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Electrodynamic metaphors: communicating particle physics with Feynman diagrams

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The aim of this project is to communicate the basic laws of particle physics with Feynman diagrams - visual tools which represent elementary particle processes. They were originally developed as a code to be used by physicists and are still used today for calculations and elaborations of theoretical nature. The technical and mathematical rules of Feynman diagrams are obviously the exclusive concern of physicists, but on a pictorial level they can help to popularize many concepts, ranging from matter and the antimatter; the creation, destruction and transformation of particles; the role of 'virtual' particles in interactions; the conservation laws, symmetries, etc. Unlike the metaphors often used to describe the microcosm, these graphic representations provide an unequivocal translation of the physical content of the underlying quantum theory. As such they are perfect metaphors, not misleading constructions.

A brief introduction on Feynman diagrams will be followed by the practical realization of this project, which will be carried out with the help of an experiment based on three-dimensional manipulable objects. The Feynman rules are expressed in terms of mechanical constraints on the possible conjuctions among the various elements of the experiment. The final part of the project will present the results of this experiment, which has been conducted among high-school students.

Scientific metaphor is the 'interface' between the work of a scientist and that of the science communicator. They both deal with a still unknown world and need to find a language accessible to everyone to talk about it. In the case of the science communicator this becomes even more fundamental if scientific subjects are considered in very abstract terms, as in the case of genetics, chemistry or particle physics. As far as the scientist is concerned, not only does the metaphor play a teaching role, but it can also lead to scientific discoveries, as discussed in Miller's Insights of Genius [Miller, 1996].

Thus, the science communicator uses the metaphor to describe, the scientist to explore and experiment. The former creates icons for a wide and differentiated audience, his aim being a clear and user-friendly language. The latter makes for himself a toy version of the reality he will be exploring. The terms of the analogy are not absolute, they are rather meant to answer the questions that may arise each time. It must be also very simple, as to avoid redundancy and therefore misleading conclusions. This scientific reality is not only to be observed, as in the case of the science communicator, but rather manipulated. In short, the scientist uses the metaphor as an authentic virtual laboratory.

Mental experiments, to which Galileo and Einstein gave great contribution, represent the best example of scientific metaphors. The scientist first imagines an extreme experimental situation, unachievable to re-create in a real laboratory. In the case of Galileo this could be, the total absence of friction, or the possibility of running at the speed of light in the case of Einstein. At this point, the scientist's task is to emphasize the crucial aspects of certain phenomena or demonstrate that a generally accepted theory can have paradoxical consequences. In these types of metaphors objects and concepts are obviously connected to the field taken into consideration, even if their properties are carried to extremes.

James Maxwell's mechanical models, used to study the electromagnetic field, belong to another class of scientific metaphors. In On Physical Lines of Force (1861), Maxwell imagined space as a fluid in which 'numerous vortices' rotate in the direction of the magnetic field, this being due to the 'electricity particles', which act as ball-bearings. When vortices rotate, they expand because of centrifugal force and, as a consequence, contract longitudinally. What is known as the attraction of two magnets is actually the consequence of the contraction of the space between the two magnets. In this model Maxwell can foresee the existence of electromagnetic waves, calculate their velocity and make out how it is related to light.

Maxwell did not believe that these mechanical models could be any 'theory' of the electromagnetic field, nor did he believe in the reality of vortices and ball- bearings. Yet he observed that electric and magnetic phenomena were apparently compliant with laws which resembled those of mechanics. He wrote in On Faraday's Lines of Force: "I hope to make it clear that I am not trying to theorize about phenomena which I have not observed. My model's purpose is to demonstrate that the connection between phenomena of different classes, as pointed out by Faraday, is applicable to the field of maths." In Maxwell's view, a metaphor is therefore like a resemblance, though partial, between the rules of a known sector and those of an unknown world, which allows the elaboration of a fresh operational image of it and extrapolations on phenomena as yet unproven. The strength of these metaphors is that they are law-based: "A resemblance between relations is not a resemblance between the related objects to which these relations refer". Relational analogies are to be taken into consideration rather than the description of unknown objects in familiar terms.

The aim of this article is to popularize the basic laws of particle physics on the basis of Feynman diagrams, which can be considered as authentic metaphors created by scientists for their researches.

It is well known that the behaviour of matter on a subatomic scale, governed by anti-intuitive laws of quantum mechanics, cannot be described by metaphors and icons taken from everyday life. In this respect, Maxwell's example can help to identify their critical point. Familiar metaphors are often attributed to the elements of microcosm, namely atoms, nuclei, electrons and quarks but can no longer be used when these 'corpuscles' take on 'undulatory' features, or when the scientist talks about the decay or the transformation of particles. This is actually the same problem that the first quantum physicists had to face when they could not accept the consequences of what they had been theorizing. For reasons intrinsic to the theory itself, what is missing is a known environment in which to find the elements to be associated by analogy to the objects of particle physics. What is missing is images. Thus, Maxwell's thesis is acceptable - one needs to focus on relations rather than the specific objects.

Feynman diagrams illustrate appropriately the relations between particles, which are regulated by the laws of quantum mechanics and field theory. These graphical representations calculate the probability for elementary particle interactions to occur. Thus, they have double importance: on a physical-mathematical level they express every diagram in the corresponding formula and vice versa, with a precise vocabulary. On a visual-intuitive level they can view the various contributions/formulae of a given process and give a physical comment even before the corresponding mathematical expressions are calculated.

For our purpose of science popularization we want to focus on this second aspect. Thus, the idea is to avoid forcing our images to fit scientific concepts, but rather to pay attention to them and learn to comprehend them, always bearing in mind that these metaphors, like all scientific metaphors, are just the ‘tip of a submerged model’ (M.Black, 1993). This implies that they depend upon a mathematical system which must necessarily be left out.

Feynman diagrams are generally used within scientific laboratories an drawn on sheets of paper. For this experiment, they have been transported into schools and realized as three-dimensional, manipulable, coloured objects. The rules governing elementary particle interaction are expressed in terms of mechanical constraints on the possible conjuctions among the various elements of the experiment. This is an essential element of the project, an effective way of overcoming the barrier that is inevitably thrown up by having to deal with a subject as remote as elementary particle physics.

The article is organized as follows. Paragraph 2 introduces Feynman diagrams and their meaning. In paragraph 3 you will find what concepts of particle physics can be popularized through Feynman diagrams. Paragraph 4 is about the practical realization of this field project. In Paragraph 5 some results obtained from this experiment are presented and discussed. There will follow (paragraph 6) a discussion about possible developments of this project.

What are Feynman diagrams?

Feynman diagrams are one of elementary and solid particle physicists’ work tools. To every diagram, which is built according to fixed rules, corresponds a mathematical formula describing a certain physical process. The assembly of one or more diagrams corresponding to one physical process will yield, by means of a clearly-defined mathematical process, the probability value for that process. The greater the number of diagrams considered, the greater will be the correspondence between the calculated probability value and the actual value experimentally measured.

This method has therefore two fundamental aspects:

- physical-mathematical rigour, according to which a diagram is always built on the basis of a precise formula and vice versa.

- the graphic representation of physical processes, according to which the various contributions of a process can be viewed and commented on even before they have been calculated. This could be, for instance, the possibility of a given process in Nature to occur, any possible analogies with other processes, the importance of relations between the various diagrams and so forth.

The first aspect is what makes Feynman diagrams perfect metaphors for our purposes, as they express all and only the logical-formal content of a theory. It is not possible, given their fixed rules, to build diagrams which do not correspond to their relative mathematical solutions, and after all only one diagram corresponds to a given solution. By virtue of its very construction, the metaphor cannot be misleading.

Of course, the correspondence between maths and diagrams is not easy to deal with and it may take to years of acadamic studies to be fully comprehended. Our aim is therefore to demonstrate that the visual aspect of Feynman diagrams can be used to popularize some basic aspects of particle physics, so that even non-experts can learn to work with them. If this project is to have any chance of success, the physical-mathematical rigour that underpins everything must maintain a discreet silence.

We will now introduce the various elements of Feynman diagrams and the rules of the experiment as regards quantum electrodynamics (QED), the theory which describes photons, electrons and their interactions.

Space-time

First of all a Cartesian axis needs to be introduced, which will represent space and time. In this way, our table becomes what physicists call “space-time”. Every point represents an ‘event’, that is something which happens in a particular moment (its projection will be on the axis of time) in a particular place (its projection will be on the axis of space). This notion of ‘space-time’ is also known by those who have a knowledge of kinematics, for it is the means by which motions are defined. At this point, it will not be difficult to introduce the concept of ‘sample path’, namely a sequence of events which lead from a ‘here-now’ event to a ‘there-in a second’ event.

The only other thing that needs to be specified is a consideration on the inversion of the arrow of time. If we invert the axis of time, the sample path considered before will describe the notions between same points as before, but with inverted roles -

in a second these points will go from ‘there’ to ‘here’ and not vice versa. As we will see, this is important because it has surprising effects

The photon

This is the first true protagonist. It is traditionally drawn with a wavy line because it must be distinguished from the other elementary particles in space -time. The line in Fig.1 defines the sample path of a photon, γ, which moves from x1 to x2 in time t1-t2. In other words, it draws the events (x1, t1) and (x2, t2) together. This is our first Feynman diagram, which represent the simplest physical process. At this point, we can make our process and its corresponding diagram more complex by adding another photon. We thus have a description of the process whereby two photons are propagated in space-time. If these photons are extended, and we look at the past (left) and the future (right), we will notice that the two photons previously at the beginning are the same two photons at the end. This can be expressed with the symbols $\gamma\gamma$ - $\gamma\gamma$. The same process occurs every time a new photon is added.

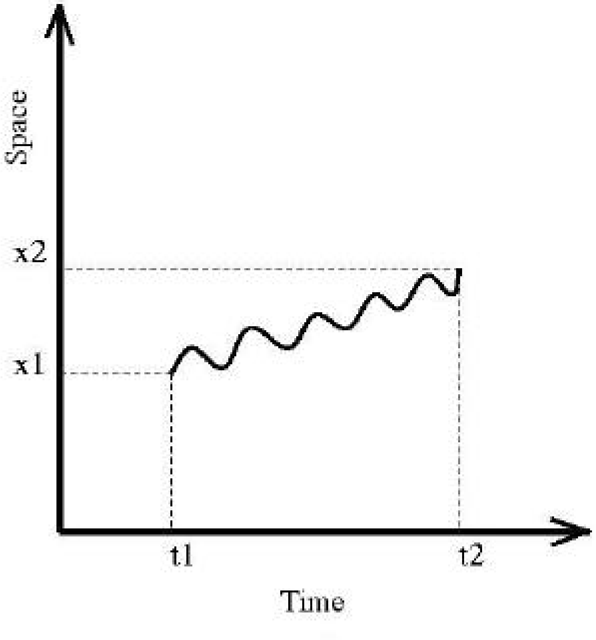


Fig. 1 A photon in space-time

The electron

The electron is also represented by a line in space-time. More precisely, it is an oriented line, an arrow with a head and a tail. It is important to remember that if these are oriented in the same direction, as happens for photons, the electron will go from (x1, t1) to (X2, t2). If the arrow goes in the opposite direction of time, even though it joins the same extreme points together, the line will correspond to the 'anti-electron' or 'positron', which always goes from (x1, t1) to (x2, t2) and vice versa. Thus, this element describes both matter (electron e^-) and anti-matter (the anti-electron e^+). They are two sides of the same coin, or, in more specific terms, two solutions connected by the inversion of time. The concept of anti-matter is surprisingly familiar to high-school students, or at least its fundamental aspects (an electron with a positive charge and a proron with a negative charge). In addition to this, science-fiction (remember Star Trek and the catastrophic explosions occurring when the world comes into contact with the anti-world) has also played an important role in the popularization of the anti-electron. At this point we can now draw diagrams which correspond, for instance, to the process $e^- e^- \to e^- e^-$, or $e^- e^+ \to e^- e^+$, or $\gamma e^- e^+ \to \gamma e^- e^+$, and so forth.

If this were all, the world would be extremely banal. Photons and electrons would go undisturbed through the cosmos, without coming into contact. The presence of an electron could not affect a proton's motion and vice versa. Everything would be perfectly transparent, for there would be no way to stop light and reflect colours.

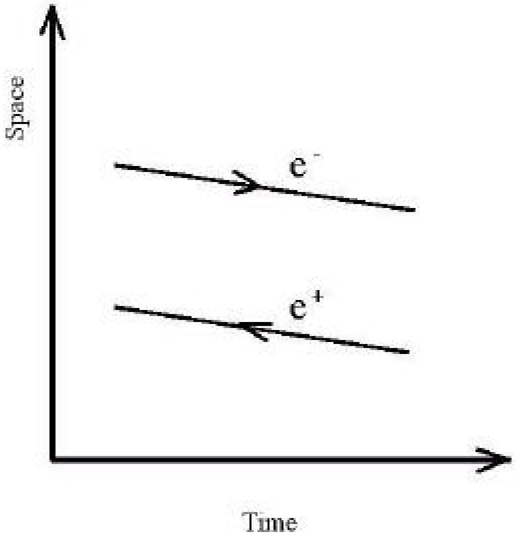


Fig. 2 An electron and an anti-electron

Actually no object would even exist, as the elements of matter, protons and electrons, would never come into contact and therefore no formation of atoms, molecules and complex structures would occur. No antenna would catch or emit any radio waves. What is missing in our experiment is clearly something fundamental which describes the phenomena we know - interaction.

The interaction

The fundamental interaction of quantum electrodynamics is the intersection of three lines, as shown in Fig.3. A photon, an incoming electron and an outgoing electron meet in the vertex. It is essential to bear in mind that this is the only possible configuration. As a matter of fact there is no other interaction in which there are, beside the photon, two incoming or outgoing electrons, or two electrons which join more than three lines together. This has important effects on the processes possible in nature.

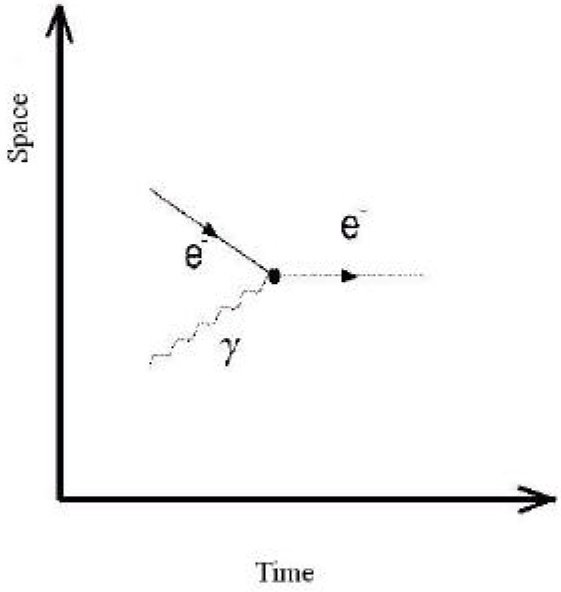


Fig. 3 The fundamental interaction, seen as the absorption of a photon by an electron

If we consider the interaction as a new Feynman diagram, always focusing on what is at the beginning (left) and at the end (right), we will notice that it can represent different physical processes. Fig.3 shows a photon and an electron at the beginning and only an electron at the end, that is $\gamma\ e^- \rightarrow e^-$. There is a clear difference between this and what we saw before: in the examples above the same particles were both at the beginning and at the end. Here the initial photon has disappeared. To put it in physical terms, the photon has been absorbed by the electron. The interaction thus allows the transformation of initial particles into other particles, modifying their motion or even making them disappear, appear or change their nature. Absorption is a frequent physical process which allows the reception of radio waves (because the antenna's electrons absorb photons) and protection from sunlight (with the help of a screen or lenses that absorb electromagnetic radiation).

If we now consider the same interaction and push the photon further, as in Fig.4, we will obtain the process $e^- \rightarrow e^- \gamma$, namely the emission of a photon by the initial electron. This process, for instance, is at the basis of the emission of colour by an object, and the emission of radio waves by the electrons in motion inside an antenna. If we rotate the two previous diagrams by 180 degrees or, similarly, invert the orientation of the axis of time, we will obtain $e^+ \rightarrow e^+ \gamma$ and $\gamma\, e^+ \rightarrow e^+$, respectively, namely the emission and the absorbment of a photon by an anti-electron, rather than by an electron.

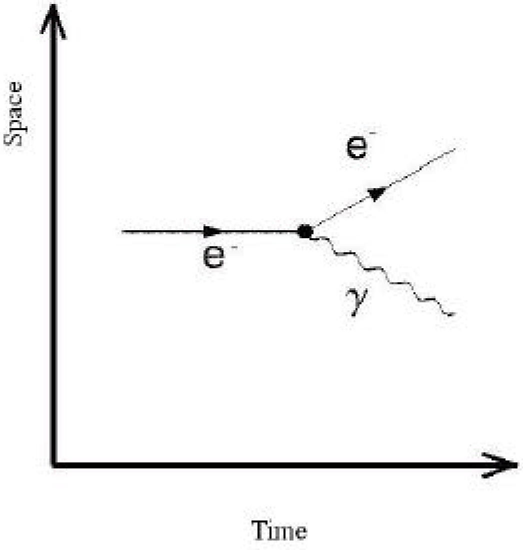


Fig. 4 Emission of a photon by an electron

The range of processes described by the fundamental interaction is even wider. If we rotate the legs as in Fig.5 we have $e^+ e^- \rightarrow \gamma$, the electron and the anti-electron come into contact, disappear and create a photon. This is the phenomenon of the annihilation between matter and anti-matter, as those who are fond of science-fiction will know. Initial matter and anti-matter are completely converted into electromagnetic energy, according to the famous formula $E= mc^2$. If we rotate this by 180 degrees, the inverse process $\gamma \rightarrow e^+ e^-$, will be obtained, in which matter and anti-matter are created by electromagnetic energy (photon).

The interaction-vertex is the fundamental building brick of QED. All processes, from the simplest to the most complex, are nothing more than a combination of elementary processes like the one described before. Let us analyse some of them.

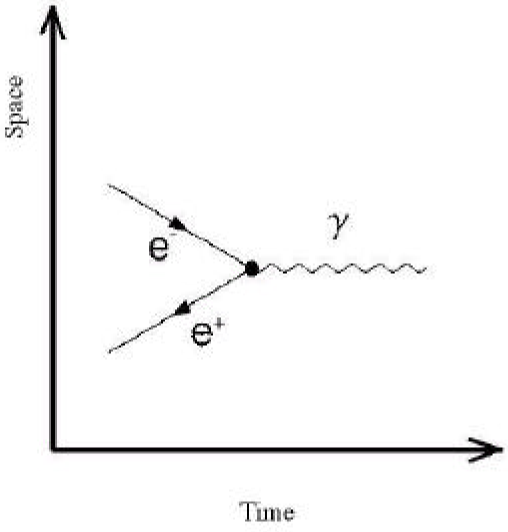


Fig. 5 Annihilation between an electron and an anti-electron

Compound processes and virtual particles

Fig.6 shows a possible realization of the process $e^- e^- \rightarrow e^- e^-$. The two electrons come from a remote past and go on undisturbed towards a remote future without ‘seeing each other’, that is they do not influence each other’s motion. Then why do two charges with the same sign repel each other? It is evident that that diagram is not the only way to represent this process.

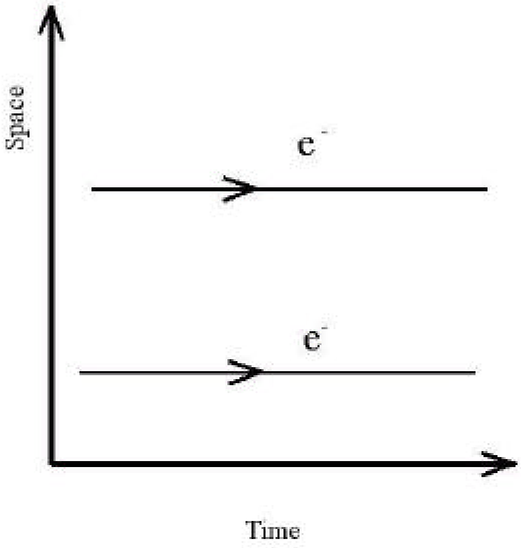


Fig. 6 Two electrons travelling without ‘seeing’ each other

Fig.7 is the answer to this question. In this case, too, we find two electrons both at the beginning and at the end, but something important happens in between. The two electrons ‘talk to each other’. One of the two emits a photon which goes as far as the other electron. At this point, the electron absorbs the photon. This exchange of photons allows the interaction between the two particles. In short, photons act as messengers which carry such information as the position or the velocity of the emitting electron for the receiving electron. Repulsion is the consequence of this process.

It is important to notice that, within the diagram, some of the particles play different roles. Some of them, the electrons in this case, have a free extremity, which means that they have been living or will be for an unlimited period of time. Others, such as the photons, have both extremities terminating with a vertex, so they will live for a limited period of time. The former are usually known as ‘real’ particles, the latter as ‘virtual’, because they do not live long enough to be directly detected. It is erroneous, though, to think that virtual particles are unimportant. As we have seen, they play an important role as they mediate real particle interactions.

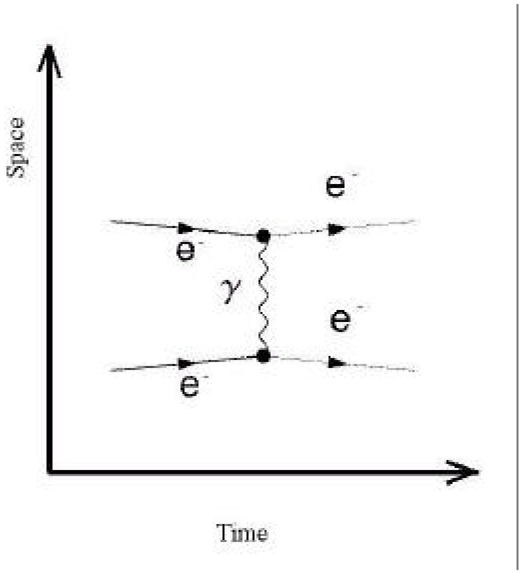


Fig. 7 Exchange of a virtual photon: the two electrons ‘see’ each other!

There are also many other diagrams with two electrons both at the beginning and at the end, for example those shown in Fig.8 and Fig 9. As was said before, a mathematical quantity corrsponds to every diagram. In order to calculate exactly how two electrons behave in a certain situation, it would be necessary to sum all quantities of the possible diagrams with two electrons at the beginning, which in most cases is practically impossible. One of QED’s properties will be of great assistance. The more significant diagrams, that is those which contibute the most to the final sum, are the simplest ones, namely those which have fewer vertices. In short, the fewer vertices a diagram contains, the more important it will be.

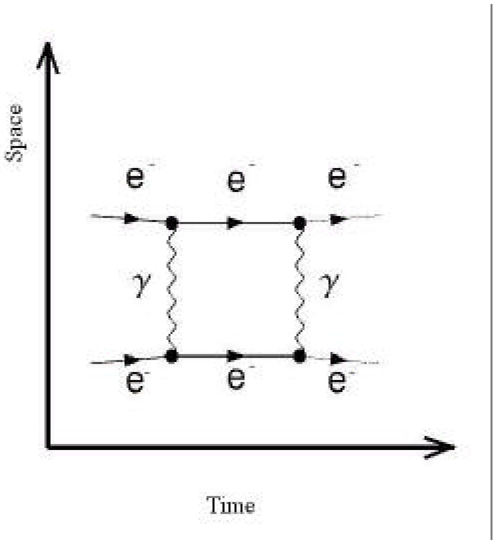


Fig. 8 One more form of interaction between two electrons…

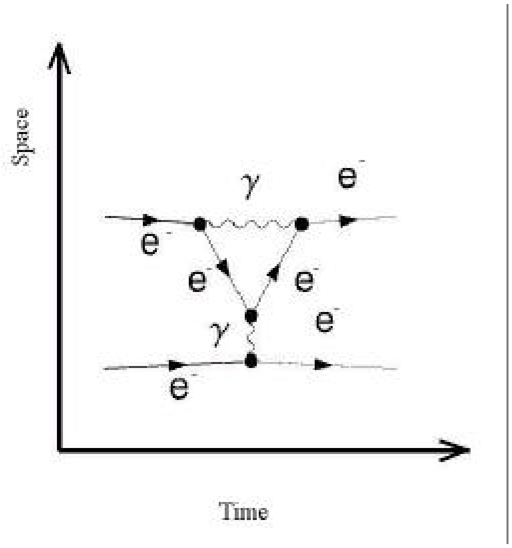


Fig. 9 … and another

What can be popularized through Feynman diagrams?

This is the crucial point of this project. As we have already said, Feynman diagrams have always been one of the most valid work tools for particle physicists. They are of essential help for accurate and rapid calculations, and allow comments on a given physical process even before any calculation has been made. Their popularity is mostly due to their versatile character, which enables professional physicists to view many kinds of physical processes in a thorough and, at the same time, intuitive way.

To what extent can these characteristics be used as means of popularization? What can they teach to all those people who do not have anything to do with particle physics? Before we answer this question, it is necessary to single out the elements which make the world of particle physics so different from that of traditional physics. These are indeed the aspects which most require the development of ‘brand new metaphors’, rather than re-elaborations from everyday life.

This question was raised by Frank Wilczek, one of the most outstanding contemporary particle physicists, in an essay which was published by Reviews of Modern Physics (F. Wilczek, 1999). Let us see what he suggested.

Identical particles

As Wilczek points out, the first aspect to be emphasized is the existence of different, though undistinguishable, elementary particles. Two electrons coming from two different parts of the universe, regardless of their origin and history, have exactly the same properties, namely the same mass, charge and spin. According to quantum field theories, of which QED is the most successful example, this is due to the fact that fields, rather than particles, are the primary reality. The various electrons are just 'excitations' of the same fundamental reality, that is the electronic field, which pervades the whole universe. The same goes for photons, quarks and the other particles.

The existence of different but 'identical' particles, which are indistinguishable even in principle, is entirely alien to common experience. Leibniz even based his metaphysics on the principle that two objects which cannot be distinguished in any way must necessarily be the same object. On the other hand, according to quantum mechanics elementary particles are to be divided into 'classes'. Two elements belonging to the same class, namely two particles of the same kind, can never be distinguished, even in principle. This notion is nothing new for those who know the rudiments of chemistry, but it is worthwhile stressing its importance as opposed to common experience, which would tell us how to distinguish two apparently identical billiard balls.

Writing for Encyclopedia Britannica under the heading Atoms, Maxwell concluded that "the formation of a molecule, therefore, is an event which does not belong to the order of nature we inhabit […] it cannot be bound up with the epoch in which the earth of the solar system were formed […] but with the epoch in which the natural order of things was established".

In terms of Feynman diagrams, this can be translated with the indistinguishability or, in practice, the interchangeability of the various photon or electron lines. Once a diagram has been built, if two electron lines are swapped or if one of the electron lines is replaced with a new one, the diagram will be exactly the same. In our diagrams, which combine elements of two different kinds (electrons and photons) this aspect is almost taken for granted, to such an extent that it goes unnoticed. For this reason, it is necessary to emphasize it explicitly through concrete examples.

Matter and anti-matter

The second typical aspect of elementary particles is the existence of anti-particles and therefore of anti-matter. This concept was first introduced by Dirac to interpret the electron equation in a reasonable way. Later on, following the formulation of quantum field theory, it obtained a true theoretical recognition, and it soon became as important as ordinary matter. From the mathematical point of view, electrons and anti-electrons are two solutions closely linked to each other. The anti-electron can be obtained by changing the electron's charge, inverting left and right, inverting the orientation of time. And vice versa. These three operations are commonly known as CPT.

The close relation between matter and anti-matter is totally unknown in common experience because anti-matter is not part of our world. In terms of Feynman diagrams, by contrast, the relations between electrons and anti-electrons is evident in the use of the same line to describe both particles. It is useful to remember that the line considered is an arrow that, if it is oriented in the same direction as time, it will represent an electron; if it is oriented in the opposite direction, it will represent an anti-electron. The change of orientation as regards the axis of time corresponds to the CPT operation described above.

As far as the photon is concerned, the two possible orientations as regards the axis of time are undistinguishable (there is no arrow on the photon line) - this means that photons and anti-photons are the same particles.

Up until now, interactions have not been taken into account. When these come into play, though, new aspects will have to be considered.

Creation and destruction of particles

The first aspect is represented by phenomena of creation and destruction of elementary particles. All four basic processes of QED described previously, namely the emission and absorption of a photon and the creation or annihilation of an elettron/anti-elettron couple, imply the creation or destruction of a photon (the former) or of an electron and an anti-electron (the latter). As we have seen, all these processes are illustrated by the same vertex-interaction, which makes the identification between interaction and particle creation-destruction evident. In the case of the Standard Model the transformational role of interaction is even more remarkable. In QED the electron emitting a photon is always an electron and the proton is always a proton. According to the Standard Model, by contrast, the electron emitting a W boson (similar to a photon) changes into a neutrino, and the proton changes into a neutron.

All this will be much clearer and easily communicable with diagrams, even at the simpler level of a fundamental interaction. It is sufficient to observe how the number of initial particles changes from that of final particles during all four basic processes.

Virtual particles as messengers of interaction

The exchange of virtual particles is the process which explains particle interaction, as we have seen in Fig.7. According to Maxwell's electromagnetism, the electric and magnetic forces between two charged particles are due to the influence of one of these particles in the electromagnetic field on the other. According to quantum field theory, fields and particles coincide, thus the influence of the electromagnetic field is interpreted as the exchange of virtual photons emitted by one of the (real) particles and absorbed by the other. As opposed to electromagnetism, field theory admits that an electron may act as a virtual particle, triggering an interaction between a real photon and a real electron occurs. The same goes for pions (which mediate nuclear interaction between neutrons and protons), W and Z particles (which mediate weak interactions) and gluons (which mediate quark interaction). Even neutrons, protons, quarks, neutrinos. etc. can in turn mediate interactions.

The idea of virtual particles as interaction mediators is clearly visible in such diagrams as those shown in Figs. 7, 8 and 9. It is sufficient to observe the difference between lines with a free extremity (real particles) and those with both extremities terminating in a vertex (virtual particles).

Conservation laws

The creation and destruction of particles, provoked by interactions, produce a possible variation in the number of particles involved. As shown in Fig.10. two initial electrons produce six final particles, namely three electrons, an anti-electron and two photons. The final charge, though, has not changed: there are two negative charges both at the beginning and at the end. In more technical terms, the electric charge is said to be 'conserved' in the process, unlike the total number of particles. The same will happen even with bizarre diagrams with a high number of elements: the total charge is the same at the beginning and at the end. Such conservation laws are to be found in other theories, too. Not only do they concern electric charges, but other quantities, for example the number of quarks minus that of anti-quarks. These are very powerful systems, for they unable us to say that no process can break any of these laws, even before the corresponding diagram has been constructed. For instance, $e^+ e^+ \rightarrow e^+ e^-$ process, which would require the passage from two initial positive charges to two final zero ones, is impossible. In this case, too, the origin of the conservatiom law is represented by the fundamental vertex. All basic processes described by the fundamental vertex conserve the electric charge and therefore all complex processes must also have the same property, as they are constructed from a series of elementary processes.

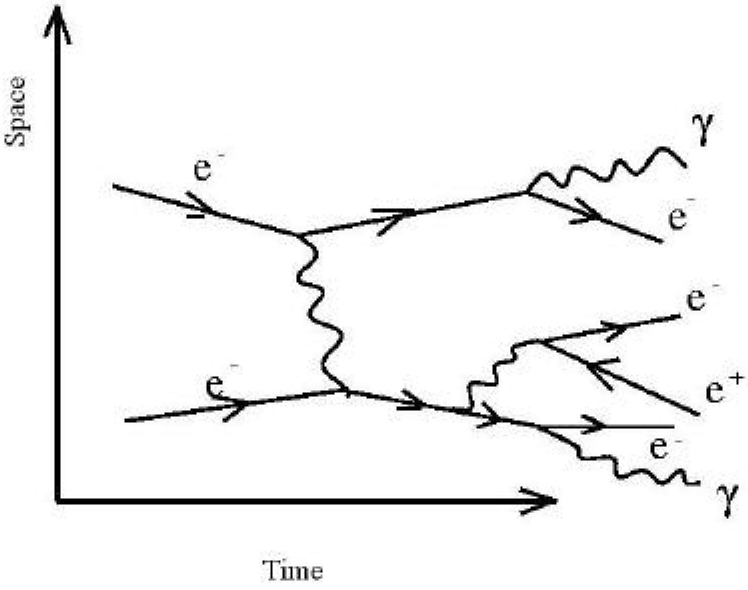


Fig. 10 From two electrons, six particles

In addition to all possible processes, Feynman diagrams allow the realization of a process not compliant with the electric charge conservation law. Although the notion of electric charge balance is widely discussed within chemistry courses we have never come across students who could immediately recognize the impossibility of that process. They all tend to build very ambitious diagrams which eventually prove to be unfeasible. This is frustrating, but on the other hand students become more aware of the meaning of charge conservation. Feynman diagrams can also demonstrate that the process could be easily realized if a new type of fundamental interaction were possible, in which both electron arrows are oriented in the direction of vertex. Thus, the very close relation between the structure of the only fundamental interaction of QED and the conservation laws is much clearer.

...And what cannot be communicated

The metaphorical use of Feynman diagrams that we are illustrating is obviously limited. What are the most important concepts which are left out of our demonstration-exercises and therefore need further clarification? As we said before, the mathematical aspect of Feynman diagrams, undeniably useful for those who deal with particle physics, is deliberately excluded from our field of interest. Indeed it will be mentioned during one of our demonstrations, yet our audience will be reassured that it is irrelevant for our purposes. We will try to be as clear as possible, so as to avoid equivocal interpretations or unintentional omissions.

There are other delicate aspects which must be taken into consideration. These are as important as some of those listed in the previous paragraph, but cannot be described as readily by constructing Feynman diagrams. This is certainly the case with the principle of energy and impulse conservation. When two particles become six, as shown in Fig.10, it is not sufficient to check the possibility of constructing a corresponding Feynman diagram and observe that the electric charge has been conserved. For this process to occur, it is necessary that the energy of initial electrons be enough to create four final electrons and two final photons. Impulse conservation raises even more subtle problems. On the basis of this principle, none of the basic processes $e^- \rightarrow e^- \gamma$, $e^+ e^- \rightarrow \gamma$, … , can occur singularly, but only if combined with other processes. For instance, the annihilation of electron/anti-electron always triggers the production of at least two photons $e^+ e^- \rightarrow \gamma\gamma$. The consequences of these fundamental principles are not made evident by Feynman diagrams, so the assistance of an expert in these cases is essential.

Feynman diagrams were originally conceived as a solution to the problem of infinites and re-normalization, that is to say the method to obtain finite results, comparable with experimental measurements. Diagrams describing infinite results are those which contain loops, as shown in Figs. 8 and 9. It is obvious that if we say nothing on how to 'calculate' a diagram the connection between loops and infinites cannot be explained, let alone the elimination of these infinites.

Field project

One of the typical aspects of our experiment, probably one of its strengths, is the transposition of Feynman diagrams from a sheet of paper or from a blackboard to the three-dimensional world of physical objects. A physical support, consisting of manipulable objects in plastic or metal, is an important resource for us to involve our audience, so that they will not be fearing a two-hour speech on QED. It is essential to point out from the beginning that our approach will be based on manual construction rather than on the factual knowledge of abstract concepts. Our experiment is based on objects and rules and therefore does not presuppose any background knowledge about electrons, photons or quantum mechanics. People who are already familiar with these notions will find it useful, later on, to use the resulting processes on a more familiar and complex level. At the beginning, though, it is necessary that people using Feynman diagrams for the first time should not feel obliged to have a certain knowledge or relate what they see or do to notions which in most cases prove to be vague and misleading. All high-school students we have come across so far have never felt uncomfortable with ‘interactions’ and ‘virtual photons’. They thought they were not supposed to know anything about these and therefore took them as what they really are, namely logical blocks of a formal discourse.

Another aspect which needs to be specified from the start is that the metaphors in question concern interactions, not objects. The objects that will be used are supposed to represent electrons and photons in a functional way, not naturalistic. The discourse can be introduced by such intentionally absurd questions as “How do you picture an electron?” After such a question, which will be inevitably followed by silence and puzzled faces, a little green stick will be of great assistance – “This is our electron today.”

Objects

The prototype we need for our experiment has been provided by ‘Bertocco’, a firm dealing with the construction of models in Padua. The hardest choice was the mechanism of conjuctions. We had to realize a system allowing only one type of vertex, precisely that in which a photon, an incoming electron and an outgoing electron meet, which would exclude every other combination. We chose a solution with a vertex containing three female fittings of three different types of conjuctions (square, hexagonal and circular). The electron has a hexagonal male fitting in the head and a square in the tail, while the photon has a circular male fitting both in the head and in the tail (see Fig.11). In addition to this, two female fittings are mounted on mobile supports which allow the variation of the angle between electron lines, so as to facilitate the realization of complex diagrams.

The electron arrow is a little green stick in flexible plastic, inserted in a truncated cone which expresses direction. For the photon we have chosen a product which is already on the market for completely different purposes – a tube for emulsifying liquid used with lathes and other industrial machines. It is zigzag-shaped and orange, so it the best candidate to represent a photon, which is drawn with a wavy line, as we have seen in the figures of the previous chapter. Space-time is a metal table on which space and time arrows, made of magnetic material, can be placed.

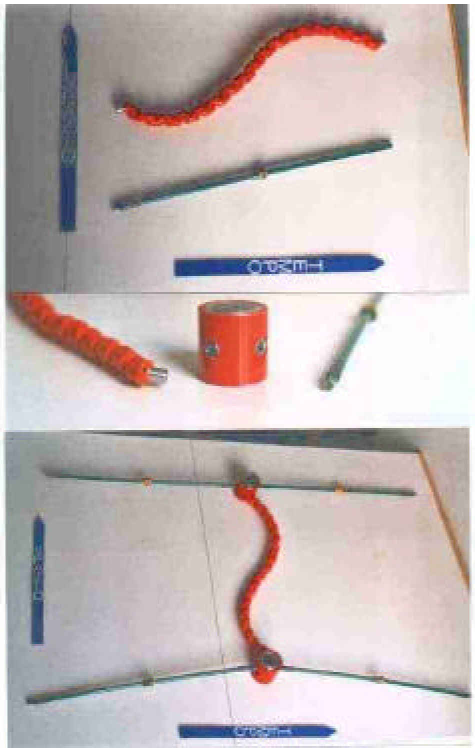


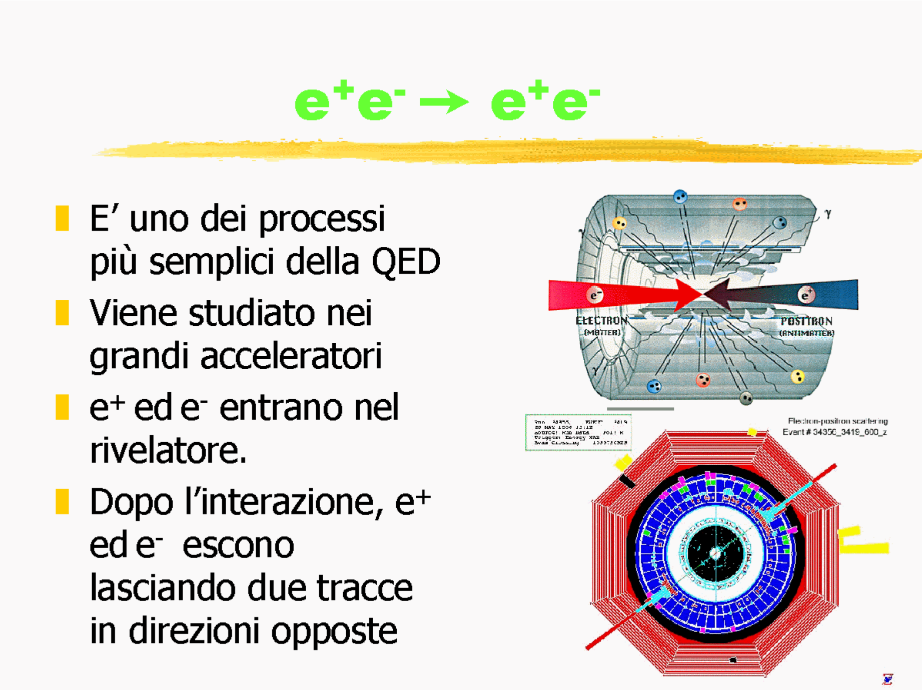
Fig. 11 The objects created

Demonstrations, questionnaires and results

About ten demonstrations have been carried out, having elder Italian high-school students as a target. Demonstrations took place both at the Physics Department of the University of Parma, in the context of the “2001 Scientific Culture Week”, and in schools, with an average duration of an hour and a half. After touching on the countless applications of QED, Richard Feynman, and the physical-mathematical rigour that renders his diagrams particularly useful, the pieces and the rules of the game are introduced, following the scheme outlined above. Then, groups of four or five are formed, each receiving a questionnaire and the pieces needed for working. Currently, the restricted amount of pieces available limits the number of students to twenty or twenty-five per demonstration. Each questionnaire begins by indicating a process, for example an electron and a photon becoming an electron and a photon, or the transformation of an electron and an anti-electron into two photons.

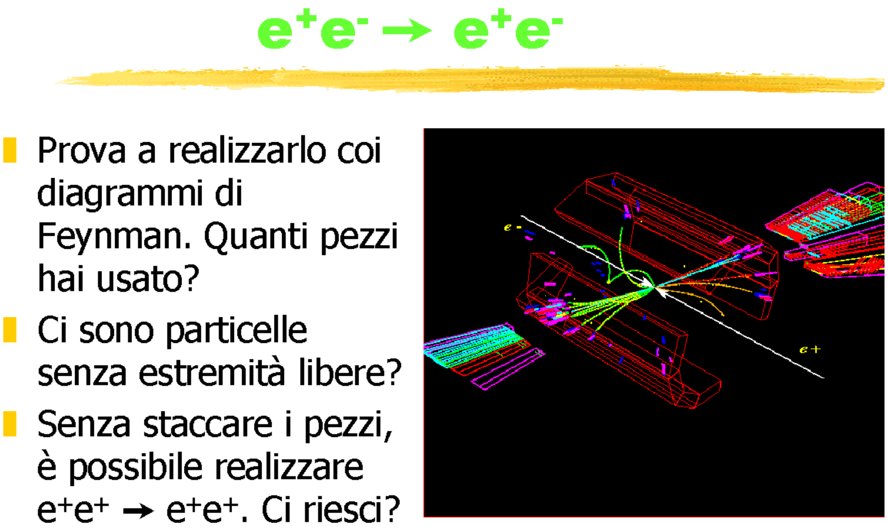
The first page presents the process and its implications for daily life and for research in physics. The second page asks students to enact the process by drawing Feynman diagrams with the pieces available, and to reflect upon the number of pieces used, the presence of ‘virtual’ particles, and the possibility of enacting the same process with a different diagram. Then, on the basis of the diagram just created, students are asked to obtain processes that are a little more complex, which may imply either adding pieces or inverting the orientation of the electronic arrows with respect to the arrow of time. Finally, the third page asks for the construction of an impossible process, such as $e^+ e^- \rightarrow e^- e^-$, so that the implications of the conservation laws may be grasped tangibly. One representative for each group is asked to write the answers to the questions on a sheet, and to draw the diagrams created.

Figures 12(a) and 12(b) show one of the questionnaires and a few examples of the answers obtained, to which our comments were added (in red). Since this pilot experience was carried out in a small number of classes, a statistical analysis was not deemed useful, one that would point out, for example, the time required for answering, the most frequent errors and so on. An approach considered more functional was that of analysing the questionnaires individually, managing to grasp any common characteristics and original ideas. Furthermore, observing how groups work, and interacting with them directly, provides information unobtainable from a statistical analysis.



$e^+e^- \rightarrow e^+e^-$

- E' uno dei processi più semplici della QED
- Viene studiato nei grandi acceleratori
- e^+ ed e^- entrano nel rivelatore.
- Dopo l'interazione, e^+ ed e^- escono lasciando due tracce in direzioni opposte



$e^+e^- \rightarrow e^+e^-$

- Prova a realizzarlo coi diagrammi di Feynman. Quanti pezzi hai usato?
- Ci sono particelle senza estremità libere?
- Senza staccare i pezzi, è possibile realizzare $e^+e^+ \rightarrow e^+e^+$. Ci riesci?

Fig. 12(a) A questionnaire*: part 1*[1]

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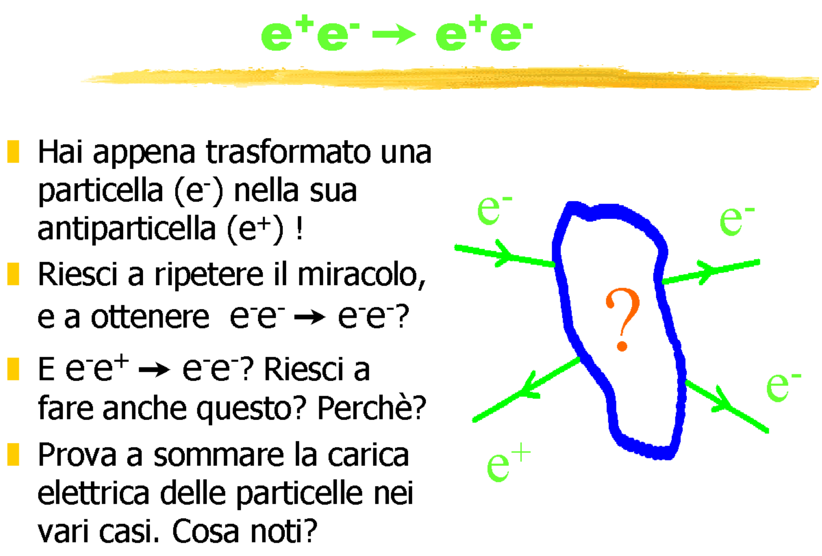
[1] - This is one of the simplest processes of QED
- It is studied in large accelerators
- e^+ and e^- enter into the detector
- After the interaction, e^+ and e^- come out and leave two tracks in opposite directions

- Try to enact it with Feynman diagrams. How many pieces have you used?
- Are there any particles with no unused joints?
- Without removing the pieces, $e^+ e^+ \rightarrow e^+ e^+$ can be represented. Can you do that?



$e^+e^- \rightarrow e^+e^-$

- Hai appena trasformato una particella (e^-) nella sua antiparticella (e^+) !
- Riesci a ripetere il miracolo, e a ottenere $e^-e^- \rightarrow e^-e^-$?
- E $e^-e^+ \rightarrow e^-e^-$? Riesci a fare anche questo? Perchè?
- Prova a sommare la carica elettrica delle particelle nei vari casi. Cosa noti?

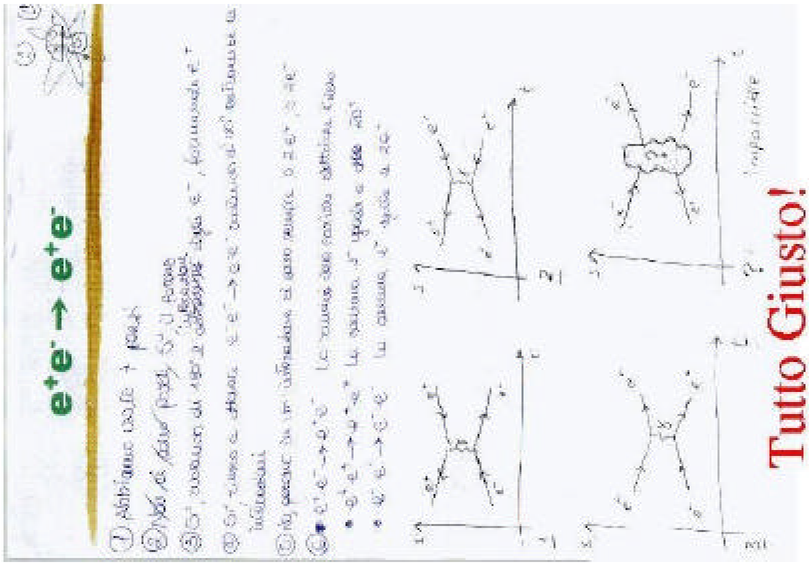


Fig. 12(b) A questionnaire: *part 2*[2]

- You have just transformed a particle (e^-) into its anti-particle (e^+)!
- Can you repeat the miracle, obtaining $e^- e^- \rightarrow e^- e^-$?
- And $e^- e^+ \rightarrow e^- e^-$? Can you obtain this one too? Why?
- Try calculating the total electric charges of the particles in each case. What do you notice?

1) We have used 7 pieces.
2) ~~There are no parti~~ Yes, the photon.
3) Yes, by rotating the interaction of the e^-'s by 180° and forming e^+'s
4) Yes, I can obtain $e^- e^- \rightarrow e^- e^-$ by rotating both interactions by 180°.
5) No, because in an interaction there are always either two e^+'s or two e-'s.
6) $e^+ e^- \rightarrow e^+ e^-$ The sum of the electric charges is zero.
$e^+ e^+ \rightarrow e^+ e^+$ The sum is 2 e^+
$e^- e^- \rightarrow e^- e^-$ The sum is 2 e^-
comment in red: Everything Correct!

Broadly speaking, all groups managed to perform the principal process of each questionnaire. Usually, the creation of the process $e^+ e^- \rightarrow e^+ e^-$ required only a few instants, while the others were a little more difficult. That is quite probably due to the similarity with the example used during the explanation: $e^- e^- \rightarrow e^- e^-$. On the basis of the diagram of the example, only the directions of the arrows of two electrons need be inverted to obtain the initial and final anti-electrons. A corroboration for this explanation is that the other diagram using the same number of pieces to obtain $e^+ e^- \rightarrow e^+ e^-$, the transformation of an electron and an anti-electron into a photon which then creates another couple $e^+ e^-$, is never given as an answer.

The two other processes requested in the questionnaires, $e^- \gamma \rightarrow e^- \gamma$ and $e^+ e^- \rightarrow \gamma \gamma$, The two other processes requested in the questionnaires $e^- e^- \rightarrow e^- e^-$. What is more, in both cases the interaction is mediated by a virtual electron, an eventuality that was not explained or even mentioned in the explanation of the example (there, the interaction was mediated by a photon). The groups asked to create these processes can, consequently, begin working only with a certain delay, since they must extend the concept of virtual particle from photons to electrons.

There was far more disparity in the answers to the processes that were a little more complex. Almost all groups answered this part of the questionnaires. Virtually no mistake was recorded for the questions requiring a simple rotation of electronic arrows with no removal of pieces, whereas the questions for which pieces had to be added were found more difficult. Only few groups did not provide any answer, and various groups answered when their time was almost up. In many cases, the answer given did not refer to the least number of pieces necessary for the process requested (a few groups indicated more than one correct solution). What is of particular note, however, is that virtually no group answered erroneously. Feynman rules, when translated into mechanical rules of joints between lines and vertices, do not allow any wrong conclusions!

The subject of the final part of the questionnaires, the law of conservation of electric charges, aroused the most problems. In some cases students were asked to create an impossible process. After realising that the pieces at their disposal were not sufficient to complete the task, groups often started raiding their friends for electrons, vertices and photons, hoping that an increased number of elements would provide for a solution. About a half of the groups concluded unassisted that, for all their efforts, a

2

valid diagram was impossible to create. Other (intentionally vague) questions asked to find a general rule, e.g. on the development of an electromagnetic shower initiated by a photon. In this case, showers could be seen to grow rapidly on the desks, but few students inferred that, however high, the number of the electrons produced is always equal to the number of the anti-electrons.

That is not a negative result per se, though. As a matter of fact, no group stated that they had found a solution to an impossible question, as they could not create it explicitly. Moreover, passing from frustration to “Ah, that’s right!” when receiving the explanation that the structure of vertices implies a conservation of electric charges, probably impressed students more deeply than the previous, easier diagrams.

On some occasions a different questionnaire was used, with the objective of comparing the results of the students working with the mechanical version of the diagrams and the answers of those who could only use pen and paper. The new questionnaire explained Feynman rules and gave a list of five processes to be created, two of which were impossible ones. Though of dubious reliability for statistical purposes, a reassuring result was recorded. The groups working only with pen and paper made more mistakes, producing diagrams that either referred to non-relevant processes, or contained a vertex different from the one of QED, such as three afferent electrons. Particularly, students did not realise that they had proposed an impossible process, precisely because they did not notice that they had used a non-existent vertex. By contrast, the answers of those working with mechanical pieces corresponded to their questionnaires, that is, whether students noticed or not that a given process was impossible, they did not create any wrong diagrams.

What remains after some time?

In one case, the effectiveness of the project could be verified after a certain amount of time. Forty days after the demonstration, twenty-one students in their third year of scientific high-school were given a test made up of ten questions, which were similar to those presented above. Only pen and paper could be used, without resorting to the models of Feynman diagrams.

The percentage of correct (C), incomplete or partially correct (P), and wrong (W) answers, and not tried (NT) questions are shown in the table.

Questions	***C***	***P***	***W***	***NT***
Orient the axis of time so as to render object A a positron and object B an electron: A: → B: ←	76	0	19	5
Draw a diagram representing the interaction $e^+ e^- \rightarrow e^+ e^-$	81	14	5	0
Create, if possible, the diagram representing $\gamma e^- \rightarrow \gamma e^+$	71	0	24	5
If the process is not possible, explain why	62	14	24	0
Draw the diagram representing the interaction $e^- e^- \rightarrow e^- e^-$	66	10	10	14
Can the same diagram represent $e^+ e^+ \rightarrow e^+ e^+$?	86	14	0	0
What needs to be done?	76	10	14	0
Represent the process $\gamma e^- \rightarrow e^+ e^- e^-$	62	14	14	10
Represent the process $e^+ e^- \rightarrow \gamma\gamma$	67	0	19	14
Comment on this process	24	24	24	28

Percentages of correct (C), incomplete or partially correct (P), and wrong (W) answers, and not tried (NT) questions.

It may be observed that all questions but the last one were answered correctly by more than sixty per cent of the students. The most difficult questions were those concerned with the creation of complex diagrams (questions 7 and 9). However, the percentage of success is surprisingly high in these cases as well, considering that the students did not have three-dimensional objects at their disposal, thus being more prone to mistakes.

Correct Answers	***From 0 to 1***	***From 2 to 4***	***From 5 to 7***	***From 8 to 10***
Percentage of students	10	10	33	47

The process $\gamma e^- \rightarrow \gamma e^+$ was recognised as an impossible one by fifteen students out of twenty-one. When comparing that with the results of the tests with people allowed to use only pen and paper, who were able to recognise an impossible process much more rarely, the conclusion can be reached that students remembered the law of conservation of electric charges (‘discovered’ during the demonstration), and did not even try to create a relevant diagram.

A total of eighty per cent of the subjects answered more than five questions correctly. With all due caution as to its statistical significance, this result exceeds all the most optimistic expectations.

Fig. 13 The objects while being used

Final considerations

Over and above the ‘explanations’ of the concepts listed in paragraph 3, the experiment was significant for the questions it aroused. Some of them were particularly rewarding because they were completely unforeseen, but above all because they revealed that curiosity had been whetted to an unexpected depth.

‘What’s the speed of a virtual photon?’ ‘Shouldn’t it travel at the speed of light?’ ‘But how can a photon be a particle, since Einstein said that nothing can travel at the speed of light?’ ‘How can I know whether virtual particles really exist?’ ‘Can I see a photon as ‘containing’ an electron and an anti-electron?’

When there is insight and motivation on the part of the teachers, as was the case with many of those we were lucky to meet for the project, Feynman diagrams, although not included in official syllabuses, can actually stimulate wide-ranging debate and further studies.

By way of conclusion, a hope and a provocation. Aesthetics is one of the main guidelines for physicists, when they are called upon to formulate or accept new theories, because it is linked to qualities such as simplicity, economy and symmetry. Can an aesthetical sense be conveyed, together with the notions discussed above? For example, the beauty of QED is due to its having one basic vertex only, from which all electrodynamic processes are reproduced. Imagine a theory needing more vertices to explain the same phenomena: for instance, a vertex for absorption and another for the creation of couples of electrons and anti-electrons (a situation that a physicist would describe as extremely anti-economical and consequently ‘unaesthetical’). What would a non-physicist choose if he or she were to provide an aesthetical judgement on the two possibilities?

Future developments

There are two preliminary questions to be faced before imagining the widespread use of the game developed by the author, thus going beyond the “door-to-door” demonstrations in schools: the pieces must be built more economically, and the subject of the game and the basic rules should be introduced differently, without the presence of the author or a representative of his. In the context of schools, an obvious solution to the second question would be the institution of training courses for particularly interested teachers. In this case, however, the problem of the cost of the objects remains, owing to the currently long time required for preparing the cylinders that represent the interactions.

Dramatically different solutions are now the subject of reflection, solutions capable of reducing the cost of producing a large amount of pieces which would be much smaller than the prototype. Such objects could be sold together with scientific journals, and sold or distributed free in science museums and exhibitions. A comic-strip character (which is being invented) would substitute the key figure of the ‘presenter’. The comic strip and the diagram kit would be accompanied by a booklet containing the questionnaires in a quiz form, and images and information on particle physics and the innumerable applications of QED.

A second line of development, not in contrast and indeed in synergy with the former, would extend the method of Feynman diagrams to the Standard Model, the theory that makes QED general. Indeed, after mention has been made of electrons, anti-electrons and photons, attention is also deserved by other inhabitants of the world of particle physics: neutrinos, muons, quarks, etc. For practical reasons, a game containing all of these elements is unthinkable, but computers and the Internet can provide interesting solutions. There are programmes, developed for professional purposes, that generate all Feynman diagrams of the Standard Model when a process and the maximum number of vertices have been entered. Therefore, a website to be created – for those who have already handled the tangible version of the diagrams – may provide non-expert users with one of these programmes. The most natural context for such an application would be a website devoted to the popularisation of particle physics, where each process could be linked to an explanatory text and images of the phenomenon as seen in a particle accelerator, for instance.

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