Feynman diagrams. But, if we accept that free-body diagrams represent, then the use of a one-to-one relation between the elements of the diagrams and physical reality is too strong of a condition to characterize the relation of representation.

Consider, for example, the painting: *A Sunday Afternoon on the Island of La Grande Jatte* by Georges Seurat. While the painting represents some people relaxing on an island in the Seine river, the persons depicted do not exist, nor did they exist. Therefore, we can not establish a one-to-one relation between the content of the painting and physical reality, and yet we maintain that the painting represents some people relaxing on La Grande Jatte. If we take the painting as a model of a Sunday on an island close to Paris in 1884, then we arrive at the same conclusion as (Van Fraassen 2010, p. 87): “A model often contains much that does not correspond to any observable feature in the domain. Then, from an empiricist point of view, the model’s structure must be taken to reveal structure in the observable phenomena, while the rest of the model must be serving that purpose indirectly”. The content of the painting tells the observer what a Sunday afternoon in Paris in 1884 on the Seine river looked like, and it would be wrong to derive, from that content, any ontological claim on the existence of the persons being depicted.

The takeaway is that the question of representation pertains to the epistemological domain, and not to the ontological one. The content of a representation does not necessarily reveal the ontology of the system being represented, and the epistemological value of a representation should not be equated to its ontology. Even without entering

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[22] I have addressed this pragmatic condition as ‘weak’ since it applies to both free-body diagrams and Feynman diagrams.

[23] It is not my intention here to discuss the conditions of resemblance. It is enough to say that such conditions cannot be of sameness and that they capture some structural qualities of the system represented and should be empirically adequate.

the debate on the distinction between ontology and epistemology, what I mean here is that what we infer from a given representation is not necessarily true or ontologically relevant. For example, Morgan (2001)'s definition of narrative specifies that the story told by the model/theory does not need to be 'true'. For example: by looking at a painting representing some people on the shore, we can infer that there were ten people on the shore that day. The inference would be true according to what we see in the painting. However, this does not rule out the possibility that, in reality, that day, there were only eight people on the shore, and that the painting is not entirely truthful.

How should we apply such considerations to the case of Feynman diagrams? Meynell (2008) discusses the relation between representation and denotation and emphasizes how equating the former to the latter is tantamount to confusing the epistemological value of the diagrams with the question about the ontology of QED. To escape the confusion, she resorts to Walton (1990)'s theory of representation wherein representations act as props in games of make-believe, and where the term 'game' implies the existence of rules which determine what we are to imagine by viewing a picture.[24] These rules (alternatively, 'principles of generation') are broadly construed and they encompass habits, psychology, and social conventions: "principles of generation, whether or not we call them rules, constitute conditional prescriptions about what is to be imagined in what circumstance" (Walton 1990, p. 41).

When pictures are viewed properly, we do not simply imagine us seeing what the pictures depicts, but rather, we already imaginatively see the objects of the picture. Using the painting *The Water Mill with the Great Red Roof* by Meindert Hobbema, Walton explains that: "the viewer imagines seeing a mill, not just that he sees one and he imagines this from the inside [...] in seeing the canvas he imaginatively sees the mill [...] The analogies I am interested in hold between the process of inspecting pictures to ascertain what is fictional and the process of inspecting reality to ascertain what is true, between visual investigations of picture worlds and visual investigations of the real world" (Walton 1990, pp. 293, 304). Therefore, concludes (Meynell 2008, p. 51):

> How we inspect Feynman diagrams so as to understand what is fictional in a given diagram is akin to how a physicist inspects bubble-chamber photographs (and diagrams) so as to understand what is true in the experiments she performs [...] The realism associated with Feynman diagrams is not attained through denoting but through prompting imagining of particles and processes that we make-believe are the case.

For example, Feynman presents his theory of positron by introducing a change of perspective with respect to Dirac's hole theory. Instead of following the motion of the electron 'step-by-step', Feynman suggests to follow the entirety of the charge within a defined spacetime boundary:

> Following the charge rather than the particles corresponds to considering the 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 the two of them come together and disappear again that he realizes that

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[24] Walton (1990, p. 295) distinguishes between representations in general and visual representations, which are called depictions.

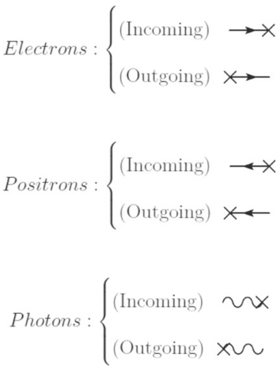
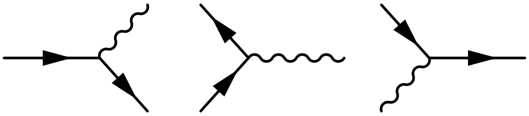


Fig. 1 Correspondence rules between graphical terms and electrons, positrons and photons

> he has simply passed over a long switchback in a single road (Feynman 1949b, p. 749).

The analogy of the bombardier constitutes a descriptive narrative which provides us with an intuitive idea of how certain phenomena might work.[25] However, it does not constitute a very helpful narrative, for it cannot be modified according to well-defined rules or principles of generation. Feynman diagrams, on the other hand, come with specific rules which dictate how the different parts of the diagrams combine with one another and how to calculate the scattering amplitude. For example, Feynman diagrams comprise notation rules such as: "[t]o each *external* line associate a momentum $p_1, p_2, \ldots p_n$, and draw an arrow next to the line, indicating the positive direction (forward in time)" (Griffiths 1984, p. 243). At the same time, other rules establish a correspondence between diagrammatic elements and mathematical terms. For example, each *vertex* of a diagram contributes a factor $ig_e\gamma^\mu$ where g_e is the coupling constant and γ^μ is the Dirac matrix. Finally, the diagrams come with interpretation rules which assign a physical interpretation to the diagrammatic terms. Some examples are listed in Fig. 1.[26]

These representation rules act as principles of generations for the explanatory narratives of the quantum phenomena. For example, the diagrams:



can represent respectively the emission of a photon by an electron, an electron-positron annihilation, and an electron absorbing a photon (in these diagrams the time-direction

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[25] Notably, Feynman will address his new perspective of 'following the charge' as an overall spacetime point of view, analogous to the one for path integrals and absorber theory.

[26] Notably, Feynman rules should not be considered as 'happening in a vacuum'. That is, the rules in themselves do not constitute a theory and thus should be considered in the context of quantum mechanics. For example: since quantum mechanics rejects the classical notion of a trajectory, we should not interpret the straight lines of the diagrams as individual paths.

is from left to right). One can start from the leading-order-diagrams to calculate the first terms of the perturbation series and then manipulate the diagrams to calculate the higher orders in the series. In this sense, the diagrams seem to offer a form of understanding of the quantum (scattering) phenomena that Meynell (2018, p. 477) describes as:

> To say that FDs [Feynman diagrams] offer 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.

More specifically, Feynman's formulation provided both the understanding of the subatomic realm and the means to calculate the proper scattering amplitudes. Indeed, Dyson proved the diagrams to be equivalent to the theory of Schwinger and Tomonaga, and thus confirmed the partial independence of the diagrams from the formulation of the time: "[…] the theory of Feynman differs so profoundly in its formulation from that of Tomonaga and Schwinger […] The advantages of the Feynman theory are simplicity and ease of application, while those of Tomonaga-Schwinger are generality and theoretical completeness" (Dyson 1949a, p. 486).[27]

In sum, the diagrams come with a descriptive narrative of the scattering processes. They are used as an aid to the calculation of the proper scattering amplitudes in that the principles of generation (Feynman rules) provide us with both the rules for the graphical combinatorics and the correspondence with the proper mathematical terms. This twofold role is addressed also by Harlander (2021) and Stöltzner (2022) in terms of topology and physical specification —the former corresponds to the graphical content and the latter to the mathematical terms. In those terms, the topology of the diagrams — which specifies the relations between the particles involved— is what we interpret in terms of explanatory narratives and physical interpretation of the scattering event.[28]

> Diagrams […] not only visualize the individual terms of the perturbation series; one can actually construct the series from these diagrams, without having to use the path integral anymore […] Feynman diagrams and the associated rules not only serve as a tool to do calculations within particle models. They actually *encode* the particle model, including its QFT character (Harlander 2021, pp. 15097-15101).

One could still contend that since the diagrams are not one-to-one representations of physical processes, the representational character is only fortuitous or *ad-hoc*. But, let us consider how (Harlander, 2021) compares diagrams representing a process of electron-positron annihilation and the corresponding measured cross-section in

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[27] This is to reiterate that Feynman's theorizing was independent from other approaches, and that it focused on the intuitive understanding of quantum phenomena.

[28] I will not discuss here the epistemic value of Feynman diagrams, nor their explanatory virtues. It remains that they are being used as models to describe phenomena, although only heuristically. This seems to reinforce the idea that they can also be considered as representations (although weak) of quantum processes.

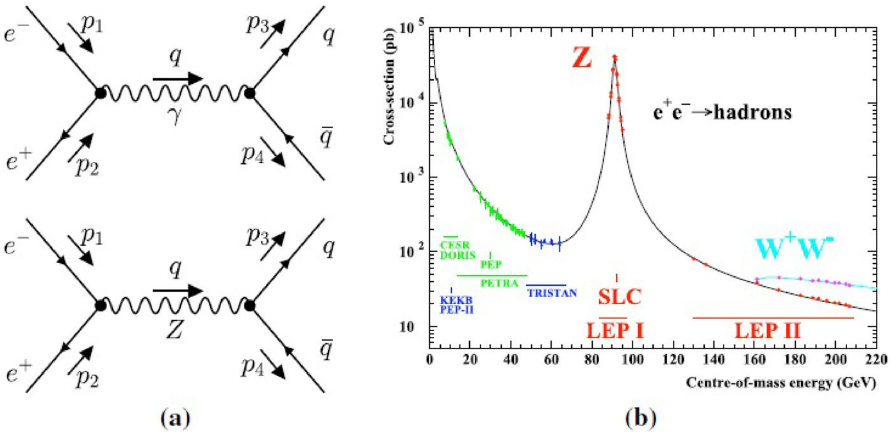

Fig. 2 (a) Feynman diagrams of leading term for the process of electron-positron annihilation into quark and anti-quark pair. (b) Corresponding measured cross-section. (Harlander 2021, p. 15101)

Fig. 2. There, we have the s-channel diagrams for the process $e^+e^- \to q\bar{q}$ with amplitude (Harlander 2021, p. 15101):

$$A_{e^+e^-\to q\bar{q}} \sim \frac{i}{s} + C\frac{i}{s - M_Z^2} \tag{1}$$

where C is a constant. From the form of the amplitude, the cross-section should exhibit peaks around $\sqrt{s} = 0$ and $\sqrt{s} \sim M_Z$, and, although the diagrams in Fig. 2(a) correspond to the leading terms only, "this peculiar behavior of the cross section somewhat suggests that the Z boson (and the photon, or their respective quantum fields) does play a special role in this process. Even though it leaves no physical track in the detector, the peak signals the existence of the Z boson" (Harlander 2021, p. 15102). This seems quite strong of an evidence for the representational role of the diagrams, since the virtual particles represented as internal lines have a correspondence in the measured cross-section. However, we need to be cautious: asking to what extent the Z boson exists as a particle in spacetime is similar to asking which slit the electron traversed in the double-slit experiment. Yet, we still regard the images of the double-slit experiment in our textbooks as representing a physical situation, we simply accept that we are faced with a classical representation of a quantum phenomenon.

The correlation between the diagrams and the cross-section on Fig. 2 presents a further difficulty. Indeed, the plot on the right is the result of a complicated unfolding process which involves, for example, the subtraction of the interference effects. These effects are not accounted for in the diagrams, thereby reinforcing the idea that they are not representations of the underlying physics.[29] I shall discuss these objections in the next section.

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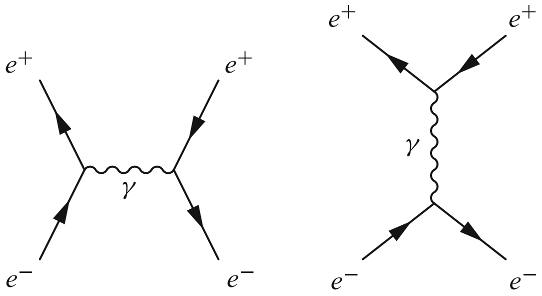
[29] I thank an anonymous reviewer for stressing this point in an earlier version of this paper.

3.2 Challenges and possible responses

Here, I shall consider a number of possible problems and challenges to the view thus far presented. The first problem is that the event described by a perturbative expansion is not associated to a single diagram. As a matter of fact, if we wanted a better representation of a scattering event *via* Feynman Diagrams we would need to include the higher-order terms in the perturbative expansion. As a consequence, we would represent a scattering event with a large number of diagrams. As (Harlander 2021, p. 15103) puts it: "the number of diagrams roughly increases factorially with the order of perturbation theory. In current calculations it is no exception that the number of diagrams to be evaluated is of the order of a million".[30]

On a smaller scale, consider, for example, an electron-positron scattering, namely, the event: $e^- + e^+ \to e^- + e^+$. The second order expansion corresponds to the two diagrams:



(2)

Since each diagram can be associated with a different narrative of what happens between the in-going and out-going states, we may ask which one is the actual representation of the scattering event. The question, though, implies that the representation should tell us about the ontology of the theory, and, along with Van Fraassen (2010) and Meynell (2018), I have maintained that we should separate the content of a representation from the ontology of what is represented. Both diagrams represent the event $e^- + e^+ \to e^- + e^+$, and they are both needed for the calculation of the scattering amplitude. For example, while the first diagram in (1) tells us about the annihilation of an electron-positron pair, followed by an electron-positron pair creation, we should not infer that electrons, positrons, and photons travel in straight-line trajectories, or that incoming and outgoing objects are as long lived as the objects represented by the internal lines (in this case, a (virtual) photon). Nonetheless, what we can infer from the diagrams is that a positron and electron have interacted via exchange of a virtual particle (photon), and this is analogous to how the diagrams in Fig. 2 track the relations between the entities involved, as also confirmed by the behavior of the corresponding

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[30] Some proponents of the superposition argument (see: Fox, 2008 and Weingard, 1988) relied on the infinite expansion of the S-matrix as an argument for the status of mathematical fiction of the virtual quanta. However, in practical uses of the theory, only a finite number of terms is calculated in the expansion. For further discussion on this see: Valente (2011).

cross section.[31] In other words, we can infer the relations between the different players of the scattering event via explanatory narrative, and we thereby obtain a form of understanding of the quantum phenomena under consideration.

Most recently, Passon (2019) has offered a more sophisticated version of the previous problem, one that is split into three distinct (and yet connected) arguments: (i) the superposition argument: (ii) the virtual particles argument, and (iii) the topological equivalence argument. Because these three problems are perhaps the strongest objections to the view presented here, I shall consider them one by one.

The main point in Passon (2019) is to demonstrate that Feynman diagrams visualize formulae and not physical processes, and this amounts to showing "why properties of Feynmamn diagrams are at odds with any representational or modeling function with regard to the underlying physical process" (Passon 2019, p. 7). What is the role of Feynman diagrams then, if they offer no representation of the underlying physical processes? Passon (2019, p. 8) answers with the following:

> Feynman diagrams are a tool to facilitate these calculations considerably. Each element of the calculation can be graphically displayed by a line or vertices between lines. Incoming and outgoing lines represent asymptotically free states and correspond to Dirac spinors (fermions) or polarization vectors (photons) in the calculation. The lines are directed to distinguish between particles and antiparticles. Internal lines correspond to propagator of Green's function $G(x - x')$ in the calculation of the S matrix element. They represent 'virtual particles', i.e. states which do not have to obey to the relativistic energy-momentum relation.

As a response to the previous quotation, one could already argue that even within an interpretation that takes the diagrams to be representing mathematical terms only, Passon is forced to refer back to terms that indicate physical entities that are graphically distinguished in the diagrams (for example: particles and antiparticles). In addition, because of the correspondence between elements of the diagrams and mathematical terms, to deny any relation between the diagrams and physical reality might also suggest the rejection of any relation between the mathematical terms used by the theory and physical reality. However, this calls for a much deeper and longer discussion about the representational character of mathematics which I shall not start here. It should be enough to assume the existence of some unspecified form of representation between mathematical terms of a given physical theory, and the elements of reality interested by that theory.[32]

The first argument against the view that Feynman diagrams represent is the *argument from superposition*. This exploits the fact that the transition amplitude of a given scattering event is calculated via perturbative expansion. Each diagram, up to a given order, represents a term in the perturbative expansion, and the probability for a scattering event is calculated by the square of the transition amplitude. Passon (2019)

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[31] Notably, the problem of having many diagrams depends on the problem of having infinitely many terms in the perturbative expansion. The problem is tightly connected with the use or renormalization techniques to tame the infinities. However, the discussion of such aspects of the theory goes beyond the purpose of the present paper.

[32] Without any such relation, the effectiveness of mathematics might appear as a miracle.

argues that to interpret a single term in the sum as a physical process amounts to ignoring the interference effects that are related to all terms in the superposition. Yet, one might answer that there are cases in which a single diagram can be considered as dominant (leading order terms) and as such as ‘more representative’ (see: Valente, 2011). However, at the same time, “[...] there are many cases in which the leading order calculation involves more than one Feynman diagram already” (Passon 2019, p. 10). This implies that, under a literal reading, many processes would contribute to the same transition amplitude, thereby determining that a single diagram (corresponding to a single term) does not represent a physical process.

The argument from superposition has also been used in relation to the notion of *virtual particles*, for example: (Weingard 1982; Fox 2008; Jaeger 2019). The peculiarity of virtual particles, which are represented as internal lines in a Feynman diagram, is that they seem to violate the relativistic energy-momentum relation. Weingard (1982) and Fox (2008) argue that, due to the superposition states, the number and type of virtual particles is indefinite and thus they are simply artifacts of perturbation theory. Thus, virtual particles can be at best considered as fictitious elements of the model/theory, but as mere-fictions they play no explanatory role.[33]

Against this latter point, Jaeger (2019) defends the view that virtual particles should be considered as real as ‘regular’ particles in quantum field theory. The position is even stronger than what is defended in Falkenburg (2007), where virtual particles are not entirely fictitious, but rather have an operational meaning: “The virtual processes described in terms of the emission and absorption of virtual particles contribute to a scattering amplitude or transition probability. Hence, infinitely many virtual particles together may be considered to cause a real collective effect” (Falkenburg 2007, p. 237). One of the examples cited in Jaeger (2019, p. 14) in support of a more realistic view can be found in Hanzel and Martin (1984, p. 197) and involves the exploration of the internal structure of the proton: “Having measured the size of the proton [with an electron beam] […] [we] take a look at its structure by increasing the [momentum] of the [virtual] photon to give better spatial resolution”. The role of the virtual particle in the cited example is not only of a fictitious entity, but of an entity that produces observational consequences, thereby supporting the realist view.[34]

Perhaps, the response that aligns best with the first part of this paper, and with the view that Feynman had of his diagrams, is also a response to the superposition argument. The crucial point is that the superposition argument rests on a peculiar feature that is proper of quantum mechanics and that is at odds with our classical intuition. That Feynman diagrams are classical descriptions of quantum processes is clear since: they are drawn on a classical medium, they represent the motion of

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[33] Whether the fictitious elements of a model play no explanatory role in that model is debatable. For example, in his recent book, Rice (2021) has argued that the idealized and fictitious elements of a model cannot be disentangled from their real counterparts, and that idealizations and fictions play a relevant role in the explanatory power of that given model.

[34] Another noteworthy position is raised in Harré (1988), where there is a physical distinction between real and virtual particles. There, virtual particles are defined as: “[…]” referent of an expression, analogous to that for real particles, for which, could we construct a track-yielding apparatus, would afford a track or tracks (Harré 1988, p. 71). Notably the debate on virtual particles was and still is a prolific one. While I will not review it here, one can refer to Fox (2008), Jaeger (2019), Valente (2011), and references therein.

quantum objects with straight lines, and they represent quantum particles as point-like objects. Thus, we should be mindful that some of the quantum properties of (quantum) phenomena might not be represented by a classical description. But, this does not necessarily imply that what is being described by the diagrams is not a physical process. A similar argument is suggested also in Valente (2011, p. 49):

> [...] we have only one global process described by this one Feynman diagram, corresponding to the black box calculation of localized 'processes', which are mathematical artifacts resulting from the point-like description of the interaction between the quantum fields [...] This does not entail that the exchange of quanta cannot be regarded (in some way) as a physical process, simply that is not a physical process in the classical sense of space-time processes that we have in classical theories.

The difficulty of visualizing (and interpreting) physical processes in quantum mechanics is (also) made evident by the history of how Feynman developed his diagrams. The so-called overall spacetime view suggests to regard a quantum physical process in the entirety of its possibilities (and temporal extension), such as, for example, in the case of the ensemble of possible trajectories in the path integrals, or the sum of possible processes (and thus Feynman diagrams) in the case of the perturbative expansion in quantum electrodynamics (and quantum field theory).[35] The point is analogous to the one I raised at the beginning of Section 3, where I sketched the apparent incompatibility between the lack of real trajectories in quantum mechanics and the use of straight lines in Feynman diagrams. There, Brown (2018) acknowledges that the objection raised against Feynman at the Pocono conference was ill-directed, and that the diagrams could not represent definite trajectories due to Heisenberg's principle. At the same time, Brown (2018) concludes that the diagrams do not represent physical processes in general. But, as I mentioned earlier, the fact that the diagrams are classical descriptions of non-classical processes does not entail that they cannot be representations of such processes, but only that the representation can be at best approximate or partial. The notion of weak representation defended here makes explicit the necessity of giving new interpretative rules to media (the diagrams) that operate at the classical scale, but represent quantum phenomena. The fact that multiple diagrams are needed to offer a better representation of a given scattering event is not detrimental to the representation role played by the diagrams, but a further evidence of the non-classical nature of those events.

The last argument presented in Passon (2019, p. 12) is the argument from topological equivalence: "Feynman diagrams which can be continuously deformed into each other while leaving the in- and out coming states unchanged are called 'topologically equivalent'". Diagrams that are topologically equivalent calculate the same amplitude, thereby constituting a sort of class of equivalence in which one diagram is representative of the whole equivalence class. What is relevant to the use of topologically equivalent diagrams against the representational view is that the diagrams within the same 'class' might tell very different stories. This is true, for example, of the diagrams depicted in Eq. 3. The stories conveyed by the two diagrams are different, but, because

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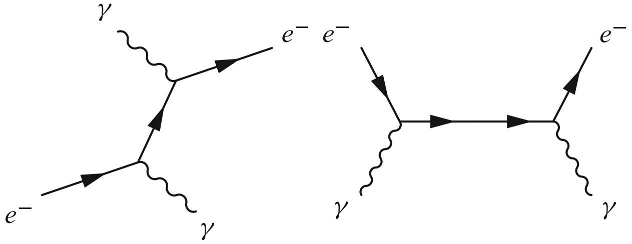
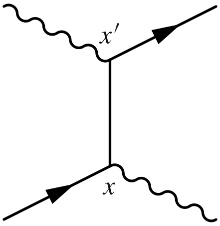
[35] The notion of 'overall spacetime view' is used in Feynman (1966b) and analyzed in Forgione (2022).

the calculated amplitude is the same, neither can be considered as accurately depicting the underlying process.



(3)

Indeed, the second order (topologically equivalent) diagrams for Compton scattering (above) can tell us very different stories with respect to what happens to the particles step-by-step. The first diagram (on the left) tells us that an electron first emits a photon and then another photon is absorbed, while the second diagram (on the right) tells us that an electron first absorbs a photon and then the photon is emitted. While this reading of the diagrams is compatible with the principles of generation of Feynman rules, it is not compatible with the context of quantum field theory (and quantum mechanics in general), and the former is not possible without the latter. As a matter of fact, the two diagrams above are different in their time orientation, but as pointed out in Mandl and Shaw (2010, p. 68): "The fermion propagator [...] includes both the contributions from Eq. 3 [Figs. 4.2(a) and (b) in the original], and we represent it by the single diagram in Eq. 4 [Fig 4.3 in the original], in which no time ordering of the vertices x and x' is implied, and consequently no time direction is attached to the internal fermion line joining x' and x."



(4)

This means that not all diagrams that can be built according to the principles of generation have a representation function with respect to the underlying processes. This, again, should not be surprising since the diagrams do not constitute a theory in themselves, but they operate in the context of quantum field theory. In addition, it is not the case that any diagram can be deformed into any other. For example, we cannot turn one of the two topologically equivalent diagrams for Compton scattering into the diagrams for the Higgs decay channel. This implies that not all diagrams can stand for any process, and thus that there is a relation between specific underlying processes and specific (classes of) diagrams. This relation is of weak representation, since topologically equivalent diagrams tell us possible stories about the unfolding of a given process, and some structural facts that are common to all those stories (for example: the in- and out- states, or the exchange of virtual particles).

A further objection could be that the example I mentioned earlier from Harlander (2021) is too simplified. Indeed, Passon (2019) argues that the interference effects with the background are not accounted for by the diagrams, although they play a significant role in the data analysis for those scattering events. The argument is presented in relation to the discovery of the Higgs boson where "[…] in principle the Higgs mass can not be measured by directly fitting the mass-distribution in the corresponding plot, but only by comparing the Standard Model prediction […] with the obtained distribution". The case bears many similarities with the $e^+e^- \to q\bar{q}$ case presented earlier. That is, the Z boson cannot be observed in isolation, and the plot is the result of a complicated un-folding process. With respect to the Higgs decay channel $H \to ZZ \to 4l$: "The interference between Higgs and background processes demonstrate that the whole talk about 'Higgs decay channels' holds only approximately. The term 'channel' suggests that all events can be grouped into disjoint classes, while actually interference takes place between signal and background contributions if the final states are the same" (Passon 2019, p. 17). This, according to Passon, reinforces the idea that the diagrams represent terms in the perturbative expansion, and not actual physical processes. Yet, the argument is very similar to that of topological equivalence and superposition, which both criticize the representational character of the diagrams without considering that we are representing quantum processes. Again, that the diagrams offer a weak representation in terms of conveying narratives from some principles of generation is valid within the context of quantum field theory.[36]

From this very last point, we can think of another possible and more general objection: one could argue that we cannot use the diagrams to pictorially represent quantum phenomena because we lack a clear definition of phenomena in the first place. Perhaps, and this is only a tentative answer, we can escape the impasse by relying on the distinction between raw-data and phenomena defended in Bogen and Woodward (1988) —and applied by Mättig and Stöltzner (2020) to elementary particle physics. Data, it is argued, are evidence for phenomena and phenomena are evidence for a theory. Data can be observed as 'clicks' on the experimental apparatus and thus they are "idiosyncratic to particular experimental contexts, and typically cannot occur outside of those contexts" (Bogen and Woodward 1988, p. 317). Phenomena, on the other hand, are mostly inferred from collections of data organized in appropriate data-models, but we remain incapable, for the most part, of experiencing such phenomena with our senses. We could decide that the only possible representations are representations of the data we experience with our senses, but this would yield a very narrow notion of representation. Alternatively, we could cast the distinction between raw-data, phenomena, and theory, in the context of Fig. 2, where the measurements are plotted on a graph that shows two spikes at around $\sqrt{0}$ and $\sqrt{M_Z}$.[37] If, together with Bogen and Wood-

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[36] For example, the cross-terms from the squaring of the transition amplitude do not have corresponding diagrams. In this sense, if we wanted a more 'accurate' representation of the scattering event, we should draw all the diagrams corresponding to the terms in the perturbative series and the interferences among them.

[37] It remains, as I have mentioned earlier, that even the plot in Fig. 2 is the result of data-analysis and subtraction of background interferences.

ward (1988) and Mättig and Stöltzner (2020), we concede that the role of a theory is to explain and predict phenomena, rather than raw-data, then Feynman diagrams are tools to explain and predict quantum phenomena. They accomplish this by enabling the derivation of appropriate equations which are substantiated by empirical data from particle accelerators. Therefore, while the theory predicts phenomena through computation of relevant quantities, the diagrams provide a weak representation in the form of narratives.

4 Conclusion

In the first part of this paper I have characterized Feynman's theorizing as focused on quantum phenomena rather than on theories. I have maintained, against (De Regt 2017), that Feynman tried to understand and visualize the phenomena, and that such attempts contributed to the development of his famous diagrams. Afterward, I have discussed whether we can take Feynman diagrams to be representations of quantum phenomena. I have discussed a pragmatic notion of representation offered in Van Fraassen (2010) and the theory of representation laid out by Walton (1990) —and applied to the diagrams by Meynell (2018). Together, they offer us a coherent interpretation of the representational character of the diagrams. The principles of generation constrain what we can imagine is happening at the quantum level (for a specific event), though without demanding a denotation between what is imagined and the actual physical reality (the ontology).

While the diagrams can be said to be representative of some quantum phenomena, they still remain neutral with respect to the ontology of the theory. I maintained that, despite their ontological neutrality, the diagrams say something about what happens at the quantum level, and that their narrative is corroborated by the measurements. That this is the case is shown by Harlander (2021) through the example of the electron-positron annihilation in Fig. 2. The fact that what is depicted as a Z-boson in the diagrams has a correspondence in the measured cross-section suggests a correspondence between the depicted diagram and the event being measured by the detectors. Therefore, under the conditions that a representation is an intentional act, and that it does not imply a one-to-one correspondence between its content and physical reality, I conclude that Feynman diagrams are indeed weak representations of physical phenomena.

In the last part of the paper, I have discussed a number of possible objections to the representational view. More specifically, I discussed the superposition argument, the virtual particles argument, and the argument from topological equivalence as offered in Passon (2019) and others. What emerged from the discussion is that the representational character of the diagrams needs to be characterized in relation to quantum field theory, that is, we need to be mindful of the fact that we are using a classical mean to represent quantum phenomena. This only reinforces the idea that the type of representation offered by the diagrams can only be weak.

One final consideration. One might still object that the representational character of the diagrams comes from the effectiveness of our mathematics. The objection, I believe, can be quite strong, since it would involve explaining why perturbation theory works so well for some theories rather than others. In addition, this would open up a much larger discussion on the representational character of mathematical terms in scientific theories. I briefly mentioned this issue on Section 3.2, but I reckon that more work needs to be done and that it might be relevant to the view suggested here.

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