Feynman diagrams as metaphors: borrowing the particle physicist's imagery for science communication purposes

A Pascolini[1,2] **and M Pietroni**[2]

[1] Dipartimento di Fisica 'G Galilei', Università di Padova, via F Marzolo 8, I-35131 Padova, Italy
[2] Istituto Nazionale di Fisica Nucleare, via F Marzolo 8, I-35131 Padova, Italy

Abstract
We report on an educational project in particle physics based on Feynman diagrams. By dropping the mathematical aspect of the method and keeping just the iconic one, it is possible to convey many different concepts from the world of elementary particles, such as antimatter, conservation laws, particle creation and destruction, real and virtual particles, and so on. We have created a construction toy in which the rules of the graphic representation are translated into mechanical constraints between the toy elements.

We report and discuss the results of public demonstrations with high school students.

It is common wisdom that Quantum Mechanics and Quantum Field Theory—the frameworks describing the world of elementary particles—are too abstract and mathematical to be communicated to the general public or to high school students. From the science communicator's perspective, the major problem lies in the difficulty of relating the bizarre behaviours of subatomic particles to everyday perceptions and experiences. Metaphors taken from the macroscopic world can convey only a very superficial account of what really goes on in the microscopic world, and they offer no access to the subtleties of genuine quantum behaviour.

For instance, the popular representation of the hydrogen atom as a miniature planetary system—Rutherford's model—correctly exhibits the fact that the positive charge is concentrated in massive particles localized at the centre of the atom, whereas lighter negative particles can be found much further away. But as soon as one tries to understand the discreteness of atomic spectra or to extend the model to the next atom in the periodic table, helium, this simple representation turns out to be completely ineffective. One is then forced to abandon the picture—in which protons and electrons are essentially charged billiard balls with well-defined trajectories—but the substitute is not obvious at all.

Similar problems are found in the description of such phenomena as particle interactions, creation, decay, and so on. There are no images, it seems, to visualize the world of elementary particles in a conceptual way that is not misleading [1].

On the other hand, professional particle physicists do not think exclusively in terms of crude mathematical formulas. Indeed, their discussions and their papers are full of images,

0031-9120/02/040324+05$30.00

the so-called Feynman diagrams. Feynman diagrams form the representational system that describes particle interactions as governed by quantum field theory. They were introduced by Richard P Feynman in the late 1940s, and today they are a fundamental professional tool for any particle physicist. Each diagram—constructed according to well-defined rules—represents a possible physical process and, making it so valuable to physicists, it can be unambiguously translated into a mathematical expression, giving the probability for that process. On the other hand, even before the translation into mathematics is done, a lot of useful information on the process can be extracted just from a visual inspection of the diagram, such as its existence in a given theory, its analogies with and differences from similar processes, and so on. A skilled theoretical physicist has typically developed an intuition based on Feynman diagrams, which allows him to postpone the actual computation to the very last stage of the work, when all the main physical considerations have already been made by mental manipulation of the diagrams.

In this article we report on an educational project in particle physics based on Feynman diagrams. Our purpose was to avoid the usual misconceptions that one is led to by imposing images from the familiar macroscopic world on the microscopic one (as in the planetary model of the atom). Instead, we decided to exploit those images that are *generated* by the mathematics of quantum field theory, that is Feynman diagrams, which we thought could play the role of accurate metaphors. Our bet was that, even without the long training required to master the mathematics of quantum field theories, a typical high school student could grasp a lot of information about the world of elementary particles, such as the relation between matter and antimatter, the indistinguibility of identical particles, the existence of *virtual* particles and their role as *mediators* of interactions, and so on.

We have taken Feynman diagrams out from particle physicists' blackboards and papers and brought them into the classrooms. In the process, we have materialized them by creating a construction toy with three kinds of elements: electrons, photons and interaction vertices. The rules of Quantum Electrodynamics (QED) were translated into mechanical constraints, allowing some configurations—corresponding to physical processes—and forbidding others—corresponding, for instance, to unphysical processes in which electric charge is not conserved. The manipulative aspect of the game turned out to be a key feature in the success of the project; it was extremely effective in lowering the barrier preventing people from getting interested in such a remote subject as particle physics. The meaning and use of Feynman diagrams have recently been described in this journal [2], so we will not discuss them here. Before reporting on the results of our project, we will instead briefly discuss the use of Feynman diagrams as tools for science communication.

What is it possible to communicate by using Feynman diagrams?

Here is the crucial question behind our project. Feynman diagrams are a fundamental working tool for professional particle physicists, who exploit both aspects of the method: its close relation to the mathematical structure of the theory, and its iconic content, which makes it possible to visualize subatomic processes in an effective way. To what extent may these properties be exploited in a science communication context? What are the messages that can be conveyed to a general public by using Feynman diagrams?

In order to answer these questions one must first identify what are the aspects of Quantum Field Theory that are genuinely new with respect to classical physics, and so require metaphors of a radically new type to be described. In an essay appearing in the special issue of *Reviews of Modern Physics* for the centennial of the American Physical Society, Frank Wilczek gives a list of such features [3]:

(a) *Identical particles*: elementary particles of the same type are not distinguishable, either in practice or in principle. The fundamental reality is the 'electron field', or the 'photon field', the particles being just excitations of it. In the language of Feynman diagrams, this property is manifest in the possibility of interchanging the roles of two lines of the same type (e.g. two photon lines) to get exactly the same process.

(b) *Matter and antimatter:* mathematically, electrons and positrons are two closely related solutions. One is obtained from the other by exchanging the sign of time[1]. In the language of Feynman diagrams, electron and positron are given by the *same* line, only its orientation with respect to the time direction changes. The photon has no antiparticle (in other words, the photon coincides with the 'antiphoton'), which corresponds to the absence of any preferred direction on the photon leg.

(c) *Particle creation and destruction*: any interaction between elementary particles proceeds via creation or destruction of some particle. This is evident from inspection of the fundamental vertex of QED (see next paragraph).

(d) *Virtual particles as messengers*: in Quantum Field Theory, the effect of the electromagnetic field is interpreted as the exchange of 'virtual' photons. The electron can act as an intermediate particle too, mediating an interaction between a real photon and a real electron. The same scheme works in the Electroweak Theory and in Quantum Chromodynamics, with W and Z bosons, gluons, quarks etc, acting as mediators. The concept of virtual particles is self-explanatory in the language of Feynman diagrams; it is sufficient to draw the user's attention to the difference between those lines that have a free end (real particles) and those where both ends terminate on a vertex (virtual ones).

(e) *Conservation laws*: creation and destruction make it possible for the total number of particles to vary between the initial and final states of a certain process. For instance, in figure 1 two initial electrons give rise to six final particles, i.e. three electrons, one positron and two photons. The total number of particles is not a conserved quantity. On the other hand, if one adds up the electric charges in the initial state ($-2e$) and final state ($-3e + 1e + 2 \times 0 = -2e$), it turns out that they are the same. Total electric charge *is* a conserved quantity. Working with our toy for Feynman diagrams, one might be asked to compose the diagram for an impossible process, such as $e^+e^- \rightarrow e^-e^-$. The mechanical constraints mean that only the correct vertices may be formed, so that after a number of unsuccessful tries, one is led to realize the existence of the conservation law.

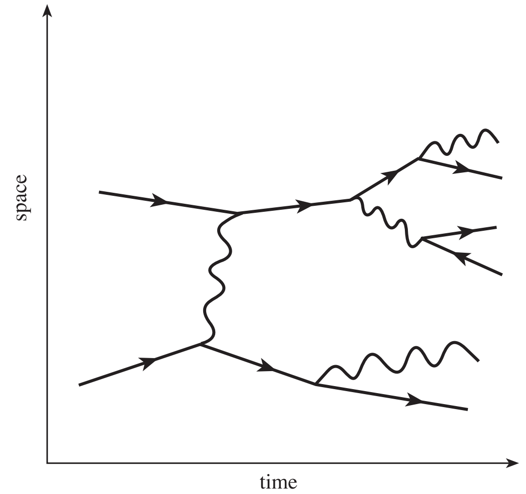

Figure 1. Two electrons in, six particles out: particle number is not conserved, but electric charge is.

Feynman diagrams at work

We have given a dozen public demonstations using our set of Feynman diagrams, which is shown in figures 2, 3 and 4. The straight sticks represent electrons, the wavy ones photons. While electrons have different ends (hexagonal head, square tail), both ends of photons are circular. The cylinders are the interactions, and each one has three different holes, one circular, one square and one hexagonal. The only possible configuration is thus the one with an incoming electron, an outgoing

Figure 2. The set of pieces to construct Feynman diagrams: notice that both ends of the photon line have the same circular shape, whereas the electron line has a hexagonal head and a square tail.

---

[1] And, at the same time, changing the sign of electric charge and changing left into right, the complete operation being termed CPT.

Figure 3. Each vertex has three holes: one circular, one hexagonal and one square. Only the configuration of figure 4 is allowed.

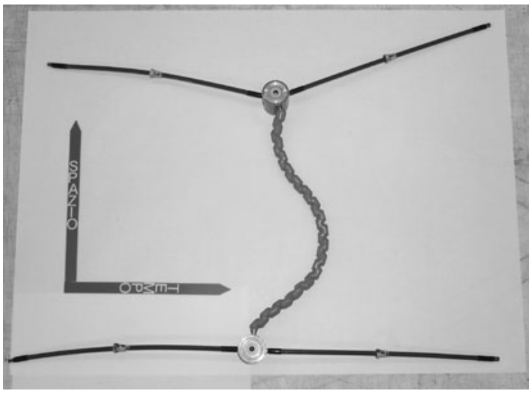

Figure 4. The process $e^-e^- \rightarrow e^-e^-$ constructed with the toy elements.

one and a photon: this is the unique fundamental interaction of QED. By combining together more electrons, photons and interactions, more and more complex processes can be obtained, such as the scattering between two electrons (figure 4).

Typically, our public was composed of high school students aged 16–18. After a brief introduction, in which we mentioned the enormous variety of phenomena described by QED (and some biographical notes on Feynman [4]), we introduced the diagrams. We started by recalling the notion of space-time and by considering how the interpretation of a given line in space-time (a trajectory) changes if we invert the orientation of the time axis. Then, we introduced each character: the photon, the electron (and the positron) and the interaction vertex. Finally, we constructed a simple process like $e^+e^- \rightarrow e^+e^-$ by using the smallest number of pieces, that is one photon, four electron lines and two vertices. At this point we split the class into groups of three or four, and provided each group with some pieces and a list of questions.

They were asked to construct simple processes, to exchange the orientation of fermion lines with respect to time and to read out the process obtained in this way, to count the number of pieces they had used, to find out whether the same process could have been realized with fewer pieces, and so on. The last question typically asked them to construct an ‘impossible’ process, in which electric charge was not conserved.

As a general rule, we observed that all groups managed to construct the configurations corresponding to the simple processes. More complex questions required a varying amount of time depending on the groups, but the common aspect was that no group proposed as a solution a wrong diagram, i.e. a diagram with a wrong intersection at the interaction point. The explanation for this result is obvious: in our game, the rules for the construction of Feynman diagrams are translated into mechanical constraints on the possible insertions of lines in the vertices. A wrong diagram would simply fall apart. As a cross-check, we also formed some control groups, to whom we gave the same questions but no pieces. They were asked to work entirely on paper. On average, their results were significantly poorer than for the groups working with the mechanical models, especially in the construction of the more complex processes. When many lines and interaction vertices are required, it is easy for an untrained person working on paper to overlook a wrong vertex—for instance one with two incoming electron lines—here and there.

The last question in the list, the one concerning the ‘impossible’ processes, was typically the more problematic. Quite soon, the students realized that it was impossible to construct the process with the small number of pieces they had at their disposal. Many of them, at this point, borrowed more pieces from nearby groups, thinking that they might succeed by increasing the complexity of the diagram. Only a minority of the groups concluded immediately that the process could not be constructed, given the pieces and the rules. On the other hand, none was able to claim that they had succeeded, again thanks to the mechanical character of the rules. In any case, we think that the frustration

Table 1. The list of questions asked one month after a presentation. Columns 2 to 5 report the percentages of correct (C), partially correct (PC) and wrong (W) answers, and of questions not answered (NA).

Questions	C	PC	W	NA
Orient the time axis so that object A is a positron and B an electron: A: → B: ←	76	0	19	5
Draw a diagram for the process $e^+e^- \to e^+e^-$	81	14	5	0
Draw a diagram for the process $\gamma e^- \to \gamma e^+$	71	0	24	5
In case the process above is not possible, explain why	62	14	24	0
Draw a diagram for the process $e^-e^- \to e^-e^-$	66	10	10	14
Is it possible, with the same configuration, to represent $e^+e^+ \to e^+e^+$	86	14	0	0
Which operation is necessary?	76	10	14	0
Draw a diagram for the process $\gamma e^- \to e^+e^-e^-$	62	14	14	10
Draw a diagram for the process $e^+e^- \to \gamma\gamma$	67	0	19	14

Table 2. Distribution of the results of the individual tests.

Correct answers	Students (%)
0 or 1	10
2–4	10
5–7	33
8 or 9	47

of the many unsuccessful tries was a powerful aid in remembering the correct explanation that we eventually gave them—the law of charge conservation.

In one case, we were able to check the effectiveness of our tools in communicating the basic concepts above in a persistent way. One month after our presentation, 21 students were asked to answer to a list of questions on Feynman diagrams *without* the aide of the mechanical model.

The results, reported in tables 1 and 2, were quite encouraging. All the questions produced more than 60% correct answers. The impossible process $\gamma e^- \to \gamma e^+$ was recognized as such by 15 students, showing that after the previous exposure to the mechanical model the law of charge conservation had been memorized and could be effectively used in a different context and working on paper. Overall, 80% of the students gave more than five correct answers out of nine, which—even recognizing the obvious statistical limitation of such analysis—goes beyond our expectations.

As the next step in our project, we are considering an improved version of our tools, suitable for production in larger numbers and for distribution in schools, science museums, etc[2].

Received 17 January 2002, in final form 2 May 2002
PII: S0031-9120(02)32805-3

References

[1] Miller A I 1996 *Insights of Genius: Imagery and Creativity in Science and Art* (Berlin: Springer)
[2] Dunne P 2001 *Phys. Educ.* **36** 366
[3] Wilczek F 1999 *Rev. Mod. Phys.* **71** S85
[4] Schweber S S 1996 *Rev. Mod. Phys.* **58** 449

Alessandro Pascolini is Associate Professor of Mathematical Methods of Physics at the University of Padua. His research is in the fields of theoretical nuclear physics and nonlinear phenomena. Since 1988 he has been in charge of a special program of INFN for raising public awareness of science.

Massimo Pietroni is a theoretical physicist of INFN. His main research interests are in particle physics and cosmology. He is currently involved in design and production of scientific toys and interactive exhibits.

---

[2] More information on the project can be requested from pietroni@pd.infn.it