AUTORICERCA

When minds entangle

My meeting with Diederik Aerts

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I studied physics at the University of Lausanne, in the eighties of last century, where I had the chance of learning quantum mechanics from *Gérard Wanders* and *Dominique Rivier*, two students of *Ernst Stueckelberg*, and from *Jean-Jacques Loeffel*, a student of *Pauli* (see Figure 1). Later, I was assistant to *Constantin Piron*, in Geneva, for his famous course in quantum mechanics. Constantin was also a student of Stueckelberg, as well as of *Josef Maria Jauch*. I then went doing my doctoral thesis with *Philippe-André Martin*, a college friend of Piron and also a student of Jauch. In other words, I had the chance of learning quantum mechanics from people who received the highest possible level training into it, and who were truly interested and invested in understanding it, both mathematically and conceptually.

Constantin Piron

Philippe A. Martin

About the teaching of quantum physics, Jauch wrote the following observation, back in 1968, which is still relevant today:[1]

> There are many students everywhere who pass their examinations in quantum mechanics with top grades without really understanding what it all means. Often it is even worse than that. Instead of learning quantum mechanics in parrot-like fashion, they may learn in this fashion only particular approximation techniques (such as perturbation theory, Feynman diagrams or dispersion relations), which then lead them to believe that these useful techniques are identical with the conceptual basis of the theory.

[1] Jauch, J. M. (1968). *Foundations of quantum mechanics*, Addison-Wesley Series in Advanced Physics, Addison-Wesley, Reading, Massachusetts.

> This tendency appears in scores of textbooks and is encouraged by some prominent physicists.

When in more recent times I got in touch with *Diederik Aerts*, after quite a long time I had not practiced physics anymore, I believe it is only because I had such authoritative teachers, providing me with the right perspective and mental posture, that a fascinating and fruitful collaboration could develop, later also with other collaborators of his very dynamic *Brussels group*, particularly *Sandro Sozzo* and *Tomas Veloz*, but also *Christian De Ronde*, *Lester Beltran*, *Lyneth Beltran*, *Suzette Gerente* and *Jonito Aerts Arguëlles*.

Figure 1 A photo from the early nineties. I am the second from the left. In the center, with the jacket, is Jean-Jacques Loeffel, with whom I did my diploma thesis. The penultimate in the row is Gérard Wanders, who founded the Institute of Theoretical Physics at the University of Lausanne, and Paul Erdös is on the far right.

Diederik was also a student of Constantin Piron, in fact he was the student Piron considered to be the most brilliant, who really took over the legacy of the Geneva school and brought it to a new phase of important developments and discoveries. When I was in Geneva – this was in the years 1990-1991 – I was not lucky enough to meet Diederik, as he obtained his PhD in Theoretical Physics ten years

before, in 1981. However, being daily in contact with Constantin during my stay at the *Département de Physique Théorique*, many times I heard his name pronounced by him, always with great admiration and emotion in his voice. For example, in relation to his more precise formulation of the key notion of *element of reality* in his thesis,[2] Piron wrote (translation from French is mine):[3]

> At first sight, it seems that there would be a conceptual difficulty in attaching properties to the empty space, like for example affirming that it is almost Euclidean and that there is a field of gravitation. Indeed, how to verify such statements without having to introduce apparatuses and in this case, we no longer have the vacuum. This apparent paradox has been solved par Dirk Aerts, thanks to a precise formulation of the notion of element of reality, together with a precise definition of the experimental projects. Indeed, according to Aerts, an experimental project is an experience, which we could certainly possibly execute, such that the positive outcome has been defined once for all. In full accordance with Einstein's definition, Aerts then claims that the system possesses an element of reality, and that the property is

[2] Aerts, D. (1981). *The One and the Many: Towards a Unification of the Quantum and Classical Description of One and Many Physical Entities*. Doctoral dissertation, Brussels Free University.

[3] « A première vue, il semble qu'il y aurait une difficulté conceptuelle à attribuer des propriétés à l'espace vide, comme par exemple affirmer qu'il est quasi-Euclidien et qu'il y règne un champ de gravitation. En effet comment vérifier de telles affirmations sans devoir y introduire des appareils et dans ce cas on n'a plus le vide. Cet apparent paradoxe a été résolu par Dirk Aerts grâce à une formulation précise de la notion d'éléments de réalité jointe à une définition précise des projets expérimentaux. En effet selon Aerts, un projet expérimental est une expérience, qu'on pourrait fort bien éventuellement exécuter, et dont le résultat positif a été défini une fois pour toutes. En plein accord avec la définition d'Einstein, Aerts prétend alors, que le système possède un élément de réalité et que la propriété est actuelle, si on peut affirmer par avance que dans l'éventualité de l'exécution du projet correspondant la réponse positive est certaine ». Piron, C. (2002). Introduction à la Physique Quantique, *arXiv:physics/0204072 [physics.gen-ph]*.

> actual, if we can affirm in advance that in case of execution of the corresponding project, the positive response is certain.

Diederik's name and work are also mentioned in all the important later texts written by Constantin. In his 1990 book of quantum mechanics, elaborated in part from the typewritten notes of his previous course (see Figure 2), he writes in the preface (translation from French is mine):[4]

> Ten years ago, the orthodox reached the goal, paradoxically they all agreed to give reason to both Bohr and Einstein. Certainly, quantum physics was more complicated, but under no circumstances and in no way the deep realism of the experimental physicist had to be abandoned. It is then that, pursuing this approach, D. Aerts, of the Free University of Brussels, defended a thesis, *The One and the Many*. By his fine-grained analysis, in everyday naive terms, he discovered and then demonstrated the impossibility of a suitable vectorial scheme for the description of separate quantum systems. He solved the famous paradox of Einstein, Podolsky and Rosen and at the same time demolished two of the four axioms of 'quantum logic'. The theory was totally renewed and almost miraculously freed from other paradoxes.

[4] « Il y a dix ans les orthodoxes touchaient au but, paradoxalement ils s'accordaient alors tous pour donner raison à la fois à Bohr et à Einstein. Certes la physique quantique était plus compliquée, mais en aucun cas et d'aucune manière le réalisme profond du physicien expérimentateur ne devait être abandonne. C'est alors, que poursuivant cette approche, D. Aerts de l'Université Libre de Bruxelles, soutenait une thèse, *The One and the Many*. Par son analyse fine, en termes naïfs de tous les jours, il découvrait, puis démontrait l'impossibilité d'un schéma vectoriel adéquat a la description des systèmes quantiques sépares. Il résolvait ainsi le célèbre paradoxe d'Einstein, Podolsky et Rosen et démolissait du même coup deux des quatre axiomes de la 'logique quantique'. La théorie en était totalement renouvelée et débarrassée quasi-miraculeusement des autres paradoxes ». Piron, C. (1990). *Mécanique quantique. Bases et applications*, Presses polytechniques et universitaires romandes, Lausanne.

The importance of Diederik's thesis was also stressed by *Bastiaan Cornelis van Fraassen*, in his book of quantum mechanics:[5]

> The three main issues in the philosophical foundation of quantum mechanics are measurement, the paradoxes and the problem of identical particles. Each of these concerns the composition of several systems – sometimes interacting and sometimes not – which is a subtle matter in quantum mechanics. Dirk Aerts very aptly sums up these issues as the problem of the One and the Many, which has here taken on a new form of life.

Figure 2 Piron's books are always in plain sight in science libraries, for example here at the EPFL Learning Center, in Lausanne. Photo, courtesy of Françoise Piron.

[5] Van Fraassen, B. C. (1990). *Quantum mechanics: an empiricist's view*, Clarendon Press, Oxford.

To come back to me, following my PhD in Lausanne, during which I worked on one of the traditional subjects of research of the Swiss school of mathematical physics – non-relativistic scattering theory and the problem of time-delay, – and after having spent the ten subsequent years working as a manager in the industry, in 2004 I decided it was the moment for me to (at least try to) go back to my passion of all time: research and teaching. It was then that Diederik's name, whom I had heard so many times from Constantin, resounded again in my mind. So, I went googling it, and discovered his very well-kept personal website, from which it was possible to download the preprints of all his published articles.

Reading his 1999 paper, entitled *The stuff the world is made of: physics and reality*,[6] was for me like an epiphany, and I remember that I immediately sent a letter (a traditional one, written with ink, on paper) to Diederik, in which I expressed, among other things, my admiration for his work. Here is an excerpt of it (the letter was dated September 8, 2004):

> Dear Prof. Aerts, [...] Recently, I had the occasion to read some of your outstanding works about quantum mechanics and relativity, which I succeeded to download from your website. I was already aware of some of the beautiful results of the Geneva-Brussels school of quantum mechanics, since in 1989 I was starting a PhD thesis under the direction of Constantin Piron in Geneva. But I was not aware of the great progresses done since that time. I have to admit that I am mostly impressed by the value of your findings which, to my opinion, are yet to be recognized as true milestones in the understanding of the physical reality (and possibly beyond), and certainly would deserve a better dissemination in the scientific community. [...] I would like to invest some time in trying to deeply understand the approach of the Geneva-Brussels school, of which I had a first taste in 1989. And I would very much appreciate your guidance on this [...].

[6] Aerts, D. (1999). The stuff the world is made of: physics and reality. In D. Aerts, J. Broekaert and E. Mathijs (Eds.), *Einstein meets Magritte: An Interdisciplinary Reflection* (pp. 129–183). Dordrecht: Springer.

I remember that I was quite disappointed not receiving any reply to my letter. So, I went purchasing two of the eight volumes of the *Einstein meets Magritte series*,[7] to read the articles published there more attentively and more deeply, and I then sent a second letter to Diederik, towards the end of that same year, this time including all sorts of questions and remarks about his work.

For instance, I was intrigued by his notion of *happening*, used to define the important notion of (personal) *experience*, which he considered to consist of two fundamental aspects, a *creation-aspect* and a *happening-aspect*, where, to quote from the previously mentioned 1999 paper: "a creation is that aspect of an experience created, controlled, and acted upon by me, and a happening is that aspect of an experience lending itself to my creation, control and action." So, I asked in my letter:

> You use the concept of *happening* in replacement of the concept of *event*, of which it is a generalization. However, to my opinion, the concept of happening is redundant with the concept of *existing*. What I think is new in your description is not so much the concept of happening, but the fact that you have given a very simple, natural and, more importantly, operational definition of existence: something exists in my present if this something is available to me to be experienced (if I only decided so in my past). Thus, my present reality is the collection of all things existing in my present, and all things existing are by definition those things which are available to my experience.

I was also very intrigued by his *creation-discovery view*, and in relation to the notion of *observation*, I also asked:

> I have found myself a little confused when you define the second aspect of an experience – the happening – as the observation-aspect.

[7] Some of Diederik's review papers were published in the proceedings volumes of the *Einstein meets Magritte* conference, an interdisciplinary reflection on science, nature, human action and society, of which he was the scientific and artistic coordinator.

> Indeed, if I understand your theory correctly, happenings are not usually observed, the characteristic of happenings being just of being available. But, as far as I understand, an observation is always an action on a piece of reality, thus affecting reality, and in that sense, it is in my view more like a creation. Indeed, also in the special cases when the observation doesn't perturb the entity, it will however perturb the surrounding of it, as well as the observer itself as a consequence of the cognitive act. Therefore, generally speaking, shouldn't an observation be considered as a special case of a creation? Of course, my difficulty is probably just related to the choice of the word "observation" in this context.

Diederik also expressed in a very clear way something that also fascinated me, which in a sense is under everyone's eyes: that *quantum non-locality* is just a word that hides a deeper possibility (provided we take quantum theory seriously enough). This deeper possibility is that our physical reality would be *non-spatial* in nature. So, always in that same long letter, I wrote:

> An important point you emphasize in your creation-discovery view is that we (as human consciousnesses) participate in the making of an entity and, consequently, also in the making of our perceived reality. Although we organize our macroscopic reality in a 3-d space, quantum non-locality shows that the micro-world cannot be fitted inside such a narrow 3-dimensional theatre. Furthermore, since the macro is made by a collection of the micros, one can also say that even the macro-objects cannot be considered as being entirely in the 3-d space, although they appear so to our senses. But this, on the other hand, means that the 3-d space is just a human construction, namely the way human beings (at least when in their intraphysical state) organize their perception of a higher dimensional entity of which the 3-d space may be looked as a kind of boundary. I have no objection to this, but then don't you think that this implies that there is no more room for the Einsteinian interpretation of relativity? Indeed, non-spatiality means reality contains space and not the other way around, that space (more precisely the physical space) contains reality. In other words, physical space is to be viewed as one of the

> entities composing reality (probably the boundary of a bigger higher dimensional entity). [...] Thus, if I travel in space what I'm doing is travelling through an entity, i.e., through the aether, so that my travel is a creation and the effect on my clock is the effect of a creation. Because my point is: if physical space is not, as you say so cleverly, an all-embracing setting, but just a human construct, then, strictly speaking, there is no space-time continuum in the sense of an (absolute) container of reality. Thus, relativity is just a dynamical effect and cannot be interpreted as a kinematical effect (due to a change of spatiotemporal coordinates). However, it seems that you take nevertheless very seriously the Einstein interpretation, and my question is then: Why? I know how risky is today to speak about the aether but, after all, don't you think that the creation-discovery view plus non-locality just mean that Lorentz interpretation is the sole possible relativistic interpretation?

Clearly, at the time I was more advocating for a Lorentz-like process view of relativity. This because I was considering that (see the above quote by Piron) if space has properties, then we must consider it as a sort of physical entity in which we are all immersed, and therefore moving through space would have effects, like precisely the slowing down of my clock if I decide to travel on a spaceship. Today I think I have changed my mind and consider space, and spacetime, more in a relational way, that is, a construction, hence not really a substance in its own, or if you prefer, not an ordinary substance. So, I'm back advocating more for an Einsteinian geometric view of relativity. But I must admit, my views on those fundamental topics are continuously evolving.

Note however that Einstein, different form Diederik, considered spacetime to be an overall theater for our physical reality, which is the reason why he could not digest the idea of *entanglement*, which he indicated as an unlikely "spooky action at a distance." The view on relativity emerging from Diederik's ideas is in that respect very different, precisely because of his abandonment of the "space contains reality hypothesis."

Anyhow, also this second letter of mine remained unanswered, so I just imagined that Professor Aerts was one of those extremely busy guys who, because of too many commitments, are unavailable to interact with unknown individuals, particularly if they are from outside of the academic world (as I was at the time). I'll find out later that I was completely wrong on that.

In those years (2006-2007), I started again teaching physics for some time, in Lugano's high school, so I had to go back to basic stuff, and had kind of learning again how to teach elementary concepts and notions to youngsters approaching the subject for the first time. Of course, the school program required to present a certain number of topics in the required way, so the room for maneuver was very small. Following a two-year teaching period, I then decided to concentrate on other things (I was also involved in teaching practices of inner exploration at the time, like yoga and meditation), but I remained with the desire to write something truly basic about physics, aimed at a very broad audience.

What came out is a book in which I tried to provide the readers what is necessary to understand the hypotheses, theories, reasonings and experiments that have characterized the great atom hunting over the centuries.[8] If I'm telling this is because, towards the end of the book, I mentioned that atoms, and more generally the elementary "particles," do not truly exist, and the reason of that is that they are not corpuscles, they are not waves, they are not fields, but truly "something else," something non-spatial. In other words, they exist, yes, but not as spatial elements of reality, not as little bricks or little waves, as people like to think them.

Of course, when in the last chapters of the book I tried to explain those kinds of things, I went back to my readings of Piron's and Aerts' texts, and more precisely the operational-realistic approach of the *Geneva-Brussels' school on the foundations of physics*, trying to find

[8] *L'atomo che non c'è – Viaggio alla ricerca dei costituenti ultimi dell'universo*. Published in 2010 on behalf of the author.

simple ways to explain how our reality construction works, and in particular devise simple situations that would explain that properties, during quantum measurements, not only are created by the measurements themselves (most of the times), but are also *ephemeral*.

Aerts conceived all sorts of "toy models" to explain the emergence of quantum structures, like the celebrated example given in his thesis of a wooden cube that has both properties of being burnable and floating on water, whose tests, however, are not compatible. Reflecting on his example, I came out at the time with the description of a situation where tests were not only incompatible, but also associated with ephemeral properties, that is, properties that do not remain actual immediately following a measurement, as it also happens with the microscopic entities (think of an electron that once detected in a given region, because of the so-called *spreading of the wave function*, almost immediately evolve in a state that is not anymore localized in it).

Maybe because of my Italian origin, my example was about a *raw spaghetti,* and the two incompatible properties I identified were its *solidity* and *lefthandedness*, defined in a very specific way, which I need not to explain here. Now, after having written the book, and self-published it,[9] I decided to try to distill some of its content in a didactically oriented article, curious to see if I was able to have it published somewhere. So, I drafted an article in which I duly referred to Aerts' and Piron's work, and of course also presented the example I found with the two incompatible experimental tests on a raw spaghetti, which I thought was a very nice illustration, on a macroscopic entity, of genuine quantum-like properties.

I did not think about sending the preprint of the article to Constantin, as I was not in contact with him since when I left

[9] Note however that in the end the example with the raw spaghetti was not published in this book, but included in a YouTube video; see *https://youtu.be/9C3vtVADL1o*. A slightly revised and expanded "transliteration" of the video can be found in *AutoRicerca 19* (2019).

Geneva, almost twenty years earlier, nor did I send it to Diederik, because of the negative impression I remained with my letters, not having received any reply, and also because I kind of feared that he would not find what I wrote particularly interesting. Since I was (and still am) a member of the *American Association of Physics Teachers* (AAPT), I first tried to publish it in the *American Journal of Physics* (AJP). Basically, the two reviewers liked the paper, but thought it was better to send it to a more philosophically oriented journal. In particular, the second reviewer wrote:

> I fully agree with this author's overall conclusion that there are no microscopic particles, there are only quantum fields. Many others have come to this conclusion, the most prominent (but surely not the first) being Steven Weinberg, whose statement about quantum fields forming the "essential reality" is often quoted. It's a view that physicists in general need to understand and adopt so that students (and physicists!) can finally begin to understand the QFT concepts behind QM, and so that many of the extravagant interpretations of QM will go away. But the author approaches this conclusion from a viewpoint that I think is too general and philosophical for AJP. His article is far longer and more comprehensive than seems justified for him to make his essential point. I'm not even sure he needs to belabor the meaning of "reality" by going back to the EPR definition. There are more direct ways of disproving the "reality" of micro particles. For example, Michael Redhead ("A philosopher looks at QFT," in Philosophical Foundations of QFT, ed. by H.R. Brown and R. Harre, Oxford UP, 1988) argues, correctly, that a particle ontology cannot be correct because of such observed quantum vacuum phenomena as the Lamb shift and the Casimir effect. In the quantum vacuum, there are no particles, only "zero-point" fields. The problem is really more educational than philosophical. Physicists and, especially, physics teachers still think in terms of the hopeless particle ontology. Many people (Weinberg, the author, Redhead, me, many others) have pointed out the incorrectness of this approach, and the confusion it's producing, but still the particle mythology persists. The problem is not in the physics, or in the philosophy, but simply in the education of the physics community

> to the "new" (but decades old) reality. How does one do this? I'm considering writing a popular book on this subject, and maybe the author should consider this too.

Long story short, following the advice I received, I sent the article to a philosophical journal (it was *The British Journal for the Philosophy of Science*), but they immediately told me that it was not suitable for their venue because it was not philosophical enough! Hence, I went back trying some other physics journals, in particular *Foundations of Physics*, as I published a paper there years ago,[10] together with Philippe Martin, in a special issue in honor of the sixty years of Piron,[11] and also because my article, however didactic, dealt with foundational issues.

The Chief Editor at the time was *Gerard 't Hooft*. He wrote to me directly and pointed out that my manuscript was too long and that the different arguments were not presented in a sufficiently sharp and focused way. He also pointed out again that it was more suitable for a philosophy journal, but he added that he would reconsider it if I would have improved the presentation, according to his suggestions, as I obviously did. But then the review was again not positive enough: the reviewer considered that the article did a good job in providing a good overview of a lot of well-established material (and therefore considered to be a fun read!), but according to him/her, I was not providing any original argument going beyond the existing literature.

I tried some other journals, even unusual ones, but had no luck, and in the end, I was surely a bit discouraged. I felt that the reviewers were all appreciating the content of the paper, but apparently not enough for accepting it. And I also felt, to be sincere, that they were

[10] Martin, Ph. A. & Sassoli de Bianchi, M. (1994). Spin precession revisited. *Foundations of Physics 24*, pp. 1371–1378.

[11] Aerts, D. (1994). Continuing a quest for the understanding of fundamental physical theories and the pursuit of their elaboration. *Foundations of Physics 24*, pp. 1107–1111.

not fully understanding all its nuances. These were feelings that I would experience many times in the years to come, working with the Brussels group, as the approach of this school seems to be able to raise strong idiosyncrasies in many researchers, not always founded on rationality, which should probably be investigated more from the perspective of psychology and sociology than physics.

On the other hand, it is also true that I was not expecting too much at the time, as I was not publishing a regular scientific paper since many years, and I wrote this article mostly for the pleasure of doing it, and also, of course, because I thought it offered an interesting view, worth sharing. But at this point, my previous qualms waned, so I took the courage to send the preprint also to Diederik. This time, fortunately, I did so by using the electronic mail, and not the regular mail, dropping to him the following short message.

> Dear Professor Aerts, please find enclosed a preprint of an essay I wrote some time ago, which you might find of some interest. In particular, I hope you will enjoy the "uncooked Italian spaghetti" example of a simple macroscopic entity showing ephemeral properties that entertain incompatibility relations.

I was certainly not expecting an answer, considering my previous experience, but I was wrong: the reply came quickly, and it was not at all the kind of reply I would have predicted. On August 13, 2010, Diederik wrote to me the following very nice words:

> Dear Massimiliano (if I may), what a beautiful and interesting article. And it also warms my heart to read that you have been assistant of Constantin Piron [...], and it is beautiful that you dedicate this article to him.[12] Also, I like your Italian spaghetti experiment very much,

[12] The dedication was: "I dedicate this article to Professor Constantin Piron, one of the founders of the Geneva-Brussels school of quantum mechanics, whose I had the pleasure being the assistant about twenty years ago. Interacting with Constantin for more than a year, almost on a daily basis, irreversibly changed my way of looking to the mysteries of the quantum world, which, somehow paradoxically, used to simultaneously become less and more mysterious when I was in his presence."

> indeed also illustrating well the difference between the type of experimental incompatibility exemplified by my piece of wood example, and quantum incompatibility. Very nice. Of course, I must be honest, one of the reasons I like your article very much, is that it does contain many of the reflections I have been making in my past work over the years, which you know of course, since you make proper reference, so that is all right. But you also have presented these things in a very clear and relevant way. I would say, hurry to put it on the archives,[13] your little jewel of subtle scientific reflections (and amazingly enough, all these things, although I have made a big effort when I was working on them to present them at conferences, etc., are not yet known to the vast majority of quantum physicists) [...].

From his response, I immediately understood that he had never received the letters I had sent him years before, so I decided not to mention the thing (Diederik only found out about my unanswered letters very recently, partly because after a while I completely forgot about the whole thing). Instead of the grumpy and inaccessible professor I had imagined, the real Diederik was an extremely available and sensitive person, with remarkable human qualities, as I would have learned to know him better over the years.

Long story short, from that first contact an intense exchange was born, made of long emails and occasionally also some very long conversations on Skype. Diederik managed to easily "infect" me with his enthusiasm for the fundamental questions of physics, and thus I began to write numerous articles on the notions that were discussed over the years by the Brussels school.

Following this initial article that I wrote on the ephemerality of quantum properties, which finally got published,[14] after a little while I wrote a second one, where I revisited some of the notions I researched during my PhD thesis, like the notion of *sojourn time* of a

[13] The reference is to the Cornell University archive (*https://arxiv.org*), where almost all physicists deposit their preprints before sending them to a journal.

[14] Sassoli de Bianchi, M. (2011). Ephemeral properties and the illusion of microscopic particles. *Foundations of Science 16*, pp. 393–409.

physical entity in a given region of space, to reinterpret them in light of Aerts' creation-discovery view and his analysis of non-spatiality.[15]

Since my PhD thesis was also about studying non-relativistic scattering processes, I was also intrigued about the possibility of inventing a macroscopic machine that would simulate in some way a one-dimensional quantum scattering process, and after reflecting on the matter for a while, with quite some satisfaction I found a way to do it (see Figure 3).[16]

Reading and going deeper in my understanding of the approach developed by Diederik and collaborators, I then continued with enjoyment to invent new macroscopic situations imitating the quantum effects, as I did in two articles I wrote on 'quantum dice' that are rolled in such a way that they can create typical quantum interference effects, but can also entangle, that is, connect, to maximally violate Bell's inequalities, providing an interesting complementary example to Diederik's famous 'vessels of water model', where this time the composite entity needs not to be broken in order for the creation of correlations to happen.[17]

I also wrote articles aimed solely at raising more awareness on the results of the Brussels school, as I remained quite surprised about how this original approach remained largely unknown outside the small circles of insiders.[18] This by the way is something I'm still committed in our day, as important results are often forgotten in science, or are not duly appreciated when they are published the first

[15] Sassoli de Bianchi, M. (2012). From permanence to total availability: a quantum conceptual upgrade. *Foundations of Science 17*, pp. 223–244.

[16] Sassoli de Bianchi, M. (2013). The delta-quantum machine, the k-model, and the non-ordinary spatiality of quantum entities. *Foundations of Science 18*, pp. 11–41.

[17] Sassoli de Bianchi, M. (2013). Quantum dice. *Annals of Physics 336*, pp. 56–75. Sassoli de Bianchi, M. (2014). A remark on the role of indeterminism and non-locality in the violation of Bell's inequality. *Annals of Physics 342*, pp. 133–142.

[18] Sassoli de Bianchi, M. (2013). Using simple elastic bands to explain quantum mechanics: a conceptual review of two of Aerts' machine-models. *Central European Journal of Physics 11*, pp. 147–161.

time, and so must be brought again to the attention of the scientific community.

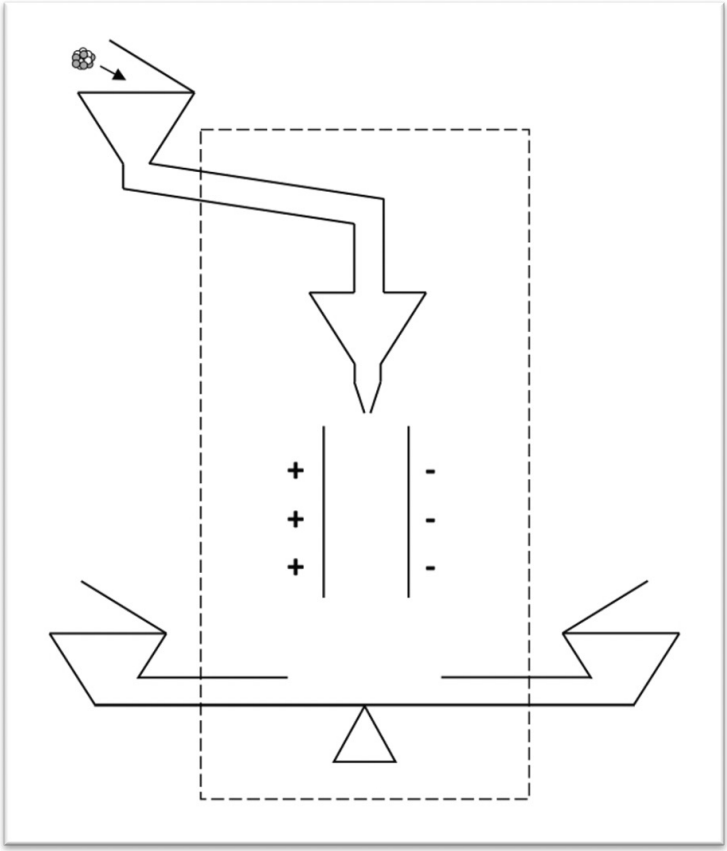

Figure 3 A simplified description of a δ-quantum machine, able to generate the transmission and reflection probabilities of a one-dimensional quantum scattering process.

An example is the important analysis contained in Diederik's PhD thesis, about the structural incompleteness of the standard formalism of quantum mechanics, unable to properly describe separate systems.[19]

[19] Sassoli de Bianchi, M. (2019). On Aerts' overlooked solution to the EPR paradox. In: *Probing the Meaning of Quantum Mechanics. Information,*

About this, as the *quantum measurement problem* intrigued people active in consciousness research, particularly in relation to the *mind-body problem* and the possibility of explaining the controversial "parapsychological effects," and since I was quite active in this domain (more from the viewpoint of self-research than of academic research), I thought it interesting to also try to communicate some of Diederik's results to that specific audience, using for this the notion of "observer effect" and emphasizing that an observation is more than just an act of discovery, that it also involves an act of creation of what is being observed. This was very clear already in Diederik's creation-discovery view, but he used in his writings the notion of observation more as a synonym of *discovery*, whereas I thought it more interesting to understand it in a more general sense (see my previous remark, in the second letter I wrote to Diederik).

So, I wrote a few articles emphasizing that the *observer effect* is a real effect, also in physics, but trying to demystify the fact that a human mind would be necessarily involved in it.[20] The "mind" of the measuring apparatus was indeed more than sufficient for this, and so no need to bother the consciousness to explain a quantum measurement, as hypothesized by physicists like *Eugene Wigner*, and more recently *Henry Stapp*.

Now, remembering the advice given to me by that earlier reviewer, about writing a popular book, I also decided in that period of time to write a new text (see Figure 4), this time both in Italian and English, entitled *Observer Effect*,[21] in which I addressed in a pedestrian way both the measurement problem and the notion

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Contextuality, Relationalism and Entanglement. D. Aerts, M. L. Dalla Chiara, C. de Ronde & D. Krause (eds.) World Scientific, pp. 185–201.

[20] Sassoli de Bianchi, M. (2013). The Observer Effect. *Foundations of Science 18*, pp. 213–243. Sassoli de Bianchi, M. (2013). Quantum measurements are physical processes. Comment on "Consciousness and the double-slit interference pattern: Six experiments," By Dean Radin et al. *Physics Essays 26*, pp. 15–20.

[21] This essay was published in 2013 by Adea Edizioni. A second edition, enriched in its contents, has been subsequently published in *AutoRicerca 19* (2019).

of non-spatiality. From that text a new article also emerged,[22] which was the natural continuation of my previous published reflections on the observer effect.

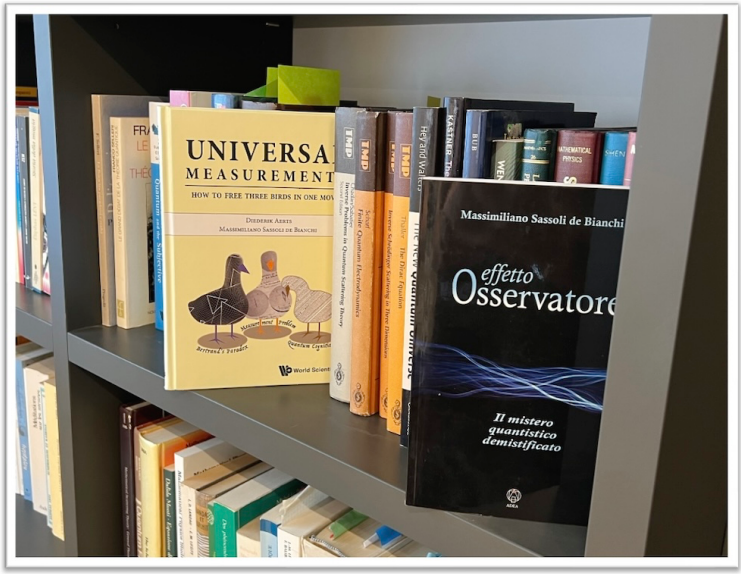

Figure 4 The cover of the Italian book on the observer effect that I wrote in 2013, and the cover of the book on universal measurements that h later wrote with Diederik Aerts in 2017 (also published in Italian in 2019).

As one can imagine, being more and more involved in reading, studying and researching the works of the Brussels school, writing articles and even a booklet about it, this allowed me to interact and discuss more frequently and in greater depth with Diederik, who was always very supportive towards me. I remember I was fascinated by all sorts of speculative ideas and conjectures he published over the years, on which of course it was necessary to further reflect, to understand if they were not only beautiful ideas, but also founded ones.

[22] Sassoli de Bianchi, M. (2015). God may not play dice, but human observers surely do. *Foundations of Science 20*, pp. 77–105.

In particular, I was fascinated, and extremely puzzled, by his hypothesis that *quantum measurements* could be understood as *universal measurements*, where the latter are defined as the most general possible condition of lack of knowledge, that is, a condition of lack of knowledge over all possible forms of non-uniform fluctuations that are in principle actualizable in a given experimental setting.

Discussions about universal measurements was really the start of our scientific collaboration. We tell a little bit about how this started in the preface of the book *Universal Measurements – How to free three birds with one move* (World Scientific), which I had the pleasure writing with Diederik in 2017 (see Figure 4).[23] Surprisingly enough, in the beginning I was very critical of the validity of his hypothesis, and an interesting and long written exchanged emerged from this initial contraposition, me trying to kind of prove that the hypothesis was wrong – hence in the beginning also trying to find a counterexample – and Diederik every time offering precise and profound thoughts in response to my objections.

What I remember is that at some point, in a long reply to an equally long email of mine, towards the end of the message Diederik wrote to me the following (the message is dated August 10, 2013):

> In case this would interest you, we could possibly write a paper together specifically containing the elements of our discussion on the notion of universal measurement [...]. Like you can see, I have never found the energy to write a real paper on all this, where things would be very well specified and explained. It has always been part of papers that mainly were focused on other things. However, do not feel obliged at all to even consider the above. So only if you would find this interesting, we can consider it.

My enthusiastic (and at the same time a little concerned) reply, the day after, was:

[23] The book is now also available also in Italian, with the title*: Misure universali – Come prendere tre piccioni con una fava* (Aracne editrice, 2019).

> It would not only interest me to write a paper with you on these topics, but I would also actually consider it a great honor. My only concern is if I can contribute sufficiently to our exchange, considering the little I know about these topics, compared to you.

From that moment on, our discussion became increasingly rich, and despite my insecurities in being up to the exchange, it ended with me miraculously finding a way to prove what I wanted to disprove in the first place. But this was largely due to Diederik always wisely guiding my thought processes, encouraging me to go deeper and gently putting me, intellectually speaking, on the corner, where I could then better contemplate the "naked matter" we were jointly trying to elucidate.

To cut a long story short, since we published our first article together, which was in 2014, we have co-authored nearly fifty articles to date (many in collaboration with other members of the Brussels scientific family), as well as the book I mentioned earlier. This is to emphasize the fertility of our exchanges, as is the case with all the numerous collaborations that Diederik has cultivated during the years and is still cultivating today. In fact, he is one of those rare scientists who can always maximize the intellectual and human resources that are potentially available in a teamwork, and this without ever forcing anyone to do anything, but still always magically find a way to have everybody putting their best on the table. To define this quality of his, the word *charisma* comes to my mind.

I will not try to calculate the number of people who have scientifically interacted so far with Diederik, they are too many. Let me mention, however, that they come from all kinds of fields of inquiry: mathematicians, physicists, philosophers, psychologists, computer scientists, medical doctors, just to cite a few. This is because his approach to reality has always been extremely broad, as far-reaching are the ideas he has crafted and developed along the way. Therefore, to only define him as a physicist, it would be too reductive, even though physics is certainly the discipline that is at the core of his interests, and also the one he cherishes the most.

A few years ago, he has been elected as the winner of the *2020 Prigogine Medal*, which was established in 2004 by the university of Siena and the Wessex Institute to honor the memory of *Ilya Prigogine*, Nobel Prize Winner for Chemistry (see Figure 5). This was a well-deserved recognition for his outstanding work, which extends far beyond the strict confines of physics.

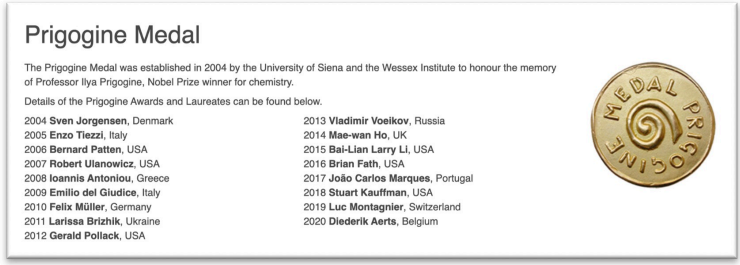

Figure 5 The Prigogine medal is awarded annually to a leading scientist in the field of ecological systems. All recipients have been deeply influenced by Prigogine's work, who established the basis of ecological systems research.

When I asked Diederik what he would talk about at the conference scheduled in Seville for the award ceremony, he told me that he wanted to try to outline the highlights of the research path which led him, in more recent times, to the formulation of a new interpretation of quantum mechanics, called the *conceptuality interpretation*, which considers that quantum entities are better characterized as being conceptual (although distinct from human concepts), instead of being like objects (see Figure 6).

When I first read about this interpretation, in the first article written by Diederik in 2009 (see the list of articles below), I remember being really impressed and fascinated. In fact, none of the countless attempts to interpret quantum mechanics that I had read over the years had, in my opinion, managed to make sense of the seemingly incomprehensible and undoubtedly paradoxical behavior of quantum entities. Diederik's approach, on the other hand, made their behavior understandable for the first time, and in my mind had

the effect of a ray of light in the darkness. His was undoubtedly a radical approach, which, if proven true, would dramatically change the way we understand physical reality.

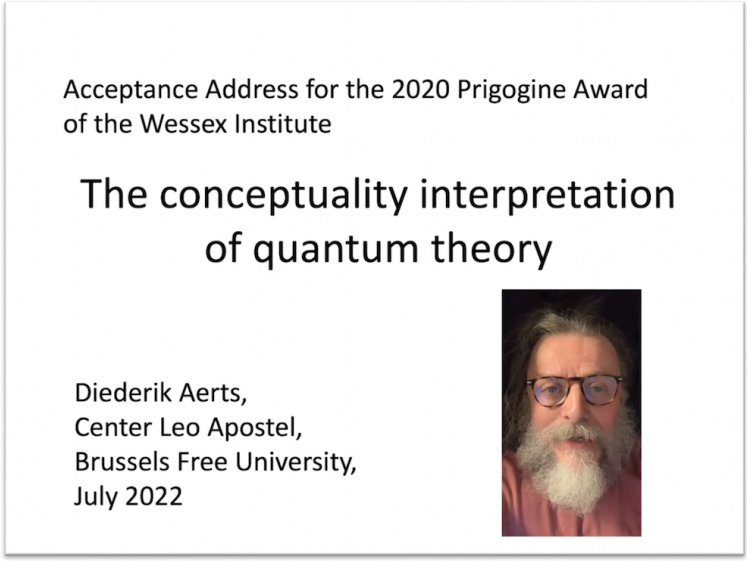

Figure 6 The ceremony for the Prigogine Medal 2020 was postponed to 2022 and was held solely online. The full title of Diederik' presentation was: *A Quantum Quest. From operational quantum axiomatics to quantum conceptuality, or how to unveil meaning in reality*.

Over the years, I too participated in his effort to explore and clarify this surprising interpretation, together with other colleagues from the Brussels group. Below, I list some of the most important articles that resulted from this joint effort, starting from Diederik's founding articles.

Aerts, D. (2009). Quantum particles as conceptual entities: A possible explanatory framework for quantum theory. *Foundations of Science 14*, pp. 361–411.

Aerts, D. (2010a). Interpreting quantum particles as conceptual entities, *Int. J. Theor. Phys. 49*, pp. 2950–2970.

Aerts, D. (2010b). A potentiality and conceptuality interpretation of quantum physics, *Philosophica 83*, pp. 15–52.

Aerts, D. (2013). La mecánica cuántica y la conceptualidad: Sobre materia, historias, semántica y espacio-tiempo, Scientiae Studia 11, pp. 75–100. Translated from: Aerts, D. (2011). Quantum theory and conceptuality: Matter, stories, semantics and space-time, *arXiv:1110.4766 [quant-ph]*.

Aerts, D. (2014). Quantum theory and human perception of the macro-world, *Front. Psychol. 5*, Article 554.

Aerts, D. and Sassoli de Bianchi, M. (2018). Quantum Perspectives on Evolution. In Shyam Wuppuluri, Francisco Antonio Doria (Eds.), *The Map and the Territory: Exploring the Foundations of Science*, Thought and Reality. Springer: The Frontiers collection, pp. 571–595.

Sassoli de Bianchi, M. (2015). Taking quantum physics and consciousness seriously: what does it mean and what are the consequences? *Journal of Consciousness 18*, Special edition, pp. 203-268. Also translated in Italian in *AutoRicerca 10*, 2015, and subsequently republished in *AutoRicerca 21*, 2020.

Aerts, D., Sassoli de Bianchi, M. (2017). Multiplex realism. *Journal of Consciousness – Proceedings of the 2nd International Congress of Consciousness*, held in Miami (USA) from May 19th to 21st, 2017. Also published in *AutoRicerca 21*, 2020.

Aerts, D., Sassoli de Bianchi, M., Sozzo, S. and Veloz, T. (2019). From Quantum Axiomatics to Quantum Conceptuality. *Act. Nerv. Super. 61*, pp. 76–82.

Aerts, D., Sassoli de Bianchi, M., Sozzo, S. and Veloz, T. (2020). On the conceptuality interpretation of quantum and relativity theories. *Foundations of Science 25*, 5–54. Also published in *AutoRicerca 21*, 2020, and translated in Italian in *AutoRicerca 24*, 2022.

Aerts, D. and Beltran, L. (2020). Quantum structure in cognition: Human language as a Boson gas of entangled words. *Foundations of Science 25*, pp. 755–802.

Sassoli de Bianchi, M. (2021). A non-spatial reality. *Foundations of Science 26*, pp. 143–170. Also published in *AutoRicerca 21*, 2020 and translated in Italian in *AutoRicerca 24*, 2022.

Aerts, D. and Sassoli de Bianchi, M. (2022). On the irreversible journey of matter, life and human culture. In: Wuppuluri, S., Stewart, I. (Eds.), *From Electrons to Elephants and Elections*. The

Frontiers Collection. Springer, pp. 821-842. A revised and expanded version of this article, in Italian, can be found in *AutoRicerca 27* (2023). See also the dialog *The secret of life* published in *AutoRicerca* 18, 2019.

Aerts, D. and Sassoli de Bianchi, M. (2023). The physics and metaphysics of the conceptuality interpretation. *arXiv:2310.10684 [quant-ph]*. Published in this volume: *AutoRicerca 31*, 2025.

The idea of the conceptuality interpretation emerged from a field of study called *quantum cognition*, of which Diederik was undoubtedly one of the pioneers. Recently, also with Sandro Sozzo, we had the opportunity to tell the story of this scientific journey, which starts from quantum cognition and arrives to the conceptuality interpretation, in two articles to be published in the prestigious journal *Philosophical Transactions of the Royal Society* (the world's oldest scientific journal![24]).

In the first article, we explore how quantum mathematics, initially applied to human cognition, led to the conceptuality interpretation.

Aerts, D., Sassoli de Bianchi, M. and Sozzo, S. (2024). From Quantum Cognition to Conceptuality Interpretation I: Tracing the Brussels Group's Intellectual Journey. To be published in: *Philosophical Transactions of the Royal Society A*. *arXiv: 2412.06799*.

This interpretation suggests that quantum entities operate conceptually, interacting with the material world through meaning-based processes akin to those in human thought. In the second, follow-up article, we show how the conceptuality interpretation sheds light on quantum phenomena, including Heisenberg's

[24] The first issue of Philosophical Transactions appeared in March 1665 and featured Oldenburg's correspondence with leading European scientists. In its formative years *Isaac Newton* had seventeen papers published in the journal including his first paper – New Theory about Light and Colours – which effectively served to launch his scientific career in 1672. The journal has also published the work of *Charles Darwin, Michael Faraday, William Herschel* and many more celebrated names in science.

uncertainty principle, entanglement, and even relativistic effects like time dilation.

> Aerts, D., Sassoli de Bianchi, M. and Sozzo, S. (2024). From Quantum Cognition to Conceptuality Interpretation II: Unraveling the Quantum Mysteries. To be published in: *Philosophical Transactions of the Royal Society A*. *arXiv: 2412.19809*.

To this day, my scientific collaboration with Diederik continues, driven by the shared desire of exploring topics often overlooked by our colleagues, yet potentially fundamental to deepening our understanding of reality. I will try to illustrate this point with an example, which will conclude my brief autobiographical account of my encounter with Diederik.

The notion of *free choice* (and the related concept of *free will*) holds a central place in most spiritual traditions. It is deeply intertwined with the concepts of good and evil in Western thought and karma in Eastern philosophy. However, contemporary science and influential philosophers often downplay its significance, suggesting that true metaphysical freedom or true indeterminism does not exist, thus reducing free choice to a mere illusion that is very persistent.

Nevertheless, starting from the 1970s, initially in Geneva and subsequently in Brussels, a foundational, operational, and realist approach to quantum mechanics was developed with the ambition of reconstructing the theory on axiomatic grounds. This effort reached completion in 2000 with the full reconstruction of the standard Hilbertian formalism. We recently recounted the history of this reconstruction program in an article that will also be published in the *Philosophical Transactions of the Royal Society*:

> Aerts, D., Aerts Arguëlles, J., Beltran, L., Sassoli de Bianchi, M. and Sozzo, S. (2024). The Separability Problem in Quantum Mechanics: Insights from Research on Axiomatics and Human Language. To be published in: *Philosophical Transactions of the Royal Society A*. See also: *arXiv: 2409.15942*.

However, an essential point still remains insufficiently emphasized: the principle of free choice is not merely philosophical speculation but a crucial scientific requirement, without which the very foundations of our quantum and relativistic theories would crumble. For instance, relativity without this principle, ends up describing a static, incomprehensible *block-universe* reality.

The scientific significance of free choice becomes clearer when one examines those models of human cognition that have revealed profound structural similarities between cognitive and quantum processes, giving rise to the aforementioned field of quantum cognition. In particular, quantum indeterminacy is the equivalent of the inherent unpredictability of human decision making, and parallels of this kind contributed to the formulation of the conceptuality interpretation, positing the existence of a universe that is fundamentally *pancognitivistic*, with human culture representing only one of several layers in which cognitive structures can emerge.

Even the theory of evolution may find renewal within this broader operational and realist framework, one in which indeterminism and free choice take precedence. Indeed, if quantum and cognitive processes manifest across different organizational levels – from inert matter to living organisms, all the way to cultural artifacts – it becomes possible to envision alternative selection mechanisms beyond the traditional Darwinian model, mechanisms that operate at the level of *potentiality* rather than *actuality*.

This perspective outlines a rich, multifaceted theoretical framework that still requires consolidation across various research directions, seeking integration between worldviews previously considered irreconcilable. Modern science, having prematurely dismissed free choice, and spirituality, which acknowledges consciousness and freedom but struggles to identify their manifestation in the material world, may perhaps find common ground through this approach.

So, as long as life, with all its obligations and commitments, allows, Diederik and I certainly have many promising avenues to

pursue in our collaboration. I hope that our work will foster new alliances, providing in particular a common language between science and spirituality. This will undoubtedly enable human beings to become more mature and responsible actors on this planet of ours.

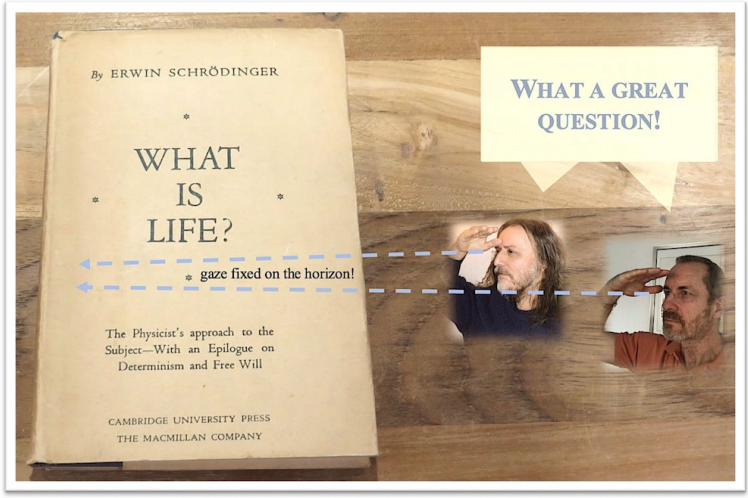

Figure 7 Diederik (left) and Massimiliano (right) symbolically scanning the horizon, in an attempt to provide new answers to Schrödinger's crucial question: *What is life?*