Chapter 2
Quantum Physics, Appearance and Reality

Round Table

Bernard d'Espagnat. You have all received the report [1] of the previous session. I will now ask those who, after having read through it, would like to comment to put their hands up. Very well, here we go! We shall start with Michel Bitbol, as he was not here last time.

Michel Bitbol. Thank you very much, Mr. d'Espagnat. Indeed, I was not here last time, and therefore I read with much interest and attention what was said during the last session. In particular, I found the debate following the excellent presentation to be very rich and very revealing. What struck me was to see, now more than ever before, a greater consensus emerging around what I would call an antirealist interpretation of quantum physics; the idea that quantum theory is not a direct and unequivocal representation of the world. It is true that certain symbols of this theory have been given names that suggest a representation, such as "vector state", which is meant to represent the state of a system; meant to represent, if we take seriously the semantics of the word "state", something that is *intrinsic* to the system. In Édouard Brézin's presentation [2], I noted a number of important points that directly call into question this standard conception of vector state. For example, Édouard Brézin asked himself whether we could not say that a quantum state is the expression of our knowledge rather than the expression of an intrinsic characteristic of the system. He cited on this matter Rudolf Peierls who would also have made such a proposal, presenting it as a solution to the problem of measurement. As soon as I read this statement in Édouard Brézin's presentation, I said to myself that it suggested a conception that was totally compatible with Carlo Rovelli's relational interpretation. According to Rovelli, the quantum state is not a characteristic of physical systems but a relational characteristic that depends on the position of the observer during the process of knowledge acquisition. This potential convergence really struck me. All the more so that the significance of this consensus was very well expressed by Olivier Rey, who pointed out that the paradoxes of quantum

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B. d'Espagnat and H. Zwirn (eds.), *The Quantum World*,
The Frontiers Collection, DOI 10.1007/978-3-319-55420-4_2

theory disappear if we accept that it is not "a science of the world as it is, but of the way we interact with it". This statement recalls the famous formulations of Heisenberg and Bohr. Consequently, this strengthened my conviction that a new consensus was emerging around a similar interpretation to that of Bohr and Heisenberg, after being out of favour for so long.

Under these conditions, it seems that our working group could devise a programme that could go even further than the debate opposing (1) strong scientific realism and (2) a conception combining scientific antirealism with "open realism", according to your definition, Mr. d'Espagnat. Our working group could consider that this debate is now more or less closed, and that it would be interesting to go as far as we can with the antirealist interpretation of quantum mechanics by trying to draw out its implications and test its validity.

We could first of all show how such an interpretation resolves or dispels the most confounding paradoxes of quantum physics. Some participants have pointed out that this interpretation could defuse certain paradoxes (such as the measurement paradox). As for me, I posit the hypothesis that a fully antirealist interpretation is capable of resolving *all* the paradoxes; it would be a good project to try to test this hypothesis point by point.

Likewise, a second project for our working group could consist of investigating why a theory that, as is now accepted, does not represent a reality that is completely external to us, completely independent of what we do in it, is nonetheless so effective. Why this effectiveness? The famous miracle argument of scientific realists claims that if a theory does not represent the world, we could not understand why it works so well. Would there be a way, going against scientific realists, to understand why a theory is effective when it does not represent the world faithfully, point by point?

Finally, the third project I see for some of us could consist of trying to understand why we have resisted this other vision of scientific theory, and in particular quantum theory, for so long; a vision where quantum mechanics is not at all a representation *of* the world, but an inventory of the ordered, coherent multitude of ways we can position ourselves *in* the world. Is there a cultural factor that makes us balk at the full acceptance of such a conception?

There is one last point, which I cannot fail to mention as it is the one that is of greatest interest to Mr. d'Espagnat, and rightly so. Since we can no longer consider our current quantum theory, which is the theory-framework for most physics theories, as a more or less faithful copy of the world, the question that needs to be asked is the following: how should we conceive of the reality we are in so that it is resistant in this way to all attempts at representation?

Bernard d'Espagnat. Yes, indeed, this would be an entire area that would be interesting to explore. However, I have one or two comments or questions to ask you.

The first comment is that you alluded to the notion I have introduced of “open realism”. I believe I have always made clear that this notion is no way contradictory with the way you present physics. On the contrary, I consider like you that physics is not capable of describing reality per se. I am even tempted to consider quantum physics as an essentially operationalist theory, in other words reducing everything, directly or indirectly, to the notion of prediction of experimental outcomes, which obviously implies that it always relates to us, what we see or feel. Is this how you consider the theory for which you have just drafted a programme? Or do you see something more than just operationalism?

Michel Bitbol. Thank you for this question, Mr. d’Espagnat. Yes, I see more than operationalism in quantum theory, but not “more” in the sense of “more representation of reality”. I see more in the sense of “more justifications of the remarkable capacity of this theory to predict the outcome of our experimental operations”. This additional justification of course calls on transcendental philosophy, meaning a philosophy derived from that of Kant. Although work remains to be done in this direction, I have good reasons to believe that the effectiveness of this theory can be understood if we think of it, somewhat in the manner of Kant, as a compilation of the conditions of possibility of a certain modality of knowledge. Of course not the same modality of knowledge that Kant reflected on; not the same modality of knowledge that the historical Kant, with only Newtonian mechanics at his disposal, examined. But the identification of the structure of knowledge as a product of knowledge can be done in the same spirit as him in any case, including when we depart considerably from Newtonian mechanics.

Working in the spirit of Kant simply consists here of trying to see in what way a modern physics theory like quantum mechanics is not just some sort of random heap of recipes, but a totally coherent structure of operative prescriptions that express the general presuppositions of our own interventions in the world around us. A good example of the relationship between theoretical structure and conditions of possibility of action was given by Olivier Rey in the report of the previous session: namely Henri Poincaré’s conception of space. For Poincaré, space is built as an inventory of our possibilities of motion, and Euclidian geometry ensues. According to this conception, the theory of space that is Euclidian geometry is neither a passive representation of an external reality nor a compilation of recipes: it expresses in an optimal manner the coherence of the motions accessible to a being both sensitive and capable of motion.

Bernard d’Espagnat. That is right. Ultimately, you relate motion, the concept of motion itself, to the concept of conscious being.

Michel Bitbol. I have not yet spoken about consciousness.

Bernard d’Espagnat. We are heading in that direction.

Michel Bitbol. Let us say that up to now, we can avoid talking about consciousness. We can avoid doing so up to the point that consists of collecting the conditions of possibility of a certain coordinated action in the world. Obviously, we could also decide to talk about consciousness, and that would be very interesting. But perhaps this would lead us too far from our topic of discussion.

Nevertheless, perhaps I could briefly introduce the theme of consciousness by saying how I apprehend the notion of independent reality. You often speak of independent reality, Mr. d'Espagnat, meaning a reality independent of the mind. At the same time, a reality independent of the mind is only thinkable by the mind. When we mention independent reality, we perform an operation of self-abstraction, we subtract ourselves from the reality we would like to think of as independent of ourselves. However, we should not forget that this operation of abstraction is itself only an act of the mind! Thus, we are forced to recognize that all reality facing us presents itself only as an object (positive or negative) of a conscious act. We must not lose sight of this absolutely fundamental fact, which is not a scientific fact but an everyday, immediate, fact. Each time I describe something, I do this through an act of consciousness; each time I think of something, it is an act of consciousness; each time I think of something my consciousness cannot grasp in its field, that again is an act of consciousness (the consciousness of something that escapes my consciousness). All in all, reality is accessible only as a direct, or indirect, correlate of consciousness.

Bernard d'Espagnat. You exclude the act of faith, which consists of saying that there is a reality outside of ourselves, in other words, that we are not the only existing beings. But what seems to me to be problematic in your approach is precisely that, ultimately, we have the impression that it amounts to saying "we are the only existing beings". So, to counter that, you could, obviously, reject the notion of existence, and say the word "existence" has no meaning.

Michel Bitbol. No, obviously, I agree with you, we are not the only existing beings, but we need to examine carefully how this certainty manifests itself in us, how, deep down, we *know* we are not the only existing beings. How can we be sure? I think we know we are not the only existing beings when we become aware of our own limits. It is ultimately the limited nature, understood as limited, of our own existence that tells us that we are not the only ones to exist. We are not able to do everything, we cannot know everything at once, we cannot will the motion of our counterparts, and therefore there is something else other than ourselves. Ultimately, even the notion of otherness must be analysed from our own experience. Such is the lesson of a well-known branch of philosophy called Husserlian phenomenology. If we wanted to express this lesson in the more abstract terms of phenomenology, we would say: *even transcendence is only apprehended in immanence*.

Bernard d'Espagnat. Thank you for this answer which gives me much food for thought. For now, others would like to join in, in particular Jean Petitot.

Jean Petitot. I would like to comment on what Michel (Bitbol) said in his second to last intervention. What is important is the term “correlate”, the fact that any reality is a correlate of consciousness. The way you criticized it was to say that a correlate of consciousness is a form of inclusion within consciousness. This brings us immediately to a modern version of solipsism. The great achievement of Husserl’s phenomenology was indeed to understand how transcendence of the outside world can be based in the immanence of consciousness all the while remaining an external transcendence, so that solipsism is avoided. This problem began with Kant. Transcendental idealism is totally compatible with empirical realism. It is not in any way—solipsism, but rather a problem of the constitution of objectivity—in particular the objectivity of the outside world—through acts of consciousness. As we maintain an objective transcendence, we do not fall into psychological solipsism. We need to investigate further the concept of correlation.

It is a very complicated concept, but it so happens that in another field—which takes our reasoning outside the realm of physics, which Husserl investigated a lot, and which is the subject of much current cutting-edge research—namely that of perception, we encounter a similar problem. The objects of the outside world that we perceive as external to us in three-dimensional space are built from the treatment of information that is internal to and immanent of the retina, and we are starting to understand better how this exteriority develops, this conviction that objects are on the outside and transcend us, that is to say how perception frees itself from solipsism. Therefore, in the case of perception, we are starting to understand what the correlation between subject and object is. In physics, we would need to do something similar for objectivity.

Bernard d’Espagnat. We would need to think in depth about the way that Husserl, you or others actually manage to free yourselves, not so much from solipsism but from the idea that there is only a single being, which is of the nature of consciousness. We would need to understand this.

Others would like to contribute to the discussion.

I will conclude by saying that the lines of thought you propose, Mr. Bitbol, would likely be of interest to scientists outside of physics. In any case, I would be very pleased if we were able to move the discussion forward here.

Hervé Zwirn. Allow me to return to the report of the previous session, as this was our starting point.

During that session, we had a discussion initiated by Bertrand Saint-Sernin on the problem of realism, in particular regarding realism sensu Cournot. This required that we define in a more precise manner the term “realism”, in order to know exactly what we meant during the discussion by the different types of realism we attempted to describe. We are already at the heart of the matter, however it seems to me that there are different levels here. What we have been talking about is essentially what we could call metaphysical realism, i.e., knowing whether, yes or no, there exists a reality that is independent of the mind of any given observer. This is the first problem.

The second problem, which is sometimes confused with the first and this introduces a number of ambiguities, is to know whether this reality is intelligible and whether current physics, as it is, adequately describes this reality.

There are, I would say, three problems of a different nature but which are obviously linked; we sometimes have a tendency to mix them up and this can lead to approximate reasoning. Is there a reality that is independent of the mind? Is this reality, if we accept it exists, intelligible? Is physics the right tool to account for it? These are three topics that were perhaps grouped together during the previous session without sufficiently differentiating them.

On the topic of metaphysical realism, there are a number of important historical and philosophical arguments—they are not new. It is true that new light is shed on these discussions by quantum mechanics.

The most important arguments, the most famous ones, what are they?

There is, first of all, what Hume called the relation of cause and effect. Why do we posit the existence of an external reality? For instance, why is it that, we when hear someone speak in the room next door, we will tend to infer that someone is there? Well, because each time we have heard someone, there was someone next door when we checked. Hume questions this as it is an inductive inference, and you are all aware of Hume's critique of induction. This type of inference is not valid.

Along the same lines, when we see a shape in front of us, a table top with four legs, we have a tendency to infer that there is a table that exists outside of us which accounts for this perception. Hume is critical of this as well, by saying that the hypothesis according to which there really exists a table is nothing more than a convenient arrangement of our perceptions, and I see in this argument the beginnings of phenomenology. Husserl went much further, and it would be very interesting to conclude on this point.

And then there is the famous argument that was also highlighted by Bernard d'Espagnat, according to which our experiments do not always produce outcomes that are congruent with our scientific theories. As he said, there is something that says "no". Therefore reality resists, and this is often taken as an argument in favour of the fact that there is something other than the mind. This argument can be criticized. The simplest example we can give of a criticism is that, in our dreams, we do not do as we please and yet our dreams are nothing but a pure invention of our mind. Our dreams resist us. Therefore the very fact that a certain number of things resist us does not prove that they are external to us.

There is another argument that can be put forward, which I defend but which takes us further, which is that we have to make two mental constructs correspond: on the one hand, we have a mental construct of external reality in the sense we have indicated previously. How do we build in our mind the fact that there are external objects? As Jean (Petitot) said, it is not because we have the impression that we are building something external that it is a sufficient reason to legitimize the fact that there is something external. On the other hand, we have a construct that we will say is mathematical, which is that of our scientific theories. We achieve these two constructs through completely different mental modes. The perception of external reality is developed from childhood and is intuitive in a certain way; the construct of scientific theories is progressive, and is based on different notions. So the fact that the two sometimes do not perfectly match up is ultimately not that surprising. I think on the contrary that the idea that something resists us is an argument for saying that these are two things we have built independently, and making them match up is not that simple. The coherence of a mathematical theory is a complex problem and the coherence of two independent constructs, the fact that they are congruent with each other, and the ability to demonstrate this congruence, is something extremely hypothetical. Obviously, these are analogies, since a mental construct of reality is not a mathematical theory; however, these analogies tend in that direction.

Lastly, as a final point, there is the argument put forward primarily by Hilary Putman that states that there are no miracles. That argument seems very weak to me. It consists of saying that our theories work simply because there is a reality to which they correspond. And if that was not the case, it would be a miracle if our theories worked… However, the large number of past theories that did work and were empirically adequate, i.e., that saved phenomena as Bas van Fraassen said, and yet which turned out to be false shows that it is not because a theory works that it corresponds to an external reality that it describes precisely.

This is an introduction to the theme of today's session which is structural realism. What seems to remain ultimately, if we really want to keep something, is not the ontology of theories, for which we can easily see that it was put into question and dismantled as scientific theories evolved, but seemingly the structure, in a sense that undoubtedly needs to be defined, of these theories, which leads us effectively to structural realism. Structural realism has had various, more abstract, developments, which seem to save a type of realism which is not an ontological realism in the sense of naive scientific realism.

Bernard d'Espagnat. In your first book and also in a recent article [3], you very clearly introduce the notion of a reality external to us. You consider, when you define your version of empirical reality—we were talking about this earlier in private—that there is something that is not us, which prevents us from thinking just anything, that there is something that resists us. I do not clearly see the link between this and what you have just said, as from what you have said you seem to conclude that, ultimately these things are built by us.

Hervé Zwirn. The link is the following: I am not a solipsist. Anyway, solipsism is a position that we know is irrefutable. I am not a solipsist because to reduce all that exists to something internal to us (or that is internal to me) is a position that seems to me to be both sterile and inappropriate, in a certain way.

Olivier Rey. An impregnable fortress defended by a madman!

Hervé Zwirn. The position that claims that nothing exists other than what I think or conceptualize does not satisfy me.

Bernard d'Espagnat. I was under the impression that it satisfied Michel Bitbol!

Michel Bitbol. Perhaps I can explain myself a bit more to dispel this idea. I am not the madman of the impregnable fortress!

Olivier Rey. I can confirm that, I share his office!

Michel Bitbol. The question is to know what the meaning of this exteriority we speak of is. What does a reality external to us mean? Given that we have an immediate intuition of external space when we speak of external reality, we have a tendency to represent this exteriority in the image of the distance between my body and all other surrounding bodies. However, I believe that the true exteriority that we should address here, the exteriority of external reality, is not of this nature. It is a non-spatial exteriority, in the sense of going beyond what I can do or grasp; it goes beyond my own finiteness. A certain number of non-spatial characterizations of the "exteriority" of the thing itself have been proposed over the course of the history of post-Kantian philosophies, and these may help us formulate an adequate, non-metaphorical, definition of its break from us. I think for instance of Schopenhauer who, instead of characterizing the thing in itself as an actual *thing*, as a thing that would be external to us in a spatial sense, characterized it as a "will", meaning a sort of completely obscure drive that we feel interiorly and that leads to us carry out actions without really knowing why. The obscurity itself of our motivation to act shows that we are overwhelmed, that we are not alone, nor are we the sole master of our lives and of our knowledge; it shows that there is something much greater than us that acts by us, within us and through us. Surpassing and freeing the "Will" sensu Schopenhauer could be an alternative characterization of the exteriority of the thing per se.

Bernard d'Espagnat. Do you accept this?

Michel Bitbol. I think it is not bad at all. In any case, it gives us a plausible alternative view of exteriority. Besides, Kant had anticipated Schopenhauer when he wrote a beautiful sentence, full of perplexity, in his *Critique of Pure Reason*. This sentence, which I wrote down with great passion and which I analysed in my book *De l'intérieur du monde* [4] is as follows: "[…] regarding this noumenon, we do not know whether it is within us or outside of us […]" [5]. Of course, Kant thought the "noumenal" thing itself (in the sense of it being only thought of as a limiting concept) could be external to us in the traditional, primarily spatial, sense; but it could also be a simple extension of ourselves, which surpasses us in every way and which shows by this excess that we are not alone, that we do not hold all that exists within the boundaries of our consciousness. Therefore, we do not fall into solipsism, but we do not either posit more exteriority in the most ordinary sense of the term nor a complete separation of what there is in relation to us.

Bernard d'Espagnat. We could attempt to bring together what you have said with the Neo-Platonic stance, in particular that of the Christian disciples of Neo-Platonism. Even Saint-Augustine, with his "interior master", makes me think of what you are saying.

Michel Bitbol. Indeed, I completely agree with you. I think it would make a wonderful topic for future discussion; but perhaps we should not address it today, as we have other topics to discuss.

Hervé Zwirn. To go in the same direction regarding the rejection of solipsism, I would say that what was said earlier could effectively suggest that I did not accept that there are things that exist that do not come from us. However, these arguments, along with the rejection of solipsism, form the basis from which we can build what exists. That is to say: rejection of solipsism, therefore everything does not stem from us, but at the same time rejection of the arguments mentioned previously i.e., to think a reality in the traditional manner in which it can be thought, i.e., as Michel (Bitbol) said, in an exterior manner, etc.

I quite like the metaphor you borrowed from Schopenhauer. In a certain way, it is all that is constrained, while being in part external to us since it does not stem from us. However, it is at the same time linked to us, as it is all that constrains the way in which we apprehend the world, all the constraints that concern our perceptions. Earlier we spoke of the difference between empirical reality and phenomenal reality. This is what I called empirical reality, which is not spatially separated from us, which is not made up of objects, things, entities, fields, vectors, whatever we want, but which is in fact a mix between something external and something that stems from our categories, of the way we can then apprehend phenomena, or create phenomena, because I think that in a certain way we create what we perceive.

Carlo Rovelli. Some thoughts as they come in reaction to what you have said and in support of what Michel (Bitbol) has said. What I would like to say concerns the certainty and the development of knowledge, particularly the certainty. It seems to me that the discussion here revolves around the possibility of basing with certainty a belief in reality, or a lack of belief in reality, or an interpretation, a reading of what knowledge is, how knowledge works. The aspect I would like to bring to the centre of the discussion, on the contrary, is that of the lack of knowledge, the lack of certainty in our knowledge.

Michel, you spoke of this fundamental intuition which is that the elements of reality are always perceived within our consciousness, and are therefore correlates of consciousness; a fundamental, and I would say very ancient intuition: these are the Upanishads [6]. It is true, without a doubt. At the same time, it is also true that this consciousness develops slowly as we learn to think about the world. Developmental sciences teach us that, at first reality is without a self, then we add a self to reality, and later do we begin to distinguish reality by the self, by developing an idea of a reality that is independent of the self. So what comes first in our development? First question.

Second question: in all this, we spoke of the mind. You have all spoken of the mind, of us, our position. Each time I hear this, I get somewhat confused. I felt this confusion when I was at school, when I was told about Hegel. Who is the mind? Is it I, Carlo? Is it you, Michel? Do we speak of all of us, as a group? The entire community that speaks together? Who is this mind? Who is consciousness? My mind? Our mind? Where must I put it? I believe there is something to be learned here. That is to say: the constitution of reality is of course as *per* the critique of classical empiricism, because there are regularities in perception, etc. There is this well-known process, but there is also something else. I have an idea of myself, I have an idea of my consciousness, but I also have friends. I have had friends from an early age: I speak with you and I have an idea of you. In my idea of you, I am starting to realize that you are very similar to me, and that when I see a shadow, you also see a shadow. You tell me "I see a shadow" and I hear that it is the same thing as when I tell you I see a shadow. Thus I have a mental construct in which there is not simply reality, but where there are also others who perceive reality, and there is a surprising similarity between my perception of reality and what others say they perceive of reality. Therefore, I place something completely new in this reality: it is I, as one of many around me who are similar to me. So within reality, something has now formed within my construct which is my consciousness—my own—perceived as an element of external reality, only a copy of what I see others say and do.

Obviously, we all go through this, humanity has been through this and we ask ourselves the question: if I want to establish knowledge that is reliable, where do I start? This is kind of the question we ask ourselves, but is it the right question? Is this what we are interested in?

You have fragmented the problem of realism. First of all, is there an independent reality? Secondly, is it intelligible? Thirdly, can it be described by physics? We have learned much since the end of classical physics. Our current theories are probably false in the sense that classical mechanics is false… Therefore we know our knowledge is limited. What does that mean? It means we accept the idea that we can think of the world with a degree of uncertainty, and despite that, live in and interact with the world. I think this is the crucial lesson of the end of the last century, that is to say that we have learned that we can think of reality without asking ourselves what the foundation of our knowledge is, while still using this knowledge. So, what is reality? It is the reality described by physics theories, with the strong awareness that there are obvious limitations: in the same way that Newton's classical mechanics is false, these are probably also false. What we have in physics is a better way of thinking about the world today, now, and a better way of conceptualizing the world now: no more, no less.

Therefore, in this theory that apparently works well, i.e., quantum mechanics, in this discovery of the world that is not personal but stems from a community of scientists who have developed science, we find strong limitations to the idea of a precise and realistic description, in a stronger sense than in classical mechanics.

It seems to me that we realize—this is how many people understand this—that quantum mechanics tells us that a certain vision of this reality, as formed for example (I am simplifying) in classical atomism or the atomism of Democritus, as the space where particles can travel, does not work. The best description we can make takes into account the fact that there are systems that interact with one another and that is more a description of these systems, and there Michel (Bitbol), as you know, I agree with you 100%.

We have learned that this complex reality we have developed is more complicated that what we thought, but we have just learned that. Is it really necessary to know the precise role of the notion of reality to use the notion of reality? I think not. This is a recent discovery of science.

I now have a more precise question. You (Michel Bitbol) speak of Kant, of Kantism. You ask us to go back to it. Obviously, I agree with you, but I also have a question. I find two things in what I know of Kant. One is a strong reminder that we must take into account the necessary conditions for knowledge. I cannot describe reality per se, I must remind myself that what I describe is a reality perceived by me and that there are conditions for perceiving it. Science itself gives us this information as—I now come back to our starting point—I can reinterpret myself not as the holder of everything but also as the object described by science, where very incomplete information about the world arrives, which generates mental images, mental constructs that concern the exterior but which are totally separate from the exterior. I think Kant himself had this idea of the unknowability of reality, due to concrete conditions. That is Kant I, however Kant II says: despite this, there is a possibility to reason on this, which gives me a priori information about the world, about the possible structure of reality as I perceive it, which I can arrive at individually through knowledge. It seems to me that the development itself of quantum mechanics leads us away from that. We realized that there were limits within realism, not by thinking about the conditions of knowledge but by doing experiments. The world is not what I thought it was; particles… they are more complicated than that. Perhaps to think it, I need to rebuild a description of the reality where I belong, thus with the construction of a relationship that includes me, and I must take into account the knowledge I could not have had a priori. In this sense, we are distancing ourselves from classical Kantism, of the Kant of *Critique of Pure Reason*.

Last point, before wrapping up. If we take the stance where we say we do not know the starting point, what we have learned of the world is what science is telling us of the world, knowing full well that there are limits to this and that there will be changes. The conceptualization we carry out of the world itself changes, therefore it is not that necessary to cling onto a central starting point of a certainty regarding what does and what does not exist. Of course there is reality! There is no need to question that. Everyone agrees there is an external reality and of course it is within my own perception. This is sufficient to start understanding how things work.

If I take this point of view, I find that structural realism on the one hand clearly tells us: "look at these structures, they are really interesting; perhaps we could conceptualize these objects in term of structures", and this interests me. However, it interests me a lot less if it is suggesting that “we have finally found the ultimate thing that does not change”. No, we have not found the ultimate thing that does not change. I was not able, in all the texts I have read, to understand what this structure that does not change during the course of the history of science could be. I cannot find, during the course of the history of science, a structure that does not change. On the contrary, I find that all structures have changed, but there are objects that have changed very little: the Sun is still the Sun, we still speak of the Sun, from Ptolemy to our current solar theory, and the Sun is still the Sun. There is a permanence of objects, a permanence of structures, and also a weakness of objects and a weakness of even the strongest structures. There are laws, it is true, like the Fresnel law, which have passed from classical mechanics to quantum mechanics without suffering too much damage, but there are laws that were good before and that were not so good afterwards. Therefore I cannot see structure as being a possible reliable anchor.

Michel Bitbol. The problem is that you have raised too many important points during your intervention! I will concentrate on one or two. Let us take your last argument, that of the constancy of certain structures throughout the course of the history of science. A number of contemporary philosophers of science, including Bas van Fraassen, have pointed out that the only structures that persist in an *absolutely* permanent manner are purely empirical structures, for example the apparent trajectory of Mars, or the calculations that are directly related to the apparent trajectory of Mars. Yes, this remains constant. There are also certain predictive formal cores that remain practically unchanged from one theory to another as of course we must find the effective predictive structures of the old theory in the new theory. Thus the constancy of certain structures is not as surprising as is sometimes said, because all it does is express the durability of certain regions of effectiveness that were attained in the past since they limited themselves to structures that were as close as possible to the empirical. There may be some permanent structures in scientific theory that are much more removed from the empirical, such as the laws of conservation or the optimization principles, however, others will speak of these better than I can.

A second very important point regarding Kant and quantum physics: what is the difference between Kant’s original approach and the Kantian approach we may take regarding quantum physics? Well, one of the major differences—I think Jean (Petitot) would see many others—is this: according to Kant, the constitution of objectivity that is suitable for the macroscopic universe, the universe described by classical physics, is sufficiently effective that in the face of this physics we can act *as if* it was describing a reality completely independent of us. It is the famous Kantian “as if” (*als ob*). By using this expression, Kant insisted implicitly that it is precisely just an *as if*: the object of classical description behaves as if it was an independent reality, however it is not, and we can easily convince ourselves of this through an epistemological argument. Indeed, if we want to explain the effectiveness of science other than through the well-known device of the highest correspondence with reality, which Kant considered highly problematic, we must absolutely consider that objects are *not* things in themselves, but are *built* from the processes we need to gain knowledge, which is valid from practically any point of view, for everyone, at any time and place. It is the famous intersubjectivity clause. However, this "as if" does not work in quantum physics. There are a number of structures of quantum predictions, a number of predicted phenomena corroborated by experiments that are not congruent with the remarkably structured way of classical physics. In the absence of these structures, we can no longer act "as if" we were dealing with objects that are completely independent of us. The main difference between these two types of physics is this possibility in one case and the near-impossibility in the other case to act "as if" what we are studying is radically independent of us. The basic epistemological idea is still the same; in classical physics as in quantum physics, the structures of knowledge follow on from the conditions of possibility to form knowledge that is shared and can be communicated. There are cases where we can forget this construct and act exactly as if all things were independent of our ability to build, and other cases where we cannot. Quantum physics is that: the scientific situation where Kant is mandatory, whereas he was only optional in classical physics.

Bernard d'Espagnat. I would tend to qualify the difference you speak of by saying that Kant believed in a descriptive physics, describing phenomena "as if" they really existed, whereas quantum physics seems to me to be essentially predictive.

Michel Bitbol. Absolutely.

Bernard d'Espagnat. Indeed. I believe that the essence of quantum physics, ultimately, is to be predictive, that is how it works. It works every time, when we see it from this angle.

Michel Bitbol. Absolutely.

Jean Petitot. However, classical mechanics is very predictive.

Bernard d'Espagnat. Yes, but it is also descriptive! It is both.

Jean Petitot. This is why it is so paradigmatic. It is predictive in an extraordinary way.

Michel Bitbol. Exactly. But classical mechanics is predictive because it is descriptive. The prediction follows on here from a description. By contrast, in quantum physics, the prediction is put forward in a sort of naked state. There is no real description of a spatio-temporal process that underlies the predictive capacity of a theory. The real reason why this is so: quantum phenomena depend entirely on the experimental conditions of their appearance; this is not the case in classical physics. These are phenomena in the most obvious sense of the term, i.e., in the sense of events that take place in the laboratory for all to see; but not in the sense used by physicists who, in my opinion, often confuse in their vocabulary process and phenomenon. A process is what we describe as happening in the world; a phenomenon is what takes place in the laboratory, or before our eyes.

Jean Petitot. There would be much to say on this matter, because, as you know, the retina is a very nice quantum device. It is an admirable photon detector.

Jean-Michel Raimond. If I may say so, the principle of quantum superposition plays absolutely no role there. The difficulties of quantum physics play no role in the way biological organisms function.

Jean Petitot. Yes, but I meant it was a very nice measuring device.

Jean-Michel Raimond. Yes, but the fact of seeing unique photons, or almost, does not imply that the way the retina functions relies on everything that makes quantum mechanics conceptually difficult.

Jean-Pierre Gazeau. I have a question on this topic: what do you actually call "descriptive"? What does this word mean? What limitations do you impose on this notion? Why do we claim that quantum mechanics is not a descriptive science? I have no background in philosophy but I am very interested in this type of discussion.

Michel Bitbol. To keep things short, we consider there is something external (to the intrinsic properties of the object) for which we give a detailed account. We say we have made a description when we present a symbolic copy of the properties and processes that exist independently of the experiments we carry out to gain knowledge of them. Suppose there is nothing that can be considered external to us, that there are no intrinsic properties, that there are only experimental phenomena in the sense of apparent manifestations generated by the workings of a device. In the latter case, we have nothing left to describe because there is nothing we can make a symbolic copy of. It is true we use symbols in quantum physics, but these symbols are simply predictors of phenomena.

Carlo Rovelli. Are we not going too far here?

Hervé Zwirn. Many of us at this table agree with the fact that this is not descriptive, however we agree because we all share a point of view that is not that obvious. It is not shared by everyone, notably by many physicists who do not ask such questions. What you have just said Michel (Bitbol), presumes that we agree to say that quantum mechanics is not descriptive, that we have already adopted the point of view that scientific realism is a not a tenable position. When we dismiss scientific realism which assumes that there is effectively a reality external to the observer, which scientific theory is meant to describe, then we say that "quantum mechanics is not descriptive". However to say this implies that we abandon the idea of an external reality.

Bernard d'Espagnat. We abandon the idea of a describable external reality but we do so for good reasons.

Hervé Zwirn. We have of course good reasons to do this, however this is an a posteriori not an a priori position, where all attempts to maintain the idea of an independent reality external to the observer appears incompatible with a number of things that pertain to quantum mechanics. Or rather, to the quantum world in the broad sense. We can include theories other than quantum mechanics. Experiments of non-locality, of contextuality, etc., do not necessarily assume that we are within the framework of traditional quantum mechanics. These experiments show that trying to maintain a realist, we could say “classical”, stance does not work. We are thus compelled after analysis to abandon this view, and if we abandon it then effectively scientific explanations are no longer descriptive, since there is nothing to describe, or at least, what there is to describe is not external to us.

Matteo Smerlak. Like Jean-Pierre Gazeau, I am troubled by this claim that quantum mechanics is not “descriptive”. I have a feeling that what underlies this opinion is the idea that phenomena are generated by the intervention of an apparatus. My question is therefore as follows: we know that neutron stars are stable as a result of the quantum repulsion of fermions; what do we mean in this case by the intervention of an apparatus? Answering this question would perhaps allow us to define the sense of the term intervention in quantum mechanics.

Carlo Rovelli. It seems to me that quantum mechanics tell us that there are limits to the possibility of describing what is going on, in the sense where classical mechanics was capable of describing what was going on. But to say that there is no description at all… seems to me to be too much of a leap.

Realism is this idea that there is a world independent of us. If realism means the belief, in the limited sense of certainty, that there is a world external to us, then I think we are realists. There is a world outside of us. Personally, I do not think that the only thing that exists in the world is Carlo Rovelli. Do you think that the only thing that exists in the world is Carlo Rovelli? I think that outside of Carlo Rovelli there are other things, which I call the world, even if it is a projection of my dreams. See the dream of the butterfly: the Chinese philosopher asking himself upon waking whether he is not the butterfly’s dream. Even that does not really change the fact that, in my dream, I interact with the world, I am confronted with the world. Therefore it seems to me the notion of reality is essential for our work. The fact that we set limits to this reality, and to what we can say about it does not mean that it is useful to abandon the notion of reality. Between realism in classical mechanics, or Democritus and Leucippe, and complete irrealism, where we do not need to think of a reality external to us, there is an enormous gap. Therefore it is not because we are compelled, empirically, to abandon a precise, strong descriptiveness that we must take unnecessary precautions, so it seems to me. For example: neutron stars.

More than that, it seems to me that quantum mechanics—to speak bluntly—does not tell us at all that my observations of a phenomenon are the only things I can speak of. Quantum mechanics does not only speak of what happens in the laboratory. It speaks of what happened at the other end of the universe, of what happens in astrophysics, of what happens inside atoms when we do not observe them, of the colour of light, constrained by the Schrödinger equation, even when we are not looking at it. I am convinced of it. It speaks of interactions, of what happens within a system when it interacts with another.

We may think about quantum mechanics without necessarily invoking the investigator's consciousness when we speak of neutron stars, for example, while rejecting the descriptiveness of reality. Thus we abandon the possibility of describing reality as precisely as in classical mechanics, but we still speak of a reality where there are interactions, where there are things I can describe.

Hervé Zwirn. I believe that in this debate on realism, Bas van Fraassen provides a good description, which is deliberately exaggerated, of what scientific realism is. He said: we must take the theory literally. What does literally mean? I means, when we have a theory like quantum mechanics which says that there are electrons, there are atoms, there are particles, there are forces, we must understand it as "there are electrons, there are atoms, there are particles, there are forces" in the same way as when we say "there is book on the table, or this is a microphone". That is scientific realism in the strong sense of the term, as described by van Fraassen, and he insists on this point: it is not a metaphor, it must be taken literally.

If we adopt this stance, well, it does not work. When we say for example that quantum mechanics speaks of things other than laboratory experiments, for example the Big Bang or the beginning of the universe, things like that, it is only a story it reconstructs to correctly and coherently organize the observations we make; quantum mechanics has no means of speaking directly of the Big Bang. All that it does is conceive of a number of things like the Big Bang, which are coherent within a formal framework, which then allows us to account for our perceptions in the laboratory, but it does not speak directly of the Big Bang. It simply speaks of what we perceive.

When it speaks of neutron stars, it speaks of the observations we make, by different means, with instruments, of what we perceive and that we interpret in a coherent manner by the algebraic formalisms of quantum mechanics which reconstructs all that we need to account for our observations. There again, what quantum mechanics does is nothing more than order our observations. And to postulate there are really neutron starts, or that the Big Bang really took place, or that there really are quarks, is itself an additional postulate of scientific realism, which raises a number of problems if I take it far enough. This is what we mean when we say that in fact external reality, in the strong sense of the term, cannot be thought of like this. This does not mean there is no reality.

Carlo Rovelli. The same thing can be said from a classical mechanics viewpoint.

Hervé Zwirn. Yes, of course.

Michel Bitbol. Yes, except that in classical mechanics, we could still act "as if"…

Carlo Rovelli. Yes, I agree, in classical mechanics we could act "as if" the world was exactly like that and in quantum mechanics we cannot act "as if" but without necessarily rejecting the notion of reality. If we see a veiled reality, a reality we cannot see completely, we can say certain things but not others, but we do not need to throw the baby out with the bathwater.

Hervé Zwirn. I did not throw it out completely since, precisely, what we are trying to do is reconstruct reality in a form that is different from the usual scientific realism, by saying that it is not built in a spatially external manner with objects that are taken literally, that are the ontology of a theory. It is something else. It is an attempt at reconstructing something external, otherwise we are solipsists, and effectively we say that there is only Carlo Rovelli, or Hervé Zwirn. As we reject this, we try to reconstruct what is compatible with the minimal postulate according to which "there is something else besides my own mind". This is the minimal postulate, and from there what can we reconstruct that is compatible with quantum mechanics or, in the broad sense because I think this is broader than that, with everything that touches upon the quantum framework or that extends beyond quantum mechanics? Non-locality or contextuality experiments do not presuppose traditional quantum mechanics. They are, at a push, independent of quantum mechanics. What these experiments teach us is that realism, let us say the usual scientific realism, raises a problem when we want to take it literally, as van Fraassen said. Therefore we need to find something else, and if want there to be something else to avoid postulating that we are alone in the world, then what is coherent with that? It is the attempts that seek to construct the minimal thing that is compatible with both the quantum world and the fact that we cannot be solipsistic.

Bernard d'Espagnat. Yes, but when we try to do this, to construct a description of this "other thing" which is not us, it seems to me that ultimately we fail. For this reason, I would say that quantum mechanics is essentially predictive, since if you try to replace particles, small dots, etc., by wave functions, to say that it is the wave function that is real, then it does not work. It does not work because if you say that what is real within a particle is the wave function, then as soon as you have a collision between two particles you no longer have a wave function for each of the two particles, you simply have a global wave function. And as soon as a third collision occurs, there is only the wave function of the three particles. And—since this has been happening for a very long time!—ultimately you only have as reality the wave function of the universe: an idea that is somewhat hard to swallow. You could try changing tack and say: "no, what really exists is not the wave function but the density matrix!". Effectively, after a collision you could associate a density matrix with each particle. But if you say that the reality of particles is described only by their density matrices, after a collision phenomenon between two particles the only reality, in your eyes, of this particle pair can only be made up of the density matrix of each one. However, data from the two matrices do not show at all the correlation resulting from the impact, even though it is there. As a result, a description by density matrices cannot be a complete description of reality, since it suggests an absence of correlation when the experiment clearly shows that there are correlations.

In other words, the density matrix is not a satisfactory description of physical reality. Ultimately, when we try to make a description, we come up against this type of problem, whereas when we decide once and for all that it will be solely predictive, predicting observations, then everything works. We only need to do calculations and experiments, nothing else. If we carry out an experiment, this is verified each time.

Jean Petitot. In this type of discussion, I always tend to reintroduce the question of mathematics. The difficulties we are addressing here seem to me to be practically intractable on a conceptual level and we are not taking into account what is, in my opinion, a fundamental characteristic of physics theories, not only quantum mechanics but all current physics theories, namely the possibility to do what some call a computational synthesis of phenomena, a mathematical reconstruct of phenomenal reality.

We have often had this discussion; however I feel it is not sufficient to say "we do calculations". I think there is much philosophy within calculations and I have a tendency to consider that the true philosophy of physics has, precisely, more to do with calculations. Why do we absolutely want to reintroduce, in addition to calculations, a conceptual, classical philosophy where there would be good old substances, like in the past, and metaphysical entities like objects and relations, including within structural realism? Old Kant, of which we spoke earlier, said there was "strictly speaking" no science unless there was mathematics. If not, there is a classificatory, taxonomic ordering like in botany, etc., coupled with conceptual analyses. All sciences perform science in that sense. They collect a substantial amount of empirical data and use our cognitive abilities to put these in order, to classify, categorize, introduce cause and effect relationships, perform conceptual analyses, find concepts that are more fundamental than others, etc. We formulate in this way sociological theories, anthropological theories, etc.

Physics does a lot more: it does calculations and uses the extraordinary generative power of mathematics to reconstruct a tremendous empirical diversity from a few principles. This generativity has a very precise meaning. It is, for example the difference between a differential equation and its solutions. Differential equations express only general principles, however the solutions nonetheless match up with the details of the empirical data. There is something spectacular about this: the principles provide the infinitesimal generators and the models of reality are derived from the associated integral.

I believe that certain debates you have had with your colleague Roland Omnès centred on the role of mathematics and on the question of whether we can shift reality towards the fundamental equations of physics. For my part, I would tend to agree with this idea that reality in physics is formulated by laws and complex equations.

Bernard d'Espagnat. Do you believe in Platonic reality? We are the ones doing the calculations.

Jean Petitot. Effectively, I have shifted the problem of physical realism towards the problem of mathematical realism. Is mathematics simply a cognitive creation? Or is there something else, within mathematics, other than our cerebral activity? This is a very delicate problem, since mathematics is based on calculations, and we must take into account what certain logicians and computer scientists are saying regarding what a calculation is. I believe we can really support the theory that there are fundamental objective aspects within calculations. I cited Alain Connes [7] during our last meeting. He is not at all a Platonist, but at the same time, he did strongly insist during his exchanges with Jean-Pierre Changeux [8] on the fact that all objectivity criteria are united by mathematics.

Michel Bitbol. Mathematics is objective *in the Kantian sense…*

Jean Petitot. Yes, all objectivity criteria, in the strictest sense, are satisfied by mathematics. And yet mathematics is not ontological. It is the proof that there is a non-ontological objectivity. Many philosophers, not only Wittgenstein, have tried to understand why mathematics expresses transcendence *par excellence* while being of purely human origin. This is why I think it is interesting to shift the paradoxes of physics towards the paradoxes of mathematics, using the fact that mathematics is fundamental in physics.

Bernard d'Espagnat. Jean-Michel Raimond has something to say.

Jean-Michel Raimond. Yes, I apologize in advance for doing a *non sequitur* with what has been previously said, but I have from the start a problem with this idea of realism, which comes back to the comments of my young colleague (Matteo Smerlak). I understand to what extent the predictions of quantum mechanics are linked to the measuring apparatus, etc. Nevertheless, when we carry out, for example, a collision experiment, as you were just saying, the outcome of this prediction is highly dependent on knowing whether the particles that meet have an integer spin or a half-integer spin, which seems to me to be the archetype of the intrinsic property and of the intrinsic reality of a particle. I understand the problem of mental conception, etc., I understand completely that we could say that "there is no realism; anyway, everything exists within the field of consciousness and within the consensus that stems from our consciousness"—I must add I know nothing about philosophy—, but I find it hard to understand how we can completely reject all objective reality, independent of the measuring apparatus, for a number of properties of objects that are manipulated by theory. I need to know the charge, the mass, the spin of an electron to do anything in quantum physics. Is this not an element of reality?

Bernard d'Espagnat. Personally, I would not systematically eliminate things like the charge of an electron or the Planck constant, things like that, from the collection of what could constitute the elements of what we call independent reality: *mind-independent reality*. Therefore I agree with you in this sense, but I think that, firstly, it is conjectural and, secondly even if it was true, even if these elements were really the constitutive blocks of independent reality, their knowledge in itself would not be sufficient to reconstruct independent reality. This is my small contribution, which far from answers the question.

Jean-Pierre Gazeau. I do not know whether I may follow on from this contribution, but I was thinking of classical physics, of the evolution of what we call a physical quantity. A physical quantity, according to the definition of the

International Bureau of Weights and Measurements is something that can be characterized qualitatively and measured quantitatively.

If we take the example of instantaneous speed, it is a concept that was impossible certainly before the 18th century. It has become with mathematics a physical quantity in its own right that is listed by the International Bureau of Weights and Measurements. This physical quantity can cross the quantum barrier, i.e., we will find the same name for the physical quantity that we now analyse within a quantum framework, such as energy, such as quantities previously identified in the classical framework that will continue to be identified in another framework. We will describe them, once again, in a quantum framework. I do not know, personally, whether we could have described them better in a classical framework. What is the length of this table? Are there natural boundaries? Is there an impossibility to define concretely the length of an object? Simply compared with units, etc., at one point or another there are limits that are impossible to overcome.

I do not know, I find it hard to discriminate between something that is descriptive within the framework of one theory and that is no longer descriptive within the framework of another theory. I think mathematics is precisely there to help us.

It seems to me that in quantum physics we speak a lot about spectrum: the spectrum of a physical quantity. It is through the spectrum that we will identify a physical quantity. We also find a spectrum within the framework of classical physics. Simply, the spectrum is different, even infinitesimal, much more idealized in the classical framework than in the quantum framework. Within the quantum framework, there are many quantities, ultimately, for which identification relies on a discrete spectrum, more easily attainable than the elements of the "classical" continuous spectrum, as it happens in classical physics with the concept of length. You see.

Bernard d'Espagnat. We can try to give a partial answer to what you are saying. You speak of speed. We can also speak of momentum, it is the same thing. If we try to construct a theory in which physical quantities such as position or momentum are not inventions, ways of describing our experience, but correspond to reality as it is, it means that we seek a theory that is ontologically interpretable, and the model for a theory that is ontologically interpretable is the theory of David Bohm. Besides, we should not say "Bohm theory", it is in fact a theory (or one of many theories) of Louis de Broglie, which Bohm developed further [9]: it is a great injustice to speak of "Bohm theory", but never mind.

We therefore need to consider Bohm theory which reproduces all the predictions of quantum mechanics and which at the same time allows us to interpret the position of an electron effectively as a reality in itself. So if we consider momentum, Bohm theory effectively defines the momentum with a very precise formula; however this momentum cannot be measured. The momentum we measure is something else. We can measure a quantity which, in textbooks, is called momentum and which corresponds to what we call momentum in classical mechanics, but this quantity is not a momentum according to Bohm theory. The momentum predicted by Bohm theory cannot be measured: when you measure a momentum, you automatically measure something else. We are therefore faced with real difficulties that were not there in classical physics but are here now.

Hervé Zwirn. I would like to try to counter the two objections, which are not exactly the same but which go in the same direction.

First of all, I would like to go back to the concept of length found in classical mechanics that is also found in quantum mechanics, as in the concept of speed. Regarding the notion of description, it is not because we have observables, properties, etc. that are comparable or similar in quantum mechanics to what we have in classical mechanics, that we necessarily recover a description. The concept of length and the concept of speed you (Jean-Pierre Gazeau) were alluding to are properties that we effectively find again; we use the same words and they intuitively mean the same thing, but in order to say "we have recovered a description" we would need to assign these properties to an object. However, the problem we have in quantum mechanics is not that we cannot speak of the same quantities; we have the same observables in quantum mechanics and many of things are similar to what we already have in classical mechanics. The main difference is that we can no longer, for the most part, consider that the property is directly assigned to the particle, either in quantum mechanics or in de Broglie-Bohm theory. In classical mechanics we could consider that these quantities could have defined values for particles, whereas in quantum mechanics we no longer can, since the values are determined only after measurement. To suppose that the measurement is there, as in classical mechanics, only to observe their value does not work. Therefore, the moment we can no longer consider that we are describing something that exists, that has values and that we content ourselves with observing using instruments, the notion of description loses much of its meaning. The problem we have in quantum mechanics stems from there, it does not arise from the fact that we can no longer think of the same quantities. We think of them, but we no longer have the right to consider that these quantities can be applied, as in classical mechanics, to objects and that we will observe and describe what there is because we do not describe what there is: if we try to think like that, we fail.

Jean-Michel Raimond. There is still one thing that physics, including quantum physics, relies on. It is the capacity, the postulate that we are capable of, to properly define what a sub-system of the universe is, without which we come up against, as Mr. d'Espagnat was saying earlier, the wave function of the universe, and we might as well just give up and go to the madhouse.

To describe a sub-system means I am capable for all practical purposes—I agree it is not a philosophical point of view—of saying that "at this time, I am working with a system that is made up of three or four electrons, which are doing things, which interact in a local quantum manner". I am dealing with a situation with predictability issues, but I am nonetheless capable of saying that my reasoning, my theory, applies to a defined sub-system. I need to be able to say this, at one time or another. This sub-system is defined, it is made up of entities which themselves have, within the limits we all understand, I think, a certain number of established properties that I would tend to call, perhaps because I am completely ignorant, reality.

Carlo Rovelli. I agree with both. It seems to me that you are in fact, by saying two complementary things that are not in contradiction, focusing the problem. We are to some extent at the heart of the discussion. On the one hand, I hear "There are things in reality that are not defined until you observe them". On the other hand, I hear, "Yes, but still, there are things in reality that seem to be defined, in any case, we can make a list". It seems to me this is where we are at.

I would be tempted, to move this discussion forward, to look for a position that does not necessarily say "since a certain type of realism, where I can imagine an precise description, in a sense, of reality, is clearly blocked by quantum mechanics…". It has been blocked in an empirical manner. Given this, are we forced from then on to abandon the notion of reality? And the notion of description? Is there not a weaker way to speak of description? Is there not a weaker way to speak of reality? Which one?

It seems to me that in this discussion, and in quantum mechanics, there are things we can use, and not construct a philosophy out of nothing. In the image of the world provided by quantum mechanics, some realistic aspects still remain. We still use the notion of sub-system that seems to work very well and at the same time is the source of all problems, since the real problem of quantum mechanics is that of the limits of the notion of sub-system. If I have a particle, I can think there is a wave function, but at the same time if I consider a bigger system, I know that this wave function will not have all the required information regarding the correlations with the rest. I need the wave function of both.

It seems to me that if we want to find "neorealism", it is in the opposite direction. We are still saying "we measure this". What does that mean? It means that a device or someone interacts with the system, and the device itself is subjected to and is affected by this interaction. The outcome of this measurement is what is considered in Heisenberg-type quantum mechanics. What is predicted by quantum mechanics, written down on paper, is not the state but the effect of the interaction.

If I take the ensemble of these "measurement outcomes" as my notion of reality, I still have a problem since I realize that what is measured can become for me, for someone who considers me within a quantum system, only a fragment of my wave function, by opposition with another me in another branch of the wave function. Therefore, the difficulty is that I have another unresolved problem. I have not resolved the problem by simply following Heisenberg, by saying "I see the electron here, here and here and I do not ask myself where it is elsewhere but that is all I see". I have not resolved the problem; however it seems to me, if I remember that I want a weaker definition of reality, that quantum mechanics is telling me that these measurement outcomes must be attached to the affected system. Therefore if I imagine that any system of the universe, any sub-system of the universe, as it interacts with other systems, produces measurement outcomes, I can think of the world without necessarily invoking the mind, that is to say without… imagining a *mind-independent* reality, where there are interacting sub-systems and, *with respect to each system*, elements of reality that are real; however, only real regarding that system. I can understand this as a theory of knowledge, as a very partial description of the world.

Let me come back to what you have said. When Newton introduced the concept of force, the whole of Europe said "No, no, no, that is irrealism!" The most vehement criticism from France, Germany, Italy and Spain of the *Principia* was that it was too antirealist: realism should be strong, in the manner of Descartes, or like the atomism of Ancient Greece. Interactions should exist only for things that are in contact. The concept of force was part of irrealism. As time went on, we all became Newtonians and, for us now, the concept of force is part of realism. We have completely changed our conception of reality.

It seems to me that we must search for a new conception of reality, one that is weaker, where the key factor would be to focus on the measurement outcome and to realize that this outcome is relative to the observed system. I think we can do this without necessarily speaking of consciousness, without necessarily speaking of the *mind*, by staying within physics, yet still speaking of a description, but obviously a description in the weak sense, in quantum mechanics. It seems to me that it is our idea of reality that must evolve to adapt itself to quantum mechanics.

Bernard d'Espagnat. It seems to me that you base most of your arguments on the notion of sub-systems. I think that in fact the notion of sub-system is a creation of our way of seeing things. To say that we have a particle that disintegrates in two, therefore that we have two sub-systems, is to say that when you look you will see two sub-systems. But until you have looked, you cannot really say that you are dealing with two sub-systems, so it seems to me. That would be to interpret them as things in themselves; this does not seem possible to me.

Jean-Michel Raimond. I know that these two particles are correlated; however, I want to be able to speak of these two particles which are not each a sub-system independent of the rest of the universe.

Bernard d'Espagnat. You speak of them because you know that when you will observe them, you will observe two things in two different locations, but you speak of future observations, you do not speak of something that is totally independent of yourself.

Michel Bitbol. Just one point to add to what Mr. d'Espagnat said: a great physicist named Asher Peres wrote a book on quantum theory from an entirely empirical perspective [10]. According to him, what we call a physical system is only one way of translating a class of experimental set ups. When we say, for example, that there is a physical system made up of two particles, that simply means that we have prepared an experimental set up such that the value associated with the value of the observable "number" is 2. The usual vocabulary where we "prepare a system" is redundant so to speak; the word "system", according to Peres, is the name we give to partially controlled potentialities that become available through preparation.

Carlo Rovelli. What of Matteo's (Smerlak) neutron star?

Matteo Smerlak. We still have the same problem of the apparatus that would interfere with the system.

Michel Bitbol. However, I do not need the apparatus to intervene straight away. Quantum mechanics allows you to predict that you will never observe a neutron star breaking spontaneously. You can try to associate a vector state with a neutron star and it allows you to predict that, in future experiments, the probability of observing the spontaneous collapse of the system is close to zero.

Matteo Smerlak. How could I prepare a neutron star? You define a sub-system through a preparation process.

Michel Bitbol. Indeed, the problem here is that the preparation is not controlled; however we can obviously define a preparation that we call for example the Big Bang, or another process that plays exactly the same role. But I have to admit this is not yet the right answer.

Carlo Rovelli. As soon as I allow myself to do this, I can think of the world as something that was prepared and which I study. Therefore the notion of preparation is not that essential after all.

Michel Bitbol. Using the notion of preparation could simply mean that we circumscribe the conditions of our experiments, meaning that we put in place instruments that allow us to select a certain number of objects, for example neutron stars. Once we have done that, we can perhaps associate a wave function with these selected objects… The problem you (Matteo Smerlak) raise is the following: in general, we associate a vector state with a system using the knowledge we have of a previous preparation. For example, I can associate an electron with the vector state $|+\frac{1}{2}\rangle$, the specific vector of a spin component, and I can say "I associate this vector state with it because I made it pass through a Stern-Gerlach device which served as a preparation, and because I have selected the upper electron beam". In the case of neutron stars, the problem is that I do not have this capacity for control…

—Addendum by Michel Bitbol—
After this discussion I realized that my response to Matteo Smerlak's objection was incomplete and unsatisfactory. A more convincing conception needed to be formulated, but I only thought of it afterwards. I therefore sent a letter to Matteo to clarify what I meant by "preparation of a physical system". Once this clarification is accepted, nothing stops us from extending the notion of preparation and attributing an associated predictive symbol to systems that are not controlled in the laboratory such as neutron stars. Here is my letter:

"Dear Matteo,

I thought about your interesting objection to neutron stars last night (and unconsciously during the night). It seems to me that I now have the answer. In short, it rests on an *informational* definition of preparation rather than on the standard idea that considers preparation as an operation that is materially controlled in the laboratory. It is amusing that I did think of this straight away: it proves I still carry with me remnants of realism despite my best efforts!

1. In the standard conception (first established by Henry Margenau in 1937), a preparation is a filtering operation of physical systems controlled in the laboratory.
2. Following this operation, depending on the type of filter used, we associate a vector state with these systems. Some very classical examples: the emission of photons by a lightbulb and the passage through a vertical polarizer, the emission of silver atoms by an oven followed by a Stern-Gerlach (device) and the selection of one of the two trajectories, the emission of electrons by a heated filament, the acceleration by an electric field and the interposition of a screen with one hole. The associated vector states are respectively: two states that are specific to a spin component and one state that is specific to the observable spatial position.
3. What matters in this process of association of vector state and preparation is not the a priori instrumental control of the systems, but the *information* made available by this control. As proof of this: the "*delayed choice experiments*". It is particularly apparent in the first thought-experiment of this type, i.e., Heisenberg's microscope, reviewed and improved by (Carl) von Weiszacker. The vector state of an electron lit up by a photon does not depend on what was initially done to the electron, or on the momentum transmitted to it by the photon, but by the position of the photographic screen near the microscope's eyepiece. What changes with the position of the screen is only that the information obtained is optimal *either* for the position variable *or* for the momentum variable. If the information is optimal for position, we assign a vector state to the electron that is nearly identical to a specific vector of the observable "spatial position", and if the information is optimal regarding the quantity of motion, we assign a vector state that is nearly identical to a specific vector of the observable "quantity of motion".
4. By extrapolation, we can perfectly speak of the "preparation of a system" even if it is absolutely not controlled in a laboratory (as is the case with astronomic objects!). "*Preparation*" *in this case is nothing more than the discrimination at a distance between different classes of objects that allows us to obtain initial information about them.* Selecting a neutron star in the sky based on spectral and/or gravitational criteria amounts to making initial information about it available, i.e., to "prepare" it (in the broad sense of the term). From this initial information, we will be able to (at best) attribute it a vector state or (at worst) a density operator.
5. It is true we can also not attribute a vector state to a neutron star and use more global strategies to show its stability. This is the case, using the most well-known example, when we prove the stability of atoms using Heisenberg inequalities. This simply means that we consider an entire class of preparations

rather than a single preparation; however, even here the initial information is made available by what we could call a "generic preparation", and we are again in the standard situation.

I confirm that ultimately quantum mechanics is a formal process that allows us to derive an instrument of probabilistic prediction from the initial information made available by an operation called "preparation". This instrument of probabilistic prediction can be modified as new information is obtained (this is the "state reduction"!)".

The case of a neutron star does not call into question the easily interpretable general operational scheme of quantum mechanics.

—Remainder of the session (31st of January 2011)—

Matteo Smerlak. My example aimed to show the limits of the very Peresian idea, of preparation of a sub-system. This operationalism is relevant in the laboratory, were experiments are carried out on atoms, on systems that we can master in our immediate vicinity. However, quantum mechanics goes beyond that. It seems to me that this type of point of view is problematic in the context of astrophysics.

Hervé Zwirn. There are effectively problems with preparation within the context of astrophysics that must be dealt with differently.

Michel Bitbol. The problem is always this one: what are we doing to attribute a vector state to something? Effectively, when we attribute a vector state to an electron in a laboratory, we know what we are doing: we prepare, we pass the electron through a Stern-Gerlach (device), we select those which are at the top, for example, and not those which are at the bottom, therefore we can attribute a vector state. What are we doing in practice—it would be interesting if you (Matteo Smerlak) could tell us—to attribute a vector state to a neutron star?

Matteo Smerlak. What I had in mind was more related to statistical physics. The properties of a neutron star are those of a very large number of neutrons that we do not try to describe individually; this is an important difference. The quantum mechanics we speak of in this type of epistemological discussion is the quantum mechanics of prepared and measured individual systems.

Michel Bitbol. I now understand, you speak of a generic system and not of an individual system. Effectively, it is not prepared, however, you consider a class of systems, with a possible hypothetical preparation, and you say "with this class of systems I associate, let us say, such and such density operator r".

Hervé Zwirn. When we observe a neutron star, we are not in same situation as when we observe an individual neutron. We have macroscopic properties that emerge independently, for which there is no need for preparation because they are affected by a sort of global thermodynamic property. What emerges is statistics. It is exactly the same thing as when we look at a table.

Matteo Smerlak. Indeed. I would like to point out the fact that quantum mechanics is also critical in this framework, which is not that of atomic physics. I think that these questions can be asked slightly differently, if we keep in mind this other aspect of quantum mechanics, i.e., its statistical aspect.

Hervé Zwirn. Is it a counter-argument to what we were saying previously, or not? Since we could easily say that, independently of the fact that every neutron of a neutron star has its own existence, quantum mechanics shows that the collective properties of this ensemble of electrons are still the same macroscopically. Therefore it works. I had some difficulty with this argument earlier, but in fact it is not a counter-argument to the fact that we refute the individual existence of each neutron.

Matteo Smerlak. I agree completely.

Hervé Zwirn. Yes, completely, since it is macroscopic and therefore it emerges without the need for a measuring device.

I would like to ask Carlo (Rovelli) a question regarding what he said earlier. Why say, if I understood correctly, that when two sub-systems interact we do not need to have the intervention of an observer to say that a measurement has been done? The interaction of two systems does not produce a measurement!

Carlo Rovelli. I think it does. I say this rhetorically. Imagine you make measurements. Someone else has made them in Beijing. There is the same Stern-Gerlach (device) in both locations, but imagine the Chinese scientist stepped out of the room. The measurements were made without him being there. Were the same measurements made? I think so. What happened had nothing to do with the mind.

Hervé Zwirn. Yes, because you made the measurements. In that case, the two systems, as long as we have not made any measurement, are considered as one. They are entangled. We are in an EPR situation. It is the same system. What do you mean by an unread measurement?

Carlo Rovelli. No, no, it is not EPR!

Hervé Zwirn. So the Chinese scientist has gone out, and has not looked?

Carlo Rovelli. There is a white dot, but he has not looked at it. There is nothing in quantum physics that tells me I must discriminate between the two. Therefore I think it has nothing to do with the mind, it has to do with something else, with an interaction between the electron and the measuring device, however if it was not a measuring device, if it was a magnetic field and neutrons, I think something would happen in exactly the same way. I am personally convinced, through the study quantum mechanics, that there is nothing that speaks of the mind, that directly speaks of consciousness. On the contrary, there is something in quantum mechanics that strongly compels me to say that I cannot take the fact that the dot is there as a property of absolute reality, but I must relate it to something else, for instance my point of view, or someone, or someone else.

Michel Bitbol. I did not expect this from you Carlo. I have the impression that you are being unfaithful to your relational interpretation. You say there is no difference between the instance when the Chinese scientist has looked and when he has not. But of course there is a difference! In one case, *relative to* the Chinese scientist who has not looked, the ensemble of the system is still in a state of superposition, whereas, *relative to* the Chinese scientist who has looked…

Jean-Michel Raimond. No!

Michel Bitbol. According to Carlo it is. According to his interpretation, there is a difference between the description relative to the Chinese scientist who has looked and the one who has not! Carlo, relative to the one who has looked, you must say…

Carlo Rovelli. I think that quantum physics forces me to say that, relative to the screen, a measurement has been made.

Hervé Zwirn. No because the screen and the electron are in a superposed state and nothing in quantum theory allows us to say there is a dot at a given location.

Carlo Rovelli. We are at the heart…

Jean-Michel Raimond. We now come to the wave function of the universe!

Carlo Rovelli. I will try a different approach. You (Hervé Zwirn) make a measurement; I am outside. You are in a box, and you can see what is there; I am outside and I have very precise instruments that allow me to see very close quantum correlations. For me, no measurement has been made. In relation to you, something has been measured; with relation to me something has not yet been measured.

Michel Bitbol. *That* is typical Rovelli!

Carlo Rovelli. Therefore, relative to the screen, a measurement has been made. Relative to you, a measurement has been made. Relative to me, a measurement has not yet been made. If we accept this weakening of reality, we can speak of reality, we can still speak of the elements of reality. It is very strong and we do not need to invoke the mind, things happen relative to other physical systems not relative to consciousness.

Jean-Michel Raimond. Except that to detect subjective correlations that prove that your friend is not in a superposition of states, we would need in practice a device that is bigger than the Universe. These correlations are so inextricably hidden (like a needle in a haystack) that we need devices of unfeasible complexity to detect them. Therefore we would need to say, perhaps, at some point—it is not philosophically correct—"in practice, we do not care, a measurement has been made". One knows the outcome, the other does not, but the measurement has been made.

Carlo Rovelli. Yes but I think that if we keep the distinction, we can salvage certain suggestions for solving certain paradoxes we do not understand. I agree but if we keep in mind that it is only *in practice* [11] that we can do this, we still have a weakening of reality, but on the other hand we gain the fact that certain paradoxes are resolved, and we do not need to invoke human consciousness. Within the universe, human beings do nothing that is unique. Except that they are capable of gathering information on the world, and perhaps of other things like interacting.

Michel Bitbol. Something human beings are capable of is understanding that they do not do everything in the world, as you do in a very strong manner Carlo when you say: “human beings do nothing that is unique other than collect information”. This ability is very important; in it resides our power to objectify, out power to define a domain of existence that we can consider as not entirely controlled by us. At the same time when you highlight the fact that human beings do nothing unique, it is a construct you are doing just now with your human intellectual powers! We had to start somewhere to define a domain which is not affected by humans, and this starting point is none other than our human point of view… Human beings also have this great capacity for defining the conditions in which they can consider that they do not intervene.

Carlo Rovelli. I follow you 100%.

Hervé Zwirn. I think everyone agrees, from a practical point of view, effectively, that the measurement has been made, since to see whether a superposition still exists would require measuring devices completely beyond our reach. From a practical point of view, it is “as if”, we all agree.
To see whether in fact, “in reality”, the system is still in a superposed state would require measuring devices completely beyond our reach. As human beings, we can consider that the measurement was made “for us”. As physicists, we do not need to ask any more questions and we can carry on doing physics, but, as a philosopher, we differentiate between “for us” and “in itself”.

Jean-Michel Raimond. This measurement is beyond the reach of the universe as a whole.

Hervé Zwirn. It is out of reach if we consider measuring devices as being created by human beings but, technically, as long as we have not reduced the density matrix by the partial trace operation linked to the fact that we will not look at certain degrees of freedom (and that is due to our own limitations), this density matrix remains non diagonal. Therefore if we want to reason not from the point of view of mankind’s capacity, but on a philosophical level, technically, we cannot say that the density matrix is diagonal and thus that the measurement has not been done.

Jean-Michel Raimond. In that case, if we want to reason on a philosophical level, it is urgent that we stop reasoning on quantum physics, since it says that from the beginnings of the universe all particles are in an entangled state to which we belong. There is no possible reasoning on all this and we come back to the wave function of the universe.

Either there is a “for all practical purposes” that is philosophically defendable, I do not know why, with a reduced sub-system that is no longer in a superposition of states, either this sub-system continues to drive away these superposition of states in the whole of the universe, the whole of the universe is in a big wave function, I am a part of it, and I do not know anything anymore.

Hervé Zwirn. Even if we say that the fact that everything remains in a superposed state has as a consequence that the measurement of the global system is not attainable, we can be interested in things which are forever beyond our reach but for which we can see the point philosophically.

Let us place ourselves in a state of the universe 10^{1000} years from now. Nobody knows what that state will be. Some theories say one thing, others say the exact opposite. However, if we suppose that the system is still in a superposed state, we can make predictions that show that a certain number of correlations can appear 10^{1000} years from now which would have been lost if the wave function had been reduced. Admittedly, 10^{1000} years is a length of time beyond our reach. Nevertheless, the predictions of what will happen in 10^{1000} years' time are not the same if we suppose a wave function that is reduced in reality compared to one where we suppose a wave function that is not reduced in reality. This is what we mean when we say they are not the same.

Jean-Michel Raimond. This is because the Poincaré recurrence time applied to the wave function of the entire universe extends far beyond 10^{1000} years, i.e., probably closer to 10 to the power of 10^{1000} years.

The point would be to arrive at a philosophy that would limit itself to what is "in practice" because that is where we are at. We are debating things that make no sense.

Bernard d'Espagnat. My dear friends, it is getting late. We must put a provisional stop to this discussion. Otherwise, we will be kicked out. Let me remind you that the next session is on the 14th of March. Jean-Michel Raimond will talk about decoherence.

Jean-Michel Raimond. From a "practical" point of view!

Bernard d'Espagnat. From an experimental point of view, which amounts to the same thing. We will then try as a group to draw out the significance of the experiment in question. This will be interesting and extremely important.

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7. Session I, “The Inescapable Strangeness of the Quantum World”.
8. See *Matière à penser*, Odile Jacob, 1989.
9. See sessions V “The Pilot-Wave Theory of Louis de Broglie and David Bohm” and VI “Pilot-Wave Theory: Problems and Difficulties”.
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11. On this expression, see the discussion at the start of session VI, “Pilot-Wave Theory: Problems and Difficulties”.

http://www.springer.com/978-3-319-55419-8

The Quantum World
Philosophical Debates on Quantum Physics
D'Espagnat, B.; Zwirn, H. (Eds.)
2017, XVII, 299 p. 11 illus., Hardcover
ISBN: 978-3-319-55419-8