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ISSUE 01 OCTOBER 2019 *Manifesto*

VISUAL CULTURE IN QUANTUM MECHANICS

IMAGE-BASED KNOWLEDGE MAKING IN A NON-INTUITIVE WORLD

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ESSAY 25/01

VISUAL CULTURE
QUANTUM MECHANICS
IMAGE-THINKING

According to a large portion of scholars, mainly coming from the fields of theoretical and experimental physics, quantum mechanics is a particularly challenging subject both to be translated into images and to be communicated without an extensive visual apparatus. This ambiguity is directly connected to the original principles of subatomic physical theories and its peculiar knowledge making routine that, historically, associates mathematical theoretical framing with iconic modeling and analogies storytelling. This research deals with some emblematic issues of quantum theories retracing some branch of image-based quantum modeling with particular attention to the visual knowledge-making that underlie the physics of subatomic particles. These examples allow to build a rhizomatic genealogy of graphical interpretations that goes back to first the atom sketches drawn by Rutherford in 1910, at the dawn of the conceptualization of electron nucleus relationship and find its maximum expression in the huge graphic and drawing production of Nobel laureate Richard P. Feynman. We know that the great majority of the quantum phenomena are hardly describable beyond the equations and the probability calculations, however the visual languages continue to play an important role in particular within the communication, training and physics learning processes.

Scientific thought is a development of pre-scientific though.
A. Einstein

There are only a few images that are not forced to provid meaning, or have to go through the filter of a specific idea.
J. Baudrillard

IN THE BEGINNING WAS THE IMAGE

For just over a hundred years the physical sciences have been coming to terms with two pillars that have brought together the entire history of knowledge: the Theory of Relativity and Quantum Mechanics. These are two essential and correlated joints that have rewritten first the whole Newtonian physics and have set the stage for particle physics, leading to the experimental discovery without which much of contemporary technology would not be possible. Both theoretical bodies, which still today are not entirely mutually consistent, are triggered by a series of new visions, models, and analogies in an attempt to understand and reconstruct the behavior of elementary particles and their relation to macroscopic phenomena. It is above all a matter of great intuitions: Einstein is notoriously the first of the early twentieth century visionaries to whom we owe the compact and elegant elaboration of the theory of relativity, but we cannot forget the propulsive and imaginative force of the great number of scientists and Nobel winners that, starting around the 'father' Niels Bohr, have assembled step by step the bricks of today's Standard Model. In the following paper I would like to try to trace some elements that connect the way to build knowledge around just a few of the nodal problems arising from the interweaving of the Relativity revolution and that of Quantum Mechanics.

In particular I will try to connect some examples that show the central importance of the visual processing and the image-based modeling in the construction of quantum physical foundational knowledge, starting from the operational necessity of drawing as an 'only-apparently' neutral language.

There is no denying it: the most common basic knowledge of the atomic world is, first of all, visual. The simple planetary model of the Bohr atom, with its iconic nucleus of neutrons and protons, and the globes of electrons on circular orbits, is indelibly engraved in our optical memories: pity that it is a completely inconsistent visualization with respect to the theories of Bohr himself and all successive developments. I It is not a question, in this case, of discussing the effects of quantum theory on popular culture, but of trying to undermine some common places still present in the same scientific community of contemporary physics that sometimes tend to confuse and overlap the aesthetic-artistic values of visual-conceptualization than maieutic-hermeneutic ones. Nonetheless there is the need to investigate personal research approaches that are very different from one another, even when the final results are common. That modern physics owes much to geometric and visual abstraction is a fact, however it is necessary to understand how the two revolutions of physics at the beginning of the twentieth century have changed the relationship between the construction of scientific knowledge, the scientific dissemination and the growth of a collective imagination. To grasp some of the most significant aspects of the question it may be useful to focus on some of the steps that led to the birth of the current Standard model and to leave in the background the centenary debate concerning the conflicts that cause general relativity to collide with quantum mechanics. The main reason for this choice concerns an evident need for subatomic sciences to use visual language to hypothesize new interpretative models, in a world of the extremely small, where almost nothing is literally and really 'visible'. However, scientific modeling involves a series of cognitive and theoretical actions that lead to the formulation of a new 'overview': "A scientific model is a conceptual system mapped, within the context of a specific theory, onto a specific pattern in the structure and/or behavior of a set of physical systems so as to reliably represent the

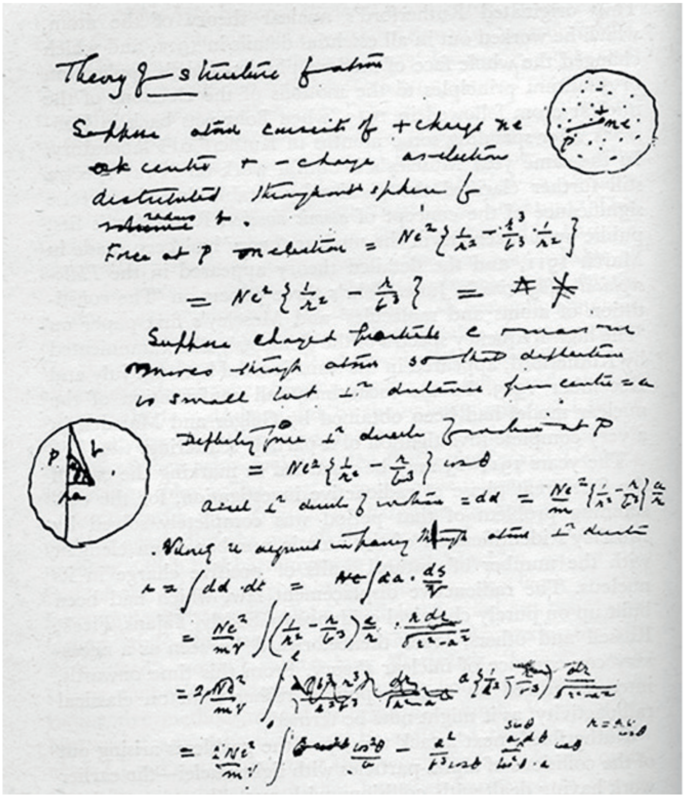


Fig. 1 A page of Rutherford's early undated (1910) rough notes, with the first sketch of the electron-nucleus structure of the hydrogen atom, from Birks, 1962, p. 70.

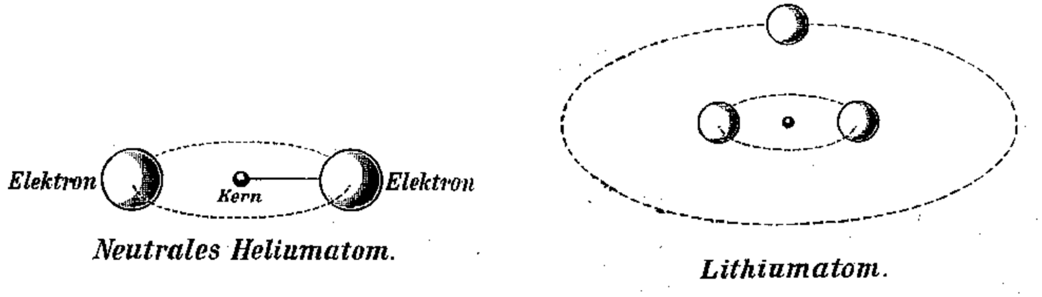
pattern in question and serve specific functions in its regard." (Halloun, 2004, p.131) One of the hypotheses of this work is that the 'mapping of a conceptual syste' is indelibly linked to the visual forms with which this system is initially processed.

In many ways it is perhaps useful to start with the atom. The first visual model of an atom as now conceptually and mathematically understood can be found in a sketch by Ernest Rutherford of 1910. It is a radical new representation, the result of the reworking of a long experimentation made by Hans Geiger and Ernest Marsden bombarding a gold sheet target with α-particles, described in this way by Rutherford himself: "The atom is supposed to consist of a central charge surrounded by a uniform distribution of the opposite sign through a sphere of radius R."(Rutherford, 1911, p. 669).

It is quite clear how fundamental is the visual assonance with a planetary system and also why an image so revolutionarily simple has remained fixed in the collective imagination well beyond the demonstration of its ineffectiveness. The entire page of Ruterford's notebook (Fig. 1) is a fascinating interpretative apparatus: a set of annotations, equations, small geometric vector patterns and a single 'foreign' drawing to the accuracy of scientific discourse, a small dirty and inaccurate sketch that will change the course of the history of modern scientific thought. As we know, the first image of hydrogen, the simplest of atoms, is a visual conceptualization that simplifies and abstracts theoretical mathematical considerations, and indirect proofs to capture the essential features of a new interpretation, however it is very curious to see how the application of the model to other atomic systems, as in the case of uranium, make a late nineteenth century visual cultural milieu, dominated by the order of Euclidean geometry, re-emerges powerfully.

The power of these symbolic atom images (Fig. 2) born within a precisely connoted scientific cultural context around the Copenhagen school, turned out to be much more long-lived than the theories that led to its elaboration. Anyhow much of the popular work has been accomplished through a very successful scientific text coauthored by Danish science critic Helge Holst and Dutch physicist and collaborator of Niels Bohr, Hendrik A. Kramers: *The Atom and the Bohr Theory of its Structure*, first published in Danish in 1922, the year in which Bohr received the Nobel Prize, and then translated into

Fig. 2 The Bohr model of helium and lithium,Graetz, 1918, note 19.



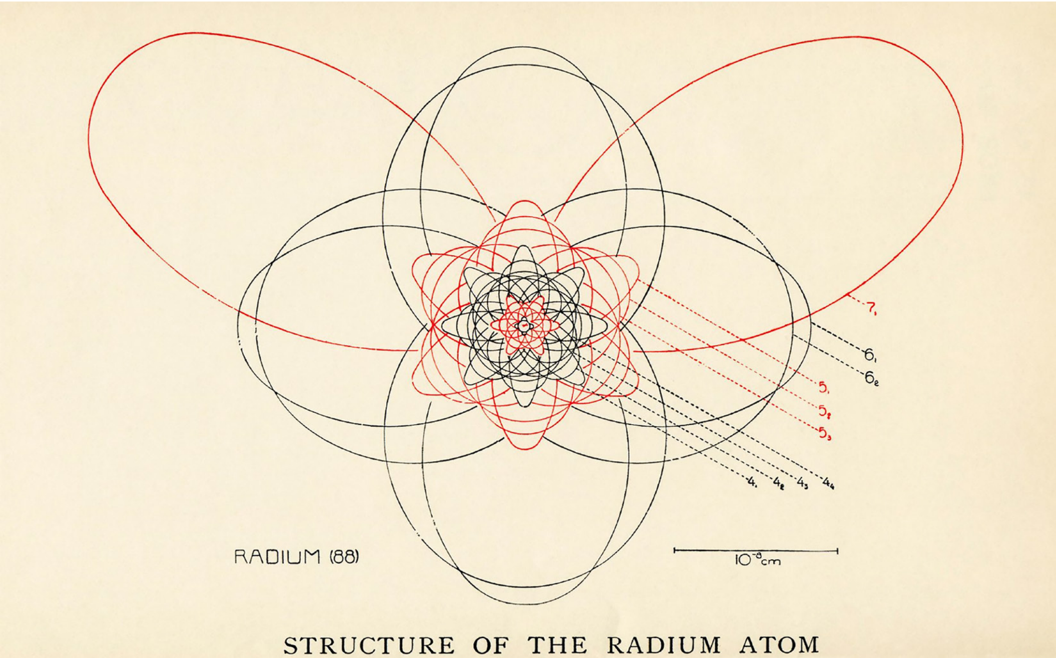


Fig. 3 The first image ever of the Structure of the Radium Atom, from Kramers-Holst, 1922, table 2.

English and published worldwide between 1923 and 1925.

The Kramers-Holst book has, among other things, two peculiar characteristics: on one hand it tells with scientific accuracy, but without a great use of mathematical modeling, the phases of the work through which Bohr reaches the formulation of his atomic model; on the other, for the first time ever, in two famous final tables it uses the geometric drawing to visualize the patterns of the fascinating and complex structure of the 88 electron orbits of a radium atom nucleus (Fig. 3).

These are images that Bohr himself will use to present his theories to the scientific community until the end of the 1920s although their strong simplification represented a double-edged sword: it allowed an intuitive pictorial summary but hid all the uncertainties of a highly counterintuitive and completely distant from the static nature of classical mechanics physical reality: “While the general public, when presented with the Kramers-Holst pictures, could hardly avoid believing that these were nearly authentic representations of what atoms really look like, specialists in atomic theory were well aware that a model should not be confused with reality. Although Bohr and Kramers considered the pictures as symbolic rather than concrete representations, still in 1923 they had little doubt about the reality of the electron orbits. Sure, the atom did not look like the picture, but it might still be something like it." (Kragh-Nielsen, 2011, p. 45) For the first time, with this text, a great work of reducing the divide between the most recent elaborations of particle physics and collective knowledge is taking off. The scientists of the Copenhagen group and their successors continue to deal with a mostly incomprehensible world, completely away from everyday perceptions, partially explained by a complicated mix of mathematical language, non-Euclidean geometries, non-visual models:

"The new physics and mathematics made it clear to everyone that scientific knowledge was difficult to access, bordering on the incomprehensible. Whereas, previously, popular science could be seen as an extension of scientific epistemology in public domains, the new physics required translating sophisticated mathematics and highly technical language into everyday language and simple cognitive models, such as images of the atom as a planetary system." (Kragh- Nielsen, 2011, p. 4). Bohr and Kramers knew perfectly that the orbital representation of the atom is nothing but a symbolic simplification, but they also understood the communicative value of these new images.

A few years were enough for guy for the youngest Pauli and Heisenberg to theorize a more radical and complex atomic structure even more difficult to become an image, refuting the existence of real electron orbits. Shortly thereafter with De Broglie and Schrödinger the first visual metaphor becomes completely broken: electrons prove to exist only when they interact with each other, they are clouds of probability with a density given by the solutions to the three-dimensional Schrödinger equation. Why, working with the increasingly intricate, multidimensional, counterintuitive and probabilistic subatomic world, scientists have continued, throughout the 20th century, to 'play' with visual languages, making it appear even when it seemed only the legacy of nineteenth-century mechanistic culture? Some answers to this question come to us directly from the scientific modus operandi of several of the major physicists of the second half of the century. It is commonly believed that two of the great fathers of the space-time revolution like Minkowski and Einstein were a visual thinker, although with different approaches:

"If Einstein may be said to have thought in concrete visual terms, running thought experiments through his mind, Minkowski thought in geometric visual terms. Where Einstein manipulated clocks, rods, light beams, and trains; Minkowski played with grids, surfaces, curves, and projections." (Galison, 1979, p. 40) but it could be fruitful to try to go further, for example by looking for 'the visual', in a broad sense, in the scientific attitude of Paul Dirac or Richard Feynman. Dirac and Feynman are just two of the possible examples, but they represent two ways of constructing scientific knowledge that are very distant from each other, while dealing with liminal quantum issues. They're two very prominent scientific personalities, both Nobel laureates, both central figures in the elaboration of the Standard Model, both sharing an unexpected interest in the world of images and drawing, although with different attitude and implications.

DIRAC'S INTIMATE GEOMETRICAL IMAGE-THINKING VS FEYNMAN'S ICONIC ENTHUSIASM

Paul Adrien Maurice Dirac was an eminent theorist, one of the most brilliant mathematicians of the last centuries, we owe to his theoretical work some of the most important theoretical discoveries in the field of particle physics, such as antimatter. Dirac frequently declared his great interest in projective geometry, explaining its importance

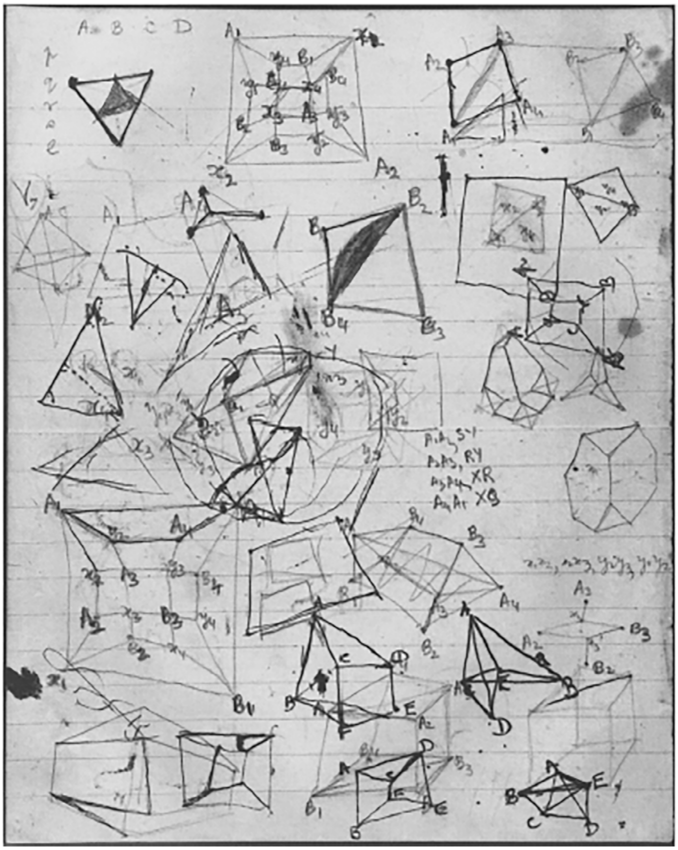


Fig. 4 P.A.M. Dirac, Geometrical Sketches, in Galison, 2000.

in terms of capability to interpret complex spaces, starting from curved ones: “Any kind of geometrical picture may be quite unworkable; there might be too many variables; too many to mention, so that it is quite hopeless to try to think of it. But usually so, there might be parts of the work which can be pictured geometrically, and I find that I can get a great deal of help by using these geometrical pictures whenever possible; the pictures bring out clearly, in my mind, the relationships between the quantities and point the way to getting further relationships.”(Dirac,1972, p. 2)

Peter Galison’s seminal research (Galison, 2000) allows us to grasp a nodal and odd aspect in Dirac’s way of researching: on the one hand strongly image-based and on the other monolithically mathematical and anti-visual.

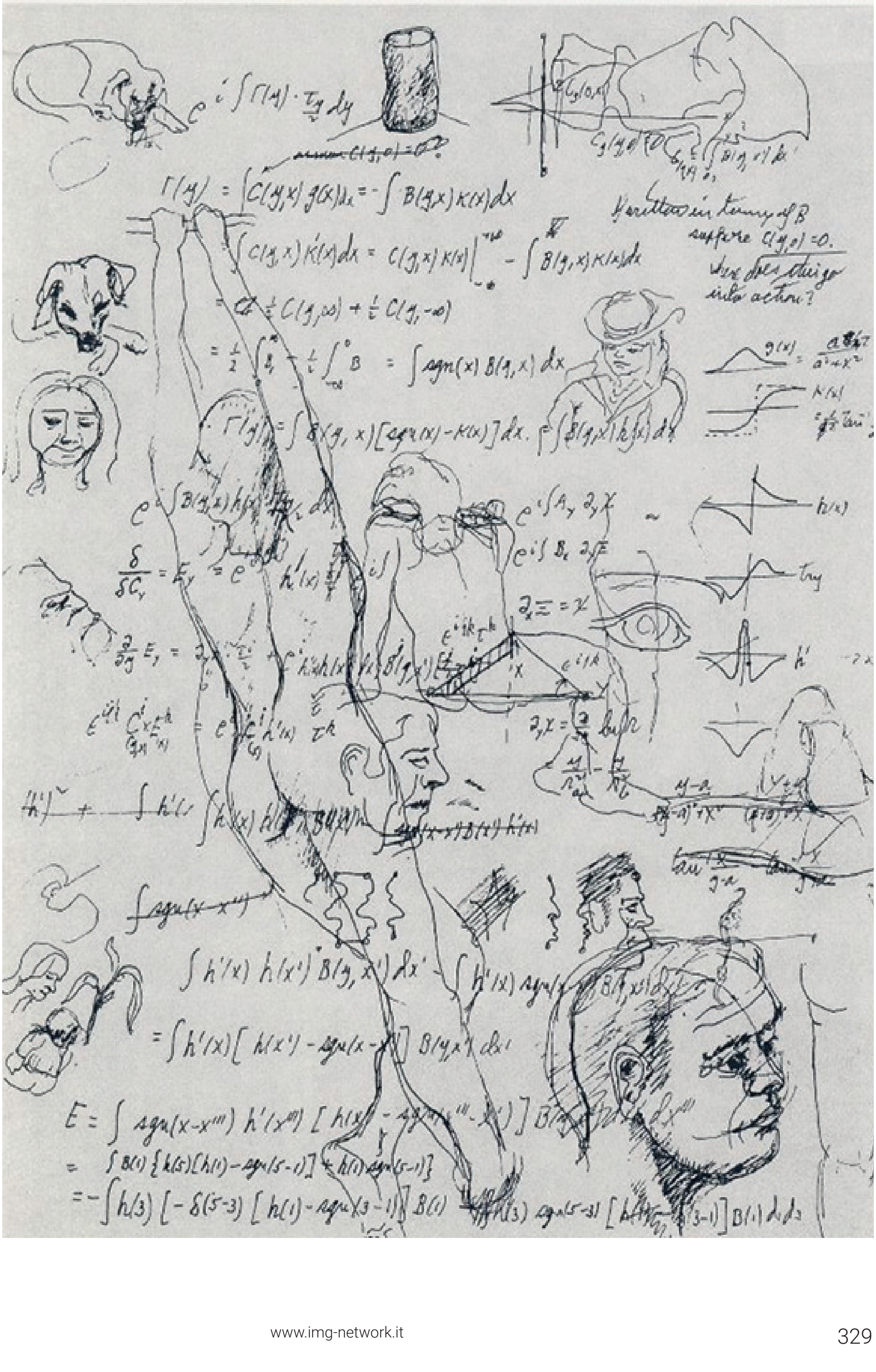
Projective geometric thought remains a personal, private tool for Dirac: his intricate and beautiful sketches are the thread of Penelope in his own intellectual labyrinth (Fig. 4).

"These pictures were not for pedagogical purposes: Dirac kept them hidden. They were not for popularization even when speaking to the wider public, Dirac never used the diagrams to explain anything. Astonishing: across the great divide of visualization and formalism that has, for generations, split both physics and mathematics, we read here that Dirac published on one side and worked on the other." (Galison, 2000, p. 146)

The reasons for this dichotomy are many, but the need to understand the plurality of ways in which the use of images remains quintessential. In any case Dirac's scientific behavior helps us to highlight a non-secondary aspect: the multiple intertwined paths of modern and contemporary quantum physics do not exclude nor contrast the rigid logic structure of the mathematical language with the instinctive persuasiveness of the images. It is therefore not a question of an opposition; visual thinking is one of the ways in which the new models of the subatomic world are first elaborated and then disseminated. Yet these considerations does not allow us to simply dismiss the issue.

How is it possible within a world so intrinsically anti-visual and non-intuitive that the apparatuses of knowledge production are still so tied to our need for images? And again: why the approach of individual scientists to the visual culture problem is so strongly different? Some further clues can be offered by the mind and the prolific drawing hand of Richard Feynman. Feynman is basically a mythological figure in the scientific world starting from the immediate post-war period. His reputation is not due exclusively to his work and his discoveries, but also to his very personal way of teaching and disseminating challenging topics such as the electrical interactions between elementary particles and the foundation of quantum electrodynamics. Observing him from the point of view of his relationship with visual imagery Feynman could be stigmatized as a particular kind of 'anti-Dirac'.

Fig. 5 R. Feynman, equations and sketches, from Feynman, R., & Feynman, M., 1995.



$\Gamma(y) = \int C(y,x)\,g(x)\,dx = -\int B(y,x)\,K(x)\,dx$

All the aspects of the drawing are pervasive in his work and it is precisely thanks to the conceptual simplification of the symbolic drawing that will come to the formulation of his famous diagrams. His schemes build a visual graphic translation of the interaction between particles, making a long sequence of mathematical formulas understandable and communicable. These representations work in a radically different way than the visual model of the Bohr atom: they schematize a particles behavior, simplify the boundary variables to capture the essence of a quantum interaction. They do not try to explain how a subatomic entity looks like, but they build a visual demonstration of how some subatomic systems interact with each other. If in quantum physics everything is interaction the images (for whatever purpose they are used) always partially capture the complexity of the problems, they are a first step or a step after the mathematical formulation, they only freeze the possibility of a stable solution. Synthesizing this point with Wittgenstein's words we could say: "The picture depicts reality by representing a possibility of the existence and non-existence of atomic facts.", and again: "The picture contains the possibility of the state of a airs which it represents" (Wittgenstein, 1922, 2.201, 2.203)

There is something that is both steady and unbalanced in the representation of images of the physical world, and the universe of the extremely small become even more complicated: also for this reason it is necessary to clarify the way in which scientists themselves use images, this cam help us to understand more clearly the role of imagination in a field only apparently enclosed in mathematical exactitude.

From this point of view Richard Feynman is a real well of surprises: his almost tactile interest in the uncertain world of images (Fig. 5) led him to start drawing not only on the blackboards of his lessons (Feynman, 1995). In the final part of his career he becomes an excellent draftsman, well beyond the frontiers of physics. His diaries are full of portraits, bodies, faces, places in a creative crescendo that always has the drawing as an expressive pivot.

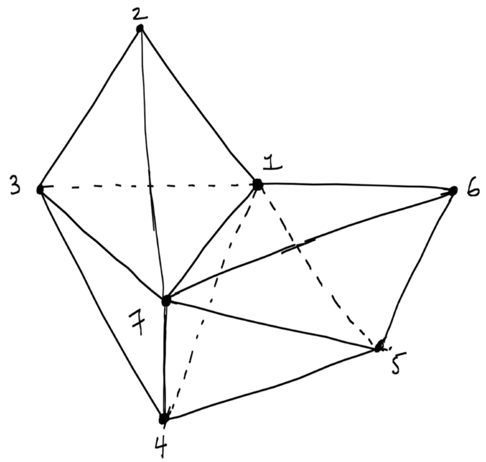


Fig. 6 The amplituhedron, from Arkani-Hamed, N., & Trnka, J., 2014, p. 7.

Condensing Feynman's work, running the risk of violent simplifications, also means appreciating the great variety of creative uses through which he let visual thinking guide his knowledge making: from the intuitive elaboration of concepts to the schematic formalization, from the nebula of contrasting images to communicative graphic coding.

MORE AND MORE INVISIBLE, MORE AND MORE IMAGINE(D)

These two prominent examples are actually just the tip of the iceberg that deserves persistent re-elaboration starting from an essential thought: to imagine how things can be and how physical systems can work means first of all looking for a supposed *visualizability* (Miller, 1984), no matter how impossible it is to be satisfied with the result. We are guided by a necessity which is also an anthropological and cognitive limit: a visual seduction that can only be transformed into an effective knowledge tool through great critical awareness. Moreover a perceptual and semantic short circuit must be reversed: it is not essential to understand first how images look but what they can do, how and where they can help us and above all how to weaken their core limits. Current developments in quantum physics are a very rich visual testing laboratory: the most advanced and still young theories (supersymmetries, strings and quantum gravity) deal with areas of matter that are too small to be indirectly displayed or too far away for today's instruments, putting a strain on the scientific need for experimental confirmation.

However, we are constantly looking for achievable images: as in the massive collaborative work that led to the elaboration of the first 'photo' of a black hole. It is also thanks to the work of dozens of physicists visual-thinkers that we have freed ourselves from the misunderstanding, of a nineteenth-century rationalist matrix, that assigned a neutral and objectifying value to the images. In today physics visual languages have dozens of operative and communicative declinations and images have not at all 'stopped working', indeed they reappear inside the most unexpected theoretical toolboxes.

A symbolic case is the powerful visual intuition of the amplituhedron. It is a geometric-visual matrix calculation tool, introduced in 2014 by the theoretical physicist Nima Arkani-Hamed which allows an incredible simplification in the calculation of interactions between elementary particles. Arkani-Hamed completed and leads to unexpected consequences the visual modeling of Feynman's elementary interactions proposing a visual shortcut, making technically possible calculations that previously were not.

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