Chapter 7
The Relational Interpretation of Quantum Mechanics and the EPR Paradox

Matteo Smerlak

Bernad d'Espagnat. Most of us, of course, have heard of the new and daring interpretation of quantum mechanics proposed by Carlo Rovelli, who is here today, called *Relational Quantum Mechanics*.

After introducing its central idea, Matteo Smerlak will tell us how Carlo Rovelli and he propose to apply this interpretation of quantum mechanics to the resolution of the EPR paradox in its current form. Thanks to the work of J. S. Bell, Alain Aspect and others, we now know that we must abandon either realism or locality. Most physicists prefer to abandon locality, but there are exceptions. Rovelli and Smerlak's approach is one of those, since, as Matteo will show us, it preserves locality at the cost of considerably weakening reality.

Matteo Smerlak, the floor is yours.

7.1 Presentation by Matteo Smerlak

Matteo Smerlak. Thank you, Mr. d'Espagnat, for giving me the opportunity to speak before this audience about ideas that are not fundamentally my own but that of Carlo Rovelli. Let things be clear, I had the opportunity to collaborate with him on one of his projects, but the basis of the relational interpretation is proposed by him, in an article published in 1996 entitled "Relational Quantum Mechanics". The relational interpretation claims that the object of quantum mechanics is not the entangled state of physical systems, as we often say implicitly or explicitly when we teach quantum mechanics, but their relations [1]. In that, it claims to extend and

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deepen the notion of Einsteinian relativity, and thus dissolve some of the persistent paradoxes of quantum mechanics, for example the measurement problem (the reason why Carlo Rovelli proposed this interpretation) but also the EPR paradox (of which I will also speak here).

7.1.1 The Relational Interpretation

The observed observer

Let us start by describing the relational interpretation itself. For that, let us consider the following situation: a quantum system S (represented below by the Feynman diagram) and two observers O and P who simultaneously observe S. Let me specify straight away that despite this drawing, the observers must be considered as measuring apparatus, i.e. observers in the sense of quantum mechanics, and not necessarily conscious beings.

O and P are two measuring apparatus capable of coupling with the degrees of freedom of the system S to measure a certain observable.

We can imagine that at the start, the state φ of the system S as quantum mechanics prescribes it is a superposition of two particular states, 0 and 1, corresponding to two specific values of an observable I will not specify, with normalized coefficients α and β.

Quantum measurement: a contradiction?

Let us consider first of all the measurement of system S as described by O. We can find this type of description in the original works of von Neumann and Wigner [2]. From the point of view of O, the measurement has induced a transformation of the state of the system, which we call a collapse or a projection, that leads the initial state towards one of two values, 0 or 1, with respective probabilities $|\alpha^2|$ and $|\beta^2|$. In both cases, after measurement, the observable takes on a defined value: either 0 or 1. There is no doubt on that point.

Let us now consider the point of view of P, the second observer, who does not interact with S but observes the measurement of S by O (in other words, the coupling of S and O). From P's point of view, the initial state of the system is a product state of φ for system S and an initial state for O. At the end of the measurement, the degrees of freedom of O are correlated with those of S and the system results in a superposition between two coupled states for S and O, without projection. There is a unitary evolution of the system from its initial state to its final state. The important point of this observation is that, from P's point of view, the value of the observable on S is not determined. *It remains indeterminate*.

We have an apparent contradiction. From O's point of view, the observable has taken on a defined value. From P's point of view, that is not the case. That is the problem of quantum measurement.

Two fundamental postulates

Commentators of this problem mention incompleteness (Einstein), a form of contextuality (Bohr) or the existence of a break between the quantum system and the classical observer (Heisenberg). Such are the classic commentaries on the measurement problem.

By contrast, Rovelli postulates that first of all (*hypothesis 1*), quantum mechanics provides a complete description of the physical world, adapted to the current level of experimental observations; and secondly (*hypothesis 2*), all systems of nature are equivalent. There is no fundamental difference between quantum systems and classical systems. Notably, macroscopic systems are quantum systems of a particular type.

Furthermore, he claims to want to deduce the interpretation of quantum mechanics from its formalism and not add metaphysical preconceptions that could lead to a reformulation of the formalism of quantum mechanics. From that point of view, the attitude of Einstein (who wanted a realist description of the world) resembles a metaphysical preconception. Rovelli claims to get rid of this type of preconception in order to take the formalism of quantum mechanics seriously.

Given these two postulates, we must accept that the points of view of O and P are equally valid. Indeed, O and P being quantum systems, there is no reason to favour one point of view over the other.

This leads us to the conclusion that the value and even the actuality of an observable of S are relative to the system with which S interacts. Indeed, I said that for O, the value of the observable of S is determined after measurement, whereas it is not for P. This means that the quantum states are relative to the system that measures them. We must therefore speak of the quantum state of system S *relative to* O. In other words, we must index quantum states no only by the system they target, but also by the observer that observes them.

Revisiting the measurement problem

Let us return to the problem of the observed observer and describe it from this point of view.

From the point of view of O who interacts with S, the state of S passes, after collapse, from superposition φ to one of the two possibilities, let us say 0, which is the final state of system S relative to O. From the point of view of P—and I note that P does not interact with S—the product state of the state of S and the initial state evolves towards the famous superposition we mentioned earlier. The important point is that 0 on the one hand and the superposition on the other hand do not correspond to the same quantum states because they are not indexed by the same observer. In the first instance, we have the state of S relative to O. In the second instance, we have the state of S and O relative to P. Different observers, different systems: there is therefore no contradiction in the fact that the states are different.

Let us note that the violation of unitarity from O's point of view results from an incomplete description of the measurement system. Indeed, S is correlated with something that evades O: O itself. That is why I have stressed that, from the point of view of O and from the point of P, there is an asymmetry: O is coupled with S, whereas P is not coupled with S. There is a physical interaction between O and S, but not in this case between P, S and O.

This could potentially explain the difference in behaviour between unitary evolution in the latter case, and non-unitary evolution in the former.

A historic leitmotiv

Rovelli proposes to clarify the interpretation of quantum mechanics, as we have seen, not by introducing new concepts but by abandoning an old concept: namely, that of a system's intrinsic state. For him, it is *one hypothesis too many*.

This reminds us of the elucidation of relativistic kinetics by Einstein, who derived Lorentz transformations not by postulating new microscopic principles, but by purely and simply abandoning the idea of absolute time. It is this analogy that Rovelli wants to push with his interpretation of quantum mechanics.

On a historical level, it seems that physics has progressed towards more and more relativity. It would therefore not be fundamentally surprising to discover that in quantum mechanics as well, we are progressing towards a new stage in relativization.

Relation and information

The relational perspective is naturally compatible with the notion of information, which we know is found nowadays in all areas of physics. Indeed, information quantifies the amplitude of (cor)relations between two systems or between two variables. If two systems S_1 and S_2 are strongly correlated, we would say that S_1 contains a lot of information on S_2 and vice versa. Formally, the information contained by an object O on another object S is the number of binary questions on S for which we can predict the answer by measuring O.

I will come back to how Rovelli uses the information concept in his relational interpretation.

Ideas for reconstruction

To go even further in the elucidation of the formalism of quantum mechanics, a number of authors have suggested a *programme* of reconstruction of the formalism of quantum mechanics, namely Hilbert space, the algebra of observables or unitary evolution from clear physical postulates. I can cite, among the earliest attempts, von Neumann himself, then Birkhoff and Mackey, who embarked on a programme of quantum logic with the aim of reconstructing Hilbert space from physical principles. There are more recent approaches, including that of Rovelli. I would like to mention on this matter Alexei Grinbaum's review paper on the reconstruction of quantum theory and on Rovelli's contribution to this reconstruction [3].

Rovelli's informational postulates

What are the clear physical postulates that Rovelli claims can allow us, in time, to reconstruct entirely the formalism of quantum mechanics? At this stage, I would say there are two postulates, even if three postulates were suggested in the original article [4]—the third one seems to me more conditional and remains, I think, to be formalized.

Rovelli's first informational postulate is that there is an upper limit to the quantity of information we can extract from a system.

The second postulate is that it is always possible to acquire new information on a system.

We are confronted with an apparent contradiction: the first postulate tells us there is limited information and the second postulate tells us that information is unlimited. In truth, these two postulates are not incompatible or incoherent, simply because in quantum mechanics there are incompatible observables and we can obtain new information on a system by measuring a new observable that does not commute with the previous one. In this way, we can obtain new information. The price to pay is that we degrade the information we had previously.

These two seemingly contradictory postulates may actually be a seed from which we can grow back the formalism of quantum mechanics, with its incompatible observables and its mechanism of information degradation that is specific to quantum mechanics and is the source of its indeterminism.

You will see in the original article that it is possible to derive certain aspects of the formalism from these principles. However, progress needs to be made. I consider, for my part—and I believe Alexei Grinbaum agrees—that the notion of entropy will certainly play a role in the reconstruction programmes of quantum mechanics.

So much for the relational interpretation in general and how I can summarize it. I now come to the EPR argument, which is so problematic in quantum mechanics, as we know, and yet is so productive—from both a theoretical and an experimental level.

7.1.2 The EPR Argument

The relational interpretation—as I will suggest—discards the concept of quantum non-locality in the EPR argument, according to an analysis described in the paper "Relational EPR" [5].

Let me remind you that similar arguments have been described previously by Michel Bitbol himself in 1983 [6] and by Federico Laudisa in 2001 [7].

The EPR-Bohm argument

Let me remind you of the EPR argument in its simplified version as given by David Bohm. We consider a source producing two quantum particles α and β that are sent in two arms of an interferometer—two arms of an experiment—in such a way that they meet two observers A and B—I can call them Alice and Bob—separated by a spatial distance such that there is no direct connection possible between A and B.

In other words, in terms of special relativity, A and B are in two regions separated by a space-like interval.

We hypothesize that the source produces the particles α and β that are in an entangled state. We could, to make things clear, consider the observable spin and say that it is a singlet spin state,

$$
\begin{aligned}
|\psi > &= 1/\sqrt{2}\big(|\downarrow\ >_{\alpha}|\uparrow\ >_{\beta} - |\uparrow\ >_{\alpha}|\downarrow\ >_{\beta}\big)| \\
&= |\ 1/\sqrt{2}\big(|\leftarrow\ >_{\beta} - |\leftarrow\ >_{\alpha}|\rightarrow\ >_{\beta}\big)|
\end{aligned}
$$

I wrote this state in two different ways, following the decomposition in two possible bases of spin space: the vertical spin and the spin in the other direction which I consider horizontal. The EPR argument is the following: the measurement of the observable spin in the vertical direction y or the horizontal direction x would actualize, because of entanglement, a defined value of the spin of β with no causal relation between α and β. If Alice measures α and finds a spin value, then instantly, according to the formalism of quantum mechanics, this produces a defined value for the spin of β as it would be measured by Bob.

This is problematic for relativistic causality, as we have said that Alice and Bob in this set up are separated by a space-like interval.

A counterfactual difficulty: *EPR and Bell's inequalities*

I repeat this argument: the counterfactual possibility of measuring incompatible observables on α, along with the previous observation, leads to tension between quantum mechanics (such that predictions are formulated by the step described above), realism (for a reason I will explain) and locality (Alice and Bob are separated by a space-like interval, without any possibility of communicating). It is as if information was communicated without being causally transferred.

As Mr. d'Espagnat said, this tension can be quantified with Bell's inequalities. This was a considerable breakthrough regarding this argument. It so happens that these inequalities can be tested experimentally and that they are violated, which rules in favour of quantum mechanics as opposed to "realism and locality". In this three-sided argument between quantum mechanics, realism and locality, it seems that it is quantum mechanics that must be maintained, and therefore the concept of local realism that must be altered.

Confusion reigns …

A more in-depth interpretation of these results seems to generate a certain amount of confusion. In the literature, we find that the majority of physicists accept the image of a "strange [quantum] non-locality"—as Christopher Isham puts it—strange because, without directly threatening relativistic causality (I have in mind the theorem where there is no possible instantaneous signalling in quantum mechanics), this non-locality undermines the foundation of our knowledge of space and time, of which relativistic causality is the fundamental expression.

Other authors speak of "non-separability", like Alain Aspect or Mr. d'Espagnat who writes: "*If the notion of reality independent to man, but accessible to its knowledge is to have any meaning at all, then such reality is necessarily non-separable.*" This quotation introduces the concept of non-separability, of which we can say, like non-locality, that it is strange. Indeed, let me remind you that there is a complete set of observables that commute for the system α and β, the pair of particles, that is only accessible by measurements on α and only on β. Is this criterion not precisely separability as we can conceive of it? In any case, the least we can say is that the concept of non-separability is unsatisfactory [8].

Critical reappraisal of the EPR argument

I do not claim to provide a reasoned criticism of these arguments, but simply show that there is a certain confusion surrounding the concepts of non-locality and non-separability.

Let us return to the EPR argument, from the point of view of the relational interpretation. Let me remind you that according to the relational interpretation of quantum mechanics, there is a redundant hypothesis in the traditional formalism: that of the entangled state of a system. However, the EPR argument is fundamentally based on this redundant hypothesis.

Indeed, when Alice measures the spin of α, the value she obtains is instantly actualized for Bob—for the state of the couple α and β, without having to specify relative to which observer this state is defined. If we asked the following question: "Relative to which observer should this non-local actualization take place?", we immediately realize that this observer should himself be non-local, since he would be simultaneously correlated with Alice and Bob. We can thus postulate that it is the existence of a super-observer, capable of knowing simultaneously the measurement outcomes of Alice and Bob, which violates locality and not the quantum probabilities themselves.

According to the relational interpretation, there is no correlation between the spin of α relative to Alice and the spin of β relative to Bob. These two states are defined in relation to two different observers. It makes no sense a priori to compare the measurement values obtained by different observers, except when considering a new observer. However, in the EPR experiment, this new observer needs to be non-local to instantiate these correlations—and therefore, does not exist.

To sum up …

If we return to the arguments and introduce very clearly the observers involved, we realize that the individual measurements are decidedly not in violation with causality.

The spin measurement taken by Alice on α in the vertical direction gives a value written as Σα/A. Let us say that afterwards, Alice decided to measure the spin of β, at a later time, and finds the value Σβ/A. According to the prediction of quantum mechanics, the correlation is such that these two values are necessarily opposite. The spin of α in relation to Alice will be the opposite of the spin of β in relation to

Alice. The important point is that the events associated with this comparison are not in violation with relative causality: the spin measurement of β by Alice will necessarily take place after the spin measurement of α in relation to Alice.

Can we go further and test the coherence of these different relational accounts of the EPR experiment? We can, for instance, ask ourselves whether the accounts of Alice and Bob are compatible. Let us imagine that Alice wants to compare the outcome of her own measurement with that of Bob. Alice will measure the state of the system <α and β and Bob> and will find, according to the standard formalism of quantum mechanics, that the value of the observable measured by Bob is such that as seen by Alice it is equal to the spin value of β as it is observed by Alice. There is thus compatibility between what Alice has seen herself regarding the spin of β and what Alice sees of B regarding the spin of β. In other words, Alice never exposes any conflict between her own description of the state and the description B has of it.

If we introduce a third observer C who compares the values obtained by Alice and Bob, then C would measure a system that would be α and β, the two particles, and the two operators, Alice and Bob, write this state for this compound system and, depending on the state, instantly deduce that the spin value measured by Alice and the spin value measured by Bob are opposite. There again, there is no contradiction. There is not, within the framework of quantum formalism, the possibility of making the different relational observations by the different observers contradict.

In other words, the quantum formalism, although fragmented into partial descriptions relative to different observers, is perfectly coherent. From this point of view, we can see that the relational interpretation frees the EPR argument from the problem of non-locality, which has caused so much debate.

7.1.3 Some Philosophical Correlates

I now come to the third part of my presentation, where I would like to mention certain philosophical correlates raised by this interpretation, in the form of three questions. I do not pretend to have unequivocal answers; for that I defer to the philosophers present at this table.

Is the relational interpretation solipsistic?

Let me quote the comment of one referee of my joint article with Carlo Rovelli [9]: "*If the authors are actually comfortable advocating for ridiculous philosophical views like Berkelian Idealism or outright solipsism (in the name of making sense of Quantic Mechanics) let them say so openly and clearly*."

Confronted with such philosophical aggressiveness, it is appropriate to defend ourselves and give a rebuttal. I would personally reply that I do not see any solipsism in saying that physical properties are sometimes only defined relative to operators. Is it solipsistic to say that Alice's eye colour, for example, is given by a wave length of 463 nanometres? I do not think anyone would take this accusation seriously. And yet, due to the Doppler effect, this is a relative claim. Let me remind you that if you move relative to Alice, if you begin to accelerate very quickly in Alice's direction, the eye colour will change. "Alice has blue eyes" is a typical relational proposition of relativistic physics. There are many relative claims in current physics, and yet we do not speak of solipsism, I believe.

Is the relational interpretation antirealist?

It is undeniable that the relational interpretation strips the object of its substantial attributes: no more intrinsic state, no more intrinsic property, nothing resembling the attributes of traditional realism. We can therefore ask ourselves if the relational interpretation is a form of antirealism. I have two comments to make on this point.

The first is the idea that the relational interpretation, namely the relativity of quantum observables, is not an ontological commitment. To modify what I call *objectivity* (i.e. the nature of what being an object is within the framework of physical theories) is not equivalent to taking sides in the realism/antirealism debate. The two metaphysical options are compatible with the relational interpretation. It simply consists of updating the concept of object. We have seen many examples of this type of update over the course of the history of physics, and none are strictly speaking equivalent to an ontological commitment.

The second point is that the relational interpretation is monist (let me remind you that all quantum systems are thought to be equivalent in the relational interpretation) and that by contrast, the question of the external nature of reality, which implies the question of realism, is fundamentally dualist. Indeed, to choose between realism and antirealism is tantamount to defining a hierarchy between me and the world. These concepts are not admissible in the relational interpretation. I would like to stress that to introduce the realism/antirealism debate in the relational interpretation is to introduce concepts that are not in it—precisely because of the property of monism.

Is the relational interpretation realist?

We can ask ourselves whether there is any sense in ontologizing the relations themselves, i.e. to say that, ultimately, relations and not objects make up the metaphysical fabric of reality. I personally consider that this is a relatively pressing issue since from the outset Rovelli has argued that quantum mechanics is complete. If we must content ourselves with qualifying relations between systems, it is perhaps because ultimately the ontology is made up of these relations. It is a difficult question. There again, I have two comments, two entry points to this question of the ontology of relations.

Firstly, because relativity is involved in the relational interpretation of all descriptions, the objects and relations are in turn naturalized and transcendental. In its relation with S, the observer is transcendental: he enables the description of S. By contrast, from the point of view of P, O belongs to the world of objects and is described by the formalism of quantum mechanics. Thus, objects and relations are not defined in themselves. Depending on our perspective, objects and relations appear either naturalized or transcendental.

Secondly, I observe that the objects of quantum mechanics, if they must have an ontological status, are “bare” since they no longer have any intrinsic property. The possible values of observables, on the contrary—e.g. the possible spin values in the EPR experiment—remain absolute. In relational quantum mechanics, we do not make the observer depend on the possible values of a measurement, but only on the actual values at the end of that measurement.

There may be here a philosophical difficulty in expressing potentialities that seem absolute, and actualities that are only relative.

I conclude this very superficial philosophical discussion by reminding you that the realism of relations is not a particularly revolutionary idea in philosophy. We find it in numerous authors, from Heraclitus to Nietzche, Bachelard and Simondon. In addition, it is an idea that has many points in common with structural realism, which is much discussed currently in philosophy. It is therefore not necessarily as radical a metaphysical option as it may initially seem.

Comments on the relational interpretation

More, and better, comments on the philosophy of the relational interpretation can be found in Bas van Fraasen’s article [10] and in one of the last chapters of Michel Bitbol’s book [11]. I recommend these two to go further in the philosophical discussion of the relational interpretation of quantum mechanics.

I would like to end my presentation with a comment on two paintings by Kandinsky. The first painting (*Bleu du ciel*, 1940) provides a view of what I consider to be pre-relational physics. We see objects floating on a blue background. There is no particular relation between them. They are there, on their own, in themselves.

By contrast, in the painting entitled *Composition X* (1939) we see that colour, shape, geometry, everything is determined relationally. None of these objects has any meaning without the others. It is an image I keep in mind as representing a more relational metaphysics.

7.2 Discussion

Bernard d’Espagnat. Thank you Matteo for this outstanding presentation. We will now move onto the discussion.

Matteo Smerlak. Let me remind you that Carlo Rovelli is here and can also answer on certain points.

Catherine Pépin. I would like start the discussion with a naive question. Actually, I have not at all understood in what way Carlo Rovelli’s hypothesis provides a position that preserves locality. I really have not understood in what way it can solve this paradox.

Roger Balian. I have a similar question. Alice measures what is close to her, i.e. she measures α, but she also measures β.

Catherine Pépin. Actually, we cannot see what has been added.

Matteo Smerlak. The problem with the traditional arguments is the fact that the measurement of α by Alice leads to a defined value for β as it will be observed by Bob. In other words, it is as if Alice's actions influenced Bob's future, when in fact they are separated by a space-like interval and that there is no possible communication between the two observers.

From a relational point of view, this cannot even be formulated, because to say that there is an influence between one and the other is already to say that there are correlations between A and B. And to instantiate these correlations, to make them real, we must say in relation to which observer they would be visible.

The measurement made by Alice on α only produces an outcome for Alice. This outcome is independent of the measurement made by Bob on β. Once again, all that matters are the measurements relative to a given observer. There is no reason to compare or relate Alice's measurement on α and Bob's measurement on β. If we want to compare these two measurements, we must introduce an observer that would take the two measurements consecutively. It can be Alice herself. Let us imagine, for example, that α and β are brought back to the same point in space at the end of the experiment and that this time Alice measures the spin of β. She will find an opposite value to the spin of α, there is no doubt about that. However, that observable will be the spin of β in relation to Alice, and will have nothing to do with the spin of β in relation to Bob. The two measurements made by Alice will be perfectly causal. They will take place one after the other. We will have two correlated measurements, but one after the other. There is no difficulty, a priori. What is outside Alice's light cone is Bob's measurement. And Bob's measurement bears no relation to Alice's description.

Is this any clearer?

Catherine Pépin. It seems to me that Alice, when she measures the spin on β, as this takes place in the future, is no longer really Alice. What is an observer? If it is in the future, it is not the same observer.

Matteo Smerlak. Why? Generally, when we speak of observers, we speak of a physical system and we imagine that it is re-identifiable over time.

Catherine Pépin. In that case, if Bob does the same thing as Alice, with the same number of particles and the same type of macroscopic observer… I mean that a future Alice or a Bob-type Alice is the same observer. Either it is the same thing or it is not the same thing when we consider the future. We have to agree at the start. It seems to me that if we perform statistics on the number of observables, we can correlate the observations in A and in B. This is how I understand Bell's paradox, regarding spin.

Carlo Rovelli. I can give a *poor man's version* of this argument. Two measurements have been made at points A and B of space-time. We note and compare the outcomes. But for that, we must have the outcomes of the two measurements at the same point C of space-time (we do not compare at a distance!). The comparison will therefore be carried out at point C which is in the future of A and of B. That is where, and only where, we carry out the comparison. We can imagine that the outcome of the measurement made (for example) in B is written down on a piece of paper and kept secret up to C. For that, the piece of paper must be considered a classical object and not a quantum object (which could be in superposed states). However, in relational quantum mechanics we consider that everything is quantum. Thus classical pieces of paper do not exist. This means that from the point of view of the observer making measurement A, the piece of paper is still in a quantum superposition of the two possible outcomes of measurement B. In relation to observer A, no measurement has been made at point B. Collapse occurs only at time C. The paradoxical EPR non-locality is only an appearance since it results from forgetting the fact that the piece of paper on which the measurement outcome in B is written is also a quantum object.

Only when observer A observes does the measurement outcome of B become well-defined. The idea that something happening here can affect something happening there in an *observer-independent* manner is wrong. If we remove this independence in relation to an observer and if we maintain the quantum nature of all elements of reality (there is reduction of the wave function because we place an indeterminate state in a determined state), we cannot speak in terms of two events separated by a space-like distance.

Jean-Pierre Gazeau. I asked myself a question when I was looking at the slide on the notion of relation. It felt like the object and the observer were playing perfectly symmetrical roles. Which is the observer and which is the object? It seems that they are interchangeable, according to this formalism. Is there a complete symmetry of S in relation to O and of O in relation to S?

Roger Balian. I can equally be an observer or a measured object.

Jean-Pierre Gazeau. However, there is a difference, because the observer is capable of producing a well-defined outcome, of saying what he detected. This means that there are other states in the formalism. It is complex. There is something else, in the way it is described, and that is what we strive for.

Matteo Smerlak. In concrete terms, a measuring apparatus in a laboratory raises a microscopic correlation to the macroscopic level, following a type of printing process on a piece of paper. But, once again, this is a physical process. In principle, nothing stops us from considering that a simple atom is a measuring apparatus for another atom, two atoms that would then interact.

Roger Balian. No, because a measurement supposes a well-defined recording and outcome. This is what characterizes a measuring apparatus that discriminates between objects.

Matteo Smerlak. What is a recording?

Roger Balian. A recording is the fabrication of a verified macroscopic outcome.

Matteo Smerlak. As we have seen in Wigner's argument on the observed observer, this recording does not take place in an absolute way. For some observers, there is a recording and for others, if we simply describe the unitary interaction between the measuring apparatus and the quantum system of interest, there is no actual recording. We can see that at the end of the coupling between S and O …

Roger Balian. … this argument supposes that the first small observer has not made a recording. If a recording was made by this small observer, then the irreversible process of fabrication of a well-defined macroscopic outcome, i.e. a measurement outcome, has taken place.

Carlo Rovelli. If the irreversible process of fabrication of a well-defined outcome has taken place, then the second hypothesis of the relational interpretation, i.e. the hypothesis that all systems are equally quantum, is wrong. If quantum mechanics is strictly correct, there cannot be any process that is perfectly irreversible.

Roger Balian. No. The systems are equivalent, perhaps. In statistical mechanics nothing distinguishes a priori a system of two molecules enclosed in a ring from a system of n particles where n is 10^{23}. And yet, one is irreversible and the other is not. It is the same thing.

Carlo Rovelli. Let us imagine that I make a spin measurement in a laboratory and I obtain spin +. Do you think it is possible in principle to measure the interferences between—to use this language—the branch where I measured the outcome *up*, and the branch with outcome *down*, or not? If you say "No, it is impossible in principle, even by measuring the state of the world, no observable can see an interference between the two", that would mean—if all systems are equivalent—that quantum mechanics is sometimes violated and that the calculation is not valid. It you tell me that is it possible…

Roger Balian. … I would say that it is possible, but extraordinarily difficult, therefore practically impossible.

Carlo Rovelli. We agree on this point.

Roger Balian. It is therefore exactly the same thing as the irreversibility paradox in statistical mechanics. We have macroscopic systems, and given that they are macroscopic, they do not behave qualitatively like microscopic systems—even though there is nothing more and they strictly obey the same laws.

Carlo Rovelli. Yes. I think that here as well, we agree. This means that the distinction between something recorded and something unrecorded…

Roger Balian. … is relative. It is relative to our possibilities. It is contingent.

Carlo Rovelli. So it has to do with the number of degrees of freedom we have lost.

Roger Balian. Exactly.

Alexei Grinbaum. I would like to say a few things about observers, since I have just written a paper on this topic. The issues that have been raised here appeared immediately, or rather reappeared, after the publication of Carlo Rovelli's article in 1996 [12]. For example, Asher Peres, referring to the work by Rovelli as well as to David Mermin's position, countered that it would be absurd to say that two electrons in state S in an atom, thus perfectly correlated, are one an observer of the other.

Let me remind you that in the history of the notion of observer in physics, there has been one contribution whose importance is comparable to that of Wigner's discussions on consciousness. It is the definition given by Hugh Everett in his famous article [13], where he introduced the idea of multiple branches of the wave function. Everett asked himself the question of knowing what an observer is. His answer was that it is a quantum system endowed with memory. But what is memory, he asked. For Everett, it is something that stores information of past correlations between our observer and the systems it interacted with in the past. So, what is the correct physical definition of an observer? What are its defining elements: it is memory? Consciousness? Neither? It is not clear.

The debate is still widely open today regarding the foundations of physics. It may even be the most controversial question. Indeed, there is a theoretical vacuum that physics has not been able to fill between the hypothesis of universal observers like that proposed by Carlo Rovelli and Matteo Smerlak, and that of singular observers, endowed with memory, consciousness, or something else. Perhaps, as Bohr said, endowed with a macroscopic description. But I wonder if this still unresolved problem does not stem from the fact that we have not understood, or that we have not pushed it to its logical conclusion, the relativization approach mentioned by Rovelli and Smerlak. More concretely, I am surprised by the opening statement of Matteo Smerlak's presentation: "There are two observers, O and P, and a system S." How do they know? How can O know that there is S? There are indeed correlated degrees of freedom between O and S, but does O have a special memory that stores this information? Has someone told him? Does this knowledge come from prior observation? How has O identified S? I therefore wonder whether the controversy we speak of does not stem from the fact that we have not yet pushed to its logical conclusion the idea that we should define, relative to observers, not only physical states but the very constitution of systems, i.e. if S is seen as S by O, perhaps P can see differently the degrees of freedom implicated in the interaction between it and S.

I wonder if we are not simply confronted with a problem of coherence in our approach, linked to the fact that we have assumed that systems belong to the fabric of the world, whereas systems should be defined in relation to the observer.

Bernard d'Espagnat. That seems to me to be true. I think that in "orthodox" quantum mechanics (with no hidden variables), physical systems, no matter how big, must be regarded as relative and not as existing "in themselves". Furthermore, this is what happens in quantum field theory. Systems do not have an existence "in themselves" since quantum field theory predicts that particles, or even systems with multiple particles, can be created or destroyed. And—a non-negligible point!—as we all know, these phenomena predicted by theory are verified experimentally…

Alexei Grinbaum. Yes.

Carlo Rovelli. I think you have touched upon what I consider to be two central problems. I agree with nearly all that you have said, except with the relationship between the two problems, which I consider to be separate. Let me start with the second, which is that of the definition of the notion of system.

All that has been done within the framework of relational quantum mechanics presupposes having a well-defined notion of what a system is. I believe that was singled out by Michel Bitbol when he said that something was missing there for understanding the world—if I understood correctly. And I agree with that. I would be happier if, for our understanding of the world, there was no need to break up the world into sub-systems. However, I do not consider this problem to be linked to the first problem, that of the definition of the observer.

I consider that defining the observer has always been the most opaque, most obscure part of all the constructions of quantum mechanics. Because, ultimately, there are many positions. The only clear position is that of Wigner, who said that the observer is consciousness. As for me, I prefer to start from another point of view.

Of course, we can consider that an observational apparatus is something that is thermodynamic. However, I find that, on the one hand, defining the observer is essential in quantum mechanics—otherwise I do not understand what the physical values, and what the specific values of the operator, are. But on the other hand, the only way I can understand an observer (and that was for me an a priori), is to say that it is any physical system. Therefore, what relational quantum mechanics tries to do is, in a way, use of the notion of observer in the largest possible sense.

Obviously, the question is not terminological: we can say "general observer", "type A observer", "type B observer", … The real question is knowing which of these notions is necessary in quantum mechanics: is it necessary to speak of consciousness, is it necessary to speak of an animal system, is it necessary to speak of a system that captures information, etc.?

Relational quantum mechanics is based on one hypothesis: it is possible to account for quantum mechanics and make it coherent even with hypothesis 2, according to which all systems are equivalent. An observer is therefore any physical system, in the sense of an observer in special relativity. It is a coincidence if we use the same term. Speed is a relational quantity in classical mechanics since Galilei. We can thus only speak of speed in relation to an observer, in relation to a frame of reference. The frame of reference may be the bottle in front of me. My hand goes at a certain speed, relative to the bottle. But the bottle does not need to observe my hand. The bottle registers nothing and is not conscious. It is only the speed of my hand that is relative to the bottle. The bottle is an observer only a very basic sense. In the same way, in quantum mechanics I consider that any pair of physical systems can function in the interaction where one is the observer of the other. Is it possible, from this starting point, to reconstruct quantum mechanics without using a more limited notion of the observer? I think so. Obviously, we cannot then use just any measuring apparatus. We need to write down on a piece of paper the properties of a system which are true in relational quantum mechanics. If we make observations as one would in a laboratory, we would use the appropriate "observer" systems.

Michel Bitbol. I would like to comment on the question of the observer. I was struck by Matteo Smerlak's choice of words—perhaps it was not intentional, but let me remind you. He said: "From observer O's point of view, there is collapse" and "From observer P's point of view, there is not collapse but the superposition remains". What is the point of view an observer that is precisely not an intentional observer in the philosophical sense of the mind i.e. where the observer is capable of representation? Would you say that a macromolecule linked to an electron has a point of view on that electron?

Carlo Rovelli. I use it in the following sense: from the Earth's point of view, my speed is 30 km/hr. From the point of view of a train, it is less. Obviously the train has no point of view.

Michel Bitbol. Could we not say, in this purely kinetic configuration, that "the relative speed of A in relation to the train is *x*"?

Carlo Rovelli. Yes we could.

Michel Bitbol. That would be sufficient. You would not even need to use the term "point of view" which implies that someone, on the train, is capable of seeing and realizing the measurement outcomes. The problem is that we cannot get off so easily. Let us suppose that instead of saying "from the point of view of the train, the speed is *v*", we say "the relative speed of A in relation to the train is *v*". The latter statement tacitly implies another real "point of view" of an intentional observer: that of the observer who is at the same time external to A and to the train, but who could compare their speeds. The observer endowed with intent is still there, underneath it all.

Alexei Grinbaum. I believe I have discussed elsewhere the link between the two problems, which you separate and I do not. I do not want to go into the details of my answer to this question, but I would like to highlight once again the statement with which hypothesis 2 begins: "All systems are equivalent". In your reply, Carlo, you have spoken of physical equivalence: "All systems are physically equivalent". When I read this statement, I see in it—including in the vocabulary used in the 1996 article—the fact that all systems are physically equivalent but not necessarily informationally equivalent. The idea, which comes from Everett, is that of an informational characterization of observation. Physically, any system can be an observer. But can the informational requirements and constraints for being an observer be assigned to any physical system?

In my opinion, there is in this statement ambivalence in the meaning of the word "equivalent" that allows us to bridge the two questions you have separated.

Carlo Rovelli. It all depends on what information you speak of. The information I was speaking of in the article is information in the sense of Claude Shannon. It is simply something that quantifies the number of possibilities. In this context, we can speak of the information a system has on another. It is the existing relationship between the states of one system and another. System A has information on system B if a measurement on A predicts something about a measurement on B.

Once again, although this basic notion of information is necessary to be able to speak of relative states, it is not sufficient for building realistic measuring apparatus. An atom is not a measuring apparatus in relation to another neighbouring atom. However, it has information (in that sense) about the other atom if something (classical or quantum) correlates them.

I would like a fundamental theory of the world to speak of physical systems, or relative information, and not of more complicated things. I will not satisfy myself with a fundamental interpretation of the world that is based on the fact that we need sentient beings, machines, or event pieces of paper! If the fundamental notions of quantum mechanics can be interpreted in the physical or informational sense, sensu Shannon, I would be happy!

Hervé Zwirn. I believe this question touches upon the most difficult problem of all: the question of knowing to which entities we are prepared to assign the role of observer. We would like to say that we can do without the notion of consciousness to describe the world. But do all these problems of interpretation not mean that, in essence, we place ourselves from an intentional point of view, as Michel Bitbol said earlier? Meaning that in reality, the problems we face are not problems of the evolution of the world independently of us—because the equation of the universe evolves…

Roger Balian. … there is no equation of the universe.

Hervé Zwirn. I will be prudent on this matter! We are speaking about interpretation problems. However, when we say interpretation, we speak about someone who asks the question of knowing how something is coherent in relation to him. It is very difficult, even if we would all like to, to avoid invoking an observer in the sense of someone with an intentional point of view. And it is in relation to this intentional point of view that we will then try to re-establish coherence.

I see, from the first equation presented by Matteo, that there is collapse. Therefore, from the point of view of O who interacts with S, there is indeed collapse. If we place ourselves from O's point of view, why is there a collapse? In quantum mechanics, without the principle of reduction of the wave packet there is no collapse. Thus the measurement problem remains unresolved. Presented in that way, since we have explicitly introduced a collapse for a given observer, whatever it may be, we need to explain this collapse. The Schrödinger equation does not provide an explanation. The unitary evolution equation does not either. Thus already, by writing down "collapse" as it appears on the slide, we say that there are two evolution principles—and thus the measurement problem remains unresolved.

I entirely agree with saying that there is a relativity of states or descriptions in relation to the observer. But we must explain why a collapse occurs here for observer O. And for it to happen there must be a mechanism that triggers it, and that is not given in the relational interpretation.

That it is necessary to call on—as Roger [Balian] said earlier—the fact that there are too many degrees of freedom and that it evades us, is just another way of saying that it is because our means are limited that things appear as they do. If our means were not limited, for example for an omnipotent super-observer, the world would remain quantum and there would never be any collapse since we would always be capable of putting in place the means to measure observables that would allow us to detect correlations. Therefore, even if we wanted to, I struggle to see how we can completely eliminate the need, at some point, to bring everything back to the level of the mind—and therefore to an observer who is, in a way, what we are. And therefore the idea that we can eliminate the observer by giving this role to any atomic system does not seem a good one to me. What we are trying to do is not explain how a macromolecule sees the world—and anyway, it is hard to see what that would mean -, but explain how, we, through quantum mechanics, manage to account for what we observe. We are not going to eliminate ourselves as observers!

A long time ago I suggested an interpretation that was very similar to the one presented today: the convivial solipsism. It has many points in common with the relational interpretation in that it also proposes that states be relative to the observers. It is in fact an extension of Everett's theory that I proposed in a book published in 2000 [14]—following the ideas of Bernard d'Espagnat. It is very similar, but there are two small differences. The first is that I describe the collapse as being a principle that I call "the hanging-up mechanism"—and I preserve the notion of a conscious observer: at a certain time, a given observer is presented with a choice and he, in a way, hangs himself up to one of the possible branches—knowing that, like for Everett, the wave function is never reduced. The second thing is that this is so relational, (i.e. relative to the observer) that two observers, with their own points of view, can observe totally different things—thus this resolves the problem for the EPR paradox since two observers can have seen things which will not be coherent from the point of view of a super-observer who does not exist. However, the principles of quantum mechanics prohibit, when two observers meet, that they realize their differences. I therefore completely agree with what you have just said about the piece of paper: we tend to think that if the piece of paper has something written on it, it was that way in the past. In fact, that is not the case. Everything remains superposed, except for the observer, who at some point hangs himself up to one the branches and remains there forever in such a way that what he will be able to control, compared to other observers, will never reveal any incoherence.

It is true that this conception is rather strange and it has consequences that bring into question the usual notion of realism: it means that each of us sees a world that is specific to him and that can be different from what others see, but we cannot make this difference visible. The problem of collapse remains complete. I have not solved it either. For obvious reasons, due to the images that are evoked, I call this the hanging-up mechanism but the collapse is not eliminated. In fact, the solution I propose consists in making the hanging-up mechanism rely on decoherence which itself is caused by the limits of our capabilities and thus, as a last resort, of our consciousness.

The point I would like to emphasize is that it seems difficult to me to completely forgo the notion of a minimal observer with intentions or consciousness.

Jean Petitot. Is the hanging-up mechanism a physical process?

Hervé Zwirn. It is not a physical process. It is a process that, at a given point, consists of an interpretation linked to the observer, of making a choice that eludes us—we do not control it—and which leads us to hang ourselves up to one of the branches of the superposed wave function, which itself continues along its path but for us disappears. The alternatives disappear.

Jean Petitot. So there is something else in addition to physics.

Hervé Zwirn. Perhaps … this needs more work.

Carlo Rovelli. I realize that I should have made more references to and comparisons with the convivial solipsism!

This question allows me to come back to one of the most important points for understanding what I wanted to do with the relational interpretation. There are obviously many ways of classifying the possible interpretations of quantum mechanics. I have learned about many of them with Bernard d'Espagnat. One of these consists in distinguishing between two radically different ways of thinking about quantum mechanics: that of Heisenberg and that of Schrödinger.

One possible point of view (we can call it Schrödinger's, but that is too vague) is to say that quantum mechanics is essentially the Schrödinger equation for the state of a system, a unitary evolution—therefore we must understand what happens when a collapse occurs. This opens up a number of discussion points.

A different point of view is the one where Heisenberg recalls how he came up with quantum mechanics. He has told that one night he was in a park in Copenhagen. He saw someone walking in the dark—but only seeing him when he walked under a streetlight. He therefore sees him appear and disappear, then reappear and disappear again. He deduced from it that this is what happens to an electron: it exists at different points, but we do not know what happens between them. Thus, the other way to think about quantum mechanics is to consider quantum events as high-order elements of the reality in question. When we see something going on, the result is a collapse.

Thus, the reconstruction effort in my article consists in discarding the state as a fundamental object, discarding the image of an "evolving state", and think of reality as these quantum events. I can see you here, not in superposition. I can see the electron, the measuring apparatus. From a standard "Copenhagen" point of view, it is very simple. There is a classical world and the quantum system manifests itself in relation to the quantum world in a series of discrete events which result from measurement. This series is the reality of the system. I tried to reformulate this by replacing "classical world" with any system in relation to another. From this point of view, the collapse is not a problem: it is a reality. The measurement outcomes are a reality. The problem is understanding how they are linked to one another and how, in a strange way, they seem real in relation to one system but not in relation to another. However, if we start to think that quantum mechanics is a state that evolves under the Schrödinger equation, we are in a completely different interpretation.

Roger Balian. I absolutely agree with the point of view *à la* Heisenberg you have just described. Anyway, it is the only one I understand! I would change just one small thing: I would not say that the successive flashes you speak of are reality, but images of reality. In the same way that a measurement is an image that we have of reality, an image created on an apparatus. A created image of reality, which eludes us since it concerns variables that are not intelligible—and of which we have no intuition mathematically. And with good reason, since our intuition is based on our world, which commutes. I would see things more in this way, as an image.

In the same way, regarding information: we would like to include it in quantum mechanics—that is true—but we face a difficulty which is that the unit of information is the bit. And we know that in quantum mechanics, the unit of information is the qubit. And we have no intuition of what a qubit is.

I believe we must take a leap and say that we have an image of the reality of quantum information in the form of classical information—but that quantum information is the qubit, which is what it is.

Alexei Grinbaum. I would like to ask Matteo Smerlak about a statement he made earlier in passing. He said that there was a collapse in relation to O because O itself is not observed. Thus, self-observation is never mentioned in his approach. Since I believe the question of the collapse in the relational interpretation is fundamental, it is necessarily linked to the question of self-observation or, more generally, self-reference.

What is the status of this prohibition of any self-reference in the relational interpretation? What motivates it? What is the current line of thought on self-observation: is it necessarily considered an additional postulate, or is it a theorem, hence something that can be deduced? If it is a postulate, it must be made explicit and added to the list of postulates.

Matteo Smerlak. There are several mysteries in quantum mechanics! One of these consists in understanding why O and P give different descriptions—the word "description" being taken with a pinch of salt after what Michel Bitbol said. The other consists in understanding the origin of indeterminism in quantum mechanics. These are two different problems. Relational quantum mechanics operates on the first problem. It does not provide any fundamental explanation regarding the second problem, namely the origin of indeterminism. It simply allows us to point out something that is not in traditional quantum mechanics, namely that the collapse is linked to an element of self-reference. The asymmetry in the relational interpretation between the interpretation of O and that of P is that O interacts with S, and P does not interact with S. There is an element of externality in P that is not found in O.

We can therefore postulate that the indeterminism of the measurement made by O—the fact there is a collapse with no possibility of knowing which value will emerge from this measurement—is linked to the intrinsic limitation of O to describe himself as interacting with S. That is to say that, from this point of view, there is nothing more than the following observation: there may be link between collapse and self-reference.

I am not aware of any recent advances on self-reference in relational quantum mechanics. All I can say is that—as already mentioned in the 1996 article—this question has been investigated by the Italian researcher Marisa Dalla Chiara.

Alexei Grinbaum. In addition to Marisa Dalla Chiara's work, there is the Breuer theorem, which is one of the most fundamental theorems on self-reference.

Matteo Smerlak. That as well. These are the two references I can cite. I do not know of anything more recent.

Catherine Pépin. I will adopt the point of view of a physicist, by going along the same line as Roger Balian. Some things remain unclear. I am thinking of three points in particular.

First of all, concerning the EPR paradox and Bell's inequalities, it seems to me that if observers cannot communicate with each other, if everything is always in relation to an observer, then we cannot even speak of a correlation between what is observed in A and what is observed in B. We can define observers as large systems that make wave functions collapse—these are classical systems. Once the classical system has interacted, we have a result, as Roger Balian said. If we make a measurement on α and on β, these classical systems provide correlations only if α and β are initially in the same quantum state. Now, if α and β are initially in different quantum states, these correlations do not take place. I really do not see how introducing something relative to the observer can overlook this.

Matteo Smerlak. You have said that it is not possible to compare the results of Alice and Bob, hence to demonstrate that there are correlations, when all measurements are relative to the observers. It is not the case. It is perfectly possible for Alice, once she has measured the spin of α, to correlate herself with Bob. It is possible to bring back β in the presence of Alice and that Alice then measures the spin of β. She will have measured, over time, the spin of α then the spin of β. She will thus observe a correlation between these two outcomes. She will find that these values are opposite.

Catherine Pépin. Fine. So how do you explain that the correlation between these two measurements is different in EPR paradox where particles are initially in the same quantum state compared to a situation where we measure particles with initially different quantum states? The fact that the initial quantum state is the same must induce a correlation in the observation, at a later time, of A or B.

Matteo Smerlak. It induces a correlation.

Jean Petitot. Yes, but at a later time.

Matteo Smerlak. Yes. This correlation is the following: the spin value of β in relation to Alice is the opposite of the spin value of α in relation to Alice. This correlation exists. However, it is causal. It happens for two events where one occurs after the other.

Catherine Pépin. If it exists, then it means there is non-locality. That is what I do not understand. If this correlation exists, causal or not…

Matteo Smerlak. … demonstrating this correlation does not involve two events separated by a space-like interval. It involves two events separated by a time-like interval.

Hervé Zwirn. I think it would be good to describe what happens step by step, over time. The particles separate. Alice measures the spin of α at a given time, and finds a certain value. There is no causal influence in the space-like interval, thus there is no violation of locality. Which means that strictly speaking the spin of the particle that is far away is still not determined.

Jean Petitot. For Alice.

Hervé Zwirn. Yes, for Alice it is still not determined. To clarify things and find a consensual explanation, perhaps we should explain how, when Alice and Bob meet again (Bob has measured independently and obtained something), if the outcome for Alice is not determined, then how come when Alice and Bob get together, that Alice finds a posteriori that Bob has indeed found the opposite of what she has measured. I think that is the point that bothers you. I think we should explain this step by step, so that it is no longer troublesome.

Catherine Pépin. Let us be clear, it is the same problem for Bell's inequalities.

Hervé Zwirn. Concerning Bell's inequalities, there is something more. Here, however, I think it is very simple and is easier to explain. To follow it step by step would enable us to understand it better.

Matteo Smerlak. I would not do any better than what you have just done.

Hervé Zwirn. I left something to one side, namely the precise explanation of the mechanism. Let me go over it. The particles separate and at some point, Alice measures the spin. Let us say she finds + along Z. But for Alice, the spin of the other particle is not—along Z. It is still indeterminate. Bob measures the spin of the other particle; and he finds what he finds.

Carlo Rovelli. And what happens for Alice?

Hervé Zwirn. For Alice, when Bob measures, nothing happens.

Carlo Rovelli. Yes, something does happen!

Matteo Smerlak. During my postdoc and when trying to write the article, I got stuck on this question for a long time. I wrote the article after finding the answer.

Hervé Zwirn. I think this is precise point that needs to be explained.

Catherine Pépin. So what happens for Alice when Bob makes a measurement?

Carlo Rovelli. It is not collapse but entanglement that occurs between the state of the particle and the state of Bob. Bob himself enters into a situation of entanglement with the particle, but the two remain in a quantum superposition. More precisely, this means that Alice knows that from that point, the measurement outcomes on Bob or the particle will be correlated.

Hervé Zwirn. This means that for Alice, there no longer are simply the two particles, but there is one particle plus Bob.

Catherine Pépin. There is thus completely non-locality. When Bob measures, as Alice interferes on Bob's measurement, it is completely non-local—since they are not in the same place.

Alexei Grinbaum. It is a process of redefining the systems.

Hervé Zwirn. It is an entanglement of the systems.

Alexei Grinbaum. The systems are redefined, of course.

Hervé Zwirn. The two particles were already entangled, Bob becomes entangled.

Catherine Pépin. Bob and Alice are not in the same place.

Hervé Zwirn. No.

Catherine Pépin. So a non-locality appears.

Hervé Zwirn. In the entanglement.

Catherine Pépin. It must reappear somewhere…

Alexei Grinbaum. It is not a change of state. It is a change of what they consider as systems.

Carlo Rovelli. Let us return to the previous question. The element of reality here is not the state, which is simply the mathematical system that allows us to calculate the probabilities of future events—based on previous observations. For Alice, when Bob makes a measurement, nothing happens other than the possibility of calculating future events. What is, for Alice, the significant future event? She will receive a call from Bob. She will then collapse the state of Bob and see if the predicted correlation is realized or not.

Catherine Pépin. Fine. I understand much better now.

Roger Balian. I would not quite say it like that. I would say that Alice carries out a series of measurements of her spin, and sifts through them. She shows that measure no. 1 has this value, measure no. 7 this value, etc. She writes down the outcomes on a piece of paper that she sends to Bob by post, asking him to select such and such measurement and to note that all the spins obtained will be prepared in a given position. It is therefore a preparation, a directive for selecting different successive measurements to be carried out, rather than a collapse. There is no collapse. There is selection. And nothing else. At each stage, for Alice, there may have been her own collapse—corresponding to the fact that her apparatus has given her a certain outcome. This collapse, in fact, is linked to the activity of the apparatus that allows her to operate a selection and to select such and such measurement in her message. What is shocking about that?

Carlo Rovelli. May I reply to your previous observation? You said that you liked the idea of linking reality not to states but to quantum events. But you added that you preferred thinking in terms of an image of reality rather than of reality itself.

Roger Balian. Because a measurement provides an image.

Carlo Rovelli. Personally, I prefer using a term other than image, by calling this the information a system can have on another system. That is how the term information is used. When an electron strikes the screen and leaves a mark, the screen has information on the fact that the electron is there. Therefore, all a system can know of another system are quantum events. Why are we able to think of them in terms of information? Because they are physical events. What the history of physics tells us is that if we know the quantum events, they allow us to predict (as physical laws) the quantum events that will follow. In this sense, if we are clever enough, if we have enough paper, we can predict the events to come on the basis of these quantum events. They are thus information on the system. Quantum mechanics tells us this information is of a particular kind, because it is lost when we look at another information.

Personally, I would like to reduce quantum mechanics to this: quantum events that are always between two systems—by nature. If we choose a system and another system, we have a set of events and we can, if there are enough, calculate the next probability. A state is only the set of future events that allows us to calculate the events to follow. This is, to my mind, what relational quantum mechanics is.

Hervé Zwirn. I would like to ask Carlo [Rovelli] again a question that was briefly addressed earlier but received no clear-cut answer—if that is even possible. Can we, yes or no, definitely abandon the notion of intentionality or consciousness—or whatever we wish to call it—for an observer?

We know that Bernard d'Espagnat, in many of his articles, insisted on the fact that quantum mechanics, unlike classical mechanics, seems to not be describable without referring to the point of view of an observer. This is one of the main points he insists on. When the decoherence phenomenon was beginning to be described and better known—we have already discussed this during our two sessions dedicated to decoherence so I will not go over it in detail [15]—in Wojciech Zurek's early descriptions, we had the impression that he presented it by saying that with decoherence, we no longer needed an observer and that the world becomes classical spontaneously. Later on, we know this point of view was disputed. Nowadays, there is still a debate although we cannot say that the world becomes classical independently of any observer since its classical "aspect" stems from the impossibility for us human beings to make measurements that would show that "in reality" it is not classical.

Can we say that the relational interpretation discards completely the notion of consciousness, hence the intentional point of view? Or are we in a "for all practical purposes" situation by specifying that even if the correlations, recurrences, etc. are inaccessible to us, they are still there. And therefore, in that case, from a philosophical point of view, we cannot say that we have eliminated the need for consciousness or an intentional point of view.

Do you think you can do without it? Or do we still retain, from a relational point of view—and it seems to me that it would be difficult to do otherwise, but I would like to know your exact position—the fact that an observer is an entity with limited means who makes cuts in relation to the degrees of freedom he cannot observe, and that because of that the world appears as it does? And if we were super-observers with unlimited means, the world would appear quantum because the world remains quantum in its very essence. It never becomes classical—even if to us, that makes no difference. If that is the case, that means that all explanations or interpretations designed to account for what we observe as human beings must refer at some point to these limits—human limits—and therefore to consciousness.

Jean Petitot. Finiteness does not imply consciousness.

Hervé Zwirn. In any case, finiteness is the cause of what appears to our consciousness and we can only use the verb "appear" in relation to consciousness.

Matteo Smerlak. I understand the relational interpretation as an effort to separate the problem of consciousness—which appears in all epistemologies, all attempts to account for the state of science—from the inherent difficulties of quantum mechanics. At all stages in the evolution of science, there will be a Michel Bitbol who will say "what about transcendence, experimental conditions, conditions of possibility, the intentional observer?". This will still be the case probably even after quantum mechanics. In my opinion, the relational interpretation operates within quantum mechanics an important clarification: it does not discard the problem of consciousness, but reduces it to something even more external—i.e. to disentangle quantum mechanics, strictly speaking, from the problem of consciousness.

Michel Bitbol. Your project aims to sufficiently disentangle the problem of the interpretation of quantum mechanics from the human intentionality of consciousness. Then let me ask you this: who benefits from this project of disentanglement?

To which intentional subject, which conscious being does it matter to free science from the intentionality of consciousness? You see, I am playing my part!

Matteo Smerlak. I do not have to answer!

Carlo Rovelli. I completely agree with what Matteo has said. I do not want to ignore the problem, or deny the fact that it differs from quantum mechanics. Our effort consists in doing everything possible to separate them. But the question remains. Do I think the effort has a modicum of success? I would like to say yes, in the sense that the effort reduces quantum mechanics to something where we only speak of physical systems, quantum events, values of quantum observables. But success comes at a price, a hefty price in this case, and reopens the connection with the problem you mentioned. That price is that the notion of the reality we speak of is weakened, as Mr. d'Espagnat said earlier, much more than the notion of speed when Descartes, Galilei or Copernicus realized that the notion of speed does not mean anything other than in relation to another object. It is true that physical properties (i.e. spin up or down) are relative to our physical system. But it is much more than that. It is the very fact that certain events are realized or not that is relative. I must therefore say that in relation to a certain physical system, such and such thing will happen—but it will not happen in relation to another system.

The notion of reality is thus weakened. It is more difficult to describe reality as a series of unambiguous events. The answer is therefore positive, as much as possible: let us try to separate the problems. But the price to pay is what I have just described.

Hervé Zwirn. I completely agree. I give the example—albeit exaggerated—of two people talking to each other and one thinks he is talking about relational quantum mechanics and the other thinks he is talking about his skiing holiday in the Alps. In fact, neither is right or wrong. Simply, they cannot, either of them, realize that there is an incoherence. Reality in itself has no meaning, since it is not collapsed. It is a superposition of everything. It must be expressed only in relation to each of the observers. This means that the notion of usual realism is completely swept aside.

Jean Petitot. You have often made the parallel with classical relativity—a parallel that Vladimir Fock was already making in the 1930s. He explicitly said that the problem of measurement and of the measuring apparatus in quantum mechanics should be considered as a strict generalization of the principle of relativity. Indeed, in all theories with relativity there is a loss of realism. In general, we define at the start the entities which, we think, possess a certain reality, then we realize that they are relative, that there is a group of relativistic invariance, and thus they lose their reality. This was the case, for instance, for speed with Galilean relativity. At the time, it was extremely traumatic to consider that speed was not a property of bodies. But beyond the principles of relativity, we can still recover some invariants. My question is therefore the following. You introduce a new relativity in your relational point of view that weakens or even dissolves the reality of the quantum state.

However, you should recover, somewhere, new invariants since there cannot be relativity without invariants. What is the purpose of these new invariants?

Jean-Pierre Gazeau. Spectra.

Roger Balian. It is the algebra of observables.

Jean Petitot. These invariants would therefore be C* algebras, or something like that. This leads us formally towards a set of mathematical considerations.

Carlo Rovelli. It is a very mathematically-inclined way of thinking. I think that these invariants are first of all spectra, i.e. a set of possibilities and transitional amplitudes. Given a certain sequence of quantum events, the probability to have one of them is a defined number which is fixed.

Jean Petitot. But these invariants are already present in non-relational theories. They are not new. The question I ask you is this: how do you recover these things that are already known in your approach which claims to be more fundamental? It is a bit like when we try to find informational axioms that allow us to recover what we already know.

Alexei Grinbaum. The history of the reconstruction of quantum mechanics (Matteo Smerlak has already mentioned this in his introduction) tries to answer this question. Attempts at reconstruction, which can in no way be considered to have been successful, consist of mathematically deriving the formal content of quantum theory.

Jean Petitot. That was my question.

Roger Balian. Has this not been achieved? Is it not the algebra of observables?

Alexei Grinbaum. No.

Carlo Rovelli. We know the starting point. We know the end point. Because we know the invariant part of quantum mechanics. If I measure a spin along Oz, then along Ox, the probability of obtaining outcome + in the second measurement is 50%. The relation between these two measurements is a fixed number, which tells us what the physical processes that are possible in the world and their intrinsic characteristics are. It therefore provides something objective.

Roger Balian. It is in the algebra.

Carlo Rovelli. But something is missing. The result we would like to have is the following. Considering this interpretation, considering this way of apprehending quantum mechanics—the clear and simple postulate according to which there are quantum elements that are relative to systems—it is a fact of nature that I take to be true that, given a certain number of quantum events, we can calculate the probability of events to come. I take that as a postulate. Can we, based on this postulate, reconstruct the whole of quantum mechanics? The answer is "nearly". Or "yes", by adding certain technical details. I we could do without these technical details, we would be very happy. But they are still there. And they tell us that in this probability we think we have found, in truth, something is missing.

Alexei Grinbaum. Along the way, you discover that these technical details are not all that technical, because they are very profound.

Carlo Rovelli. Yes.

Catherine Pépin. Could you describe these details to me?

Alexei Grinbaum. A first example would be the existence of continuous and irreversible transformations between pure states—i.e. the origin of the notion of continuity which is part of the formalism of quantum mechanics. During Matteo Smerlak's presentation, at no point did you hear the term "continuity". The postulate that leads to this continuity must be added, whatever the attempt at logical or informational axiomization. You cannot do without it. And the approach which consists in trying to understand the origin of this postulate—what can we replaced it with?—is a subject in itself.

Bernard d'Espagnat. Thank you. We have had a fascinating debate where we have touched upon (but by no means exhausted!) the main questions facing us. Should we continue with another session dedicated to this topic? The answer is not obvious. I believe we should have a second session; it would be good if someone would reopen the debate.

Alexei Grinbaum. Michel [Bitbol] and I have worked on rather different approaches: Michel has taken a more philosophical angle, whereas I have focused on more technical aspects. Perhaps we could each speak for 10 min.

Michel Bitbol. OK.

Bernard d'Espagnat. Problem solved. We will meet again on the 12th of March at 4:30.

References

1. *Cf.* Carlo Rovelli, "Relational quantum mechanics", *International Journal of Theoretical Physics*, 35, 1996, p. 1637–1678.
2. John von Neumann, *Mathematical Foundations of Quantum Mechanics* [1932], Princeton University Press, 1996; Eugene Wigner; *Group Theory and its Application to the Quantum Mechanics of Atomic Spectra* [1931], New York, Academic Press, 1959.
3. Alexei Grinbaum, "Reconstruction of quantum theory", *Brit. J. Phil. Sci.*, 58, 2007, p. 387–408.
4. See (1)
5. Matteo Smerlak & Carlo Rovelli, "Relational EPR", *Found. Phys.*, 37, 2007, p. 427–445.
6. Michel Bitbol, "An analysis of the Einstein-Podolsky-Rosen correlations in terms of events", *Phys. Lett. A*, 96(2), 1983, p. 66–70.
7. Federico Laudisa, "The EPR argument in a relational interpretation of quantum mechanics", *Found. Phys. Lett.*, 14, 2001, p. 119–132.

8. See Bernard d'Espagnat's comment at the start of session VIII, "Exchange of views on the relational interpretation".
9. See (5)
10. Bas van Fraassen, "Rovelli's world", *Found. Phys.*, 40(4), 2010, p. 390–417.
11. "The tentative advance of "immanent relativity" in contemporary interpretations of quantum mechanics. II) Relational interpretations", in *De l'intérieur du monde*, Flammarion, 2010, p. 137.
12. See (1)
13. Hugh Everett III, « 'Relative state' formulation of quantum mechanics » , *Rev. Mod. Phys.*, 29, 1957, p. 454–462.
14. Hervé Zwirn, *Les Limites de la connaissance*, Paris, Odile Jacob, 2000.
15. See sessions III « Experimental approaches on decoherence » and IV "Exchange of views on decoherence".

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Matteo Smerlak is a post-doctoral researcher at the Perimeter Institute for Theoretical Physics (Canada). His research area is at the crossroads between general relativity, quantum mechanics and statistical physics. His research interests include the "thermodynamics of the vacuum" and the different quantum phenomena related to it (Hawking effect, dynamic Casimir effect). He has also worked with Carlo Rovelli on the aforementioned relational interpretation of quantum mechanics.