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Ontological Status of Relational Quantum Mechanics

Juan Ferret, *University of Texas at El Paso*

The Ontological Import of Relational Quantum Mechanics

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> We need to go back to the insights behind general relativity and quantum field theory, learn to hold them together in our minds, and dare to imagine a world more strange, more beautiful, but ultimately more reasonable than our current theories of it. For this daunting task, philosophical reflection is bound to be of help. – John C. Baez

1 Abstract

In what he calls "a vague resemblance with Einstein's discussion with special relativity" Carlo Rovelli argues that quantum mechanics (QM) makes similar demands on the relations between systems: "The notion rejected here" Rovelli claims "is the notion of absolute, or observer-independent, state of a system; equivalently, the notion of observer-independent values of physical quantities." (Rovelli 1996, 1) Rovelli's

relational quantum mechanics (RQM) is not a rejection of the formalism of quantum mechanics, but rather "a critique of a notion generally assumed uncritically": the absolute state of a system.[1]

In this paper I emphasize the ontological import of Rovelli's claim, show the differences and similarities between relational concepts in classical mechanics (CM) and QM, and show what may be missing from Rovelli's RQM. In Section 2, I introduce a distinction between the concepts of relative and relational frames of reference with the aim to clarify the state of systems in CM and to show via a simple example from CM how the concepts of relativity and relations of systems are already part of the conceptual development of frames of reference in physics. In a relational account a system can only become a system in interaction with at least one other system that will provide the original system with boundaries. A consequence of this relational account will be that the dynamical interactions will be crucial for accounting for the state of the system. Rovelli's claim is precisely that QM is relational.[2]

In section 3, I show how RQM works and how the notion of relationism in QM becomes a deeper ontological concept. Then, I discuss what Rovelli's account lacks to become a full fledged interpretation of QM and to resolve long-standing conceptual hurdles such as the measurement problem.

2 Status of Systems in Classical Mechanics

The development of Galilean relativity of motion and Newton's laws of dynamics have been two early cornerstones of the development of classical mechanics. Galilean relativity shows that the motion of an entity is dependent on (relative to) the reference frame chosen. So if we ask what is the motion of an entity from the reference frame of that same entity, then the motion is always null. Instead, if we inquiry as to the motion of the same entity from the point of view of another entity, the motion or velocity may have a non-zero value. To speak meaningfully about velocity in the Galilean perspective one needs to specify a reference frame and any reference frame will do. The choice of reference frame is arbitrary. Since there is no preferred ref-

[1]The concept of relativity of motion formally appeared when Galileo showed that velocities are relative properties of systems. An entity's velocity depends on the frame of reference used and no no absolute velocity of a system exists. In Special Relativity (SR) Einstein demonstrated, similarly, that there is no absolute simultaneity of events, and they instead depend on the reference frame used. Einstein expanded, a few years later, the relativity of motion of inertial frames to non-inertial frames in general relativity (GR). This expansion of the relativity of all types of motion incurred a deeper and more fundamental notion of relativity.

[2]Similarly, it can also be argued that SR and GR are also relational and not just merely relative.

erence frame, we also know that motion is a meaningful property of a system only when a reference frame is selected. In short, motion of a system is relative to a chosen reference frame.

The laws of dynamics of Newton, and in particular his law of gravity, instructed us into realizing that the motion of objects depend on the relationship with other objects that affect its trajectory. An entity's motion is, through an action-at-a-distance, affected by the gravitational pull of all other entities. The entities were often assumed to be particle-like or corpuscles and the laws of motion explained the means of interaction among these corpuscles.

The development of Laplacian and Hamiltonian dynamics moved mechanics toward the recognition of the entity or the aggregation of entities and their present and future behavior. The present behavior is accounted for in terms of kinetic energy, T, the amount of work that a system exhibits thanks to its speed, and the future behavior is accounted as part of the system in terms of potential energy, V, the amount of work that can be exhibited in relation to a chosen reference frame. The potential energy is the mechanical energy that the system has in store but has not yet exhibited and an object under the pull of gravity has the potential to exhibit displacement if some constraints are removed. In the Hamiltonian picture, for instance, the energy (in terms Hamiltonian $H = T + V$) becomes the central notion that defines the state and the evolution of the system. With this move, mechanics became the account of the dynamics of a system, where the Hamiltonian encapsulates the full description and evolution of the system in a particular scenario. Since the Hamiltonian is defined in terms of kinetic and potential energy, the system is then basically defined by its energy. So we can conceive of the Hamiltonian as the energy formulation of the system and therefore the entity.

2.1 An Example from Elementary Classical Mechanics

Consider the case of a stationary car hanging at the very edge of a cliff h meters deep from the reference frame of the ground. The car has zero kinetic energy, since it is not moving, and a potential energy mgh, where m is the mass of the car, h the height of the cliff, and g the gravitational constant, which is the gravitational pull of the earth on all objects near the surface. In general, the energy of the system is:

$$E = T + V$$

and the kinetic energy is

$$T = \frac{1}{2} m v_{h'}^2$$

where m is the mass of the object and v the velocity.[3] Before the car starts falling the energy of the system is:

$$E_h = 0 + mgh$$

Once the car starts falling, the car gains a small velocity, the kinetic energy becomes non-zero and the potential energy decreases because the car is no longer at h, but at shorter distance from the ground, h'.

$$E_{h'} = \frac{1}{2}mv_{h'}^2 + mgh'$$

Right before the car crashes to the ground, the kinetic energy is large because the velocity is large, but the potential energy of the car is almost zero since h' is now very small. Once the car hits the ground, the kinetic energy is at its maximum (v_0 is the speed right before impact) and the potential energy is zero since h' is zero.

$$E_0 = \frac{1}{2}mv_0^2 + 0$$

If we treat this system as a closed system, the energy is conserved, thus $E_h = E_{h'} = E_0$ and

$$\frac{1}{2}mv_0^2 = mgh$$

This simple exercise from introductory physics illustrates the crucial role of reference frames. Consider the property of position for a moment. Imagine that in the example we remove the cliff and everything else in the universe (including its boundaries) except by the car; would it make sense to say that the car has a position? The only way we can respond positively to this question would be by assuming the existence of a background space frame of reference from which we could determine the position of the object. This background would offer a fixed frame of reference from which to measure the motion of entities and would thus be absolute. Claiming that position is given by the existence of a background space forces a demand for strong physical reasons (like Newton thought he had with the rotating bucket experiment) or evidence for a preferred absolute reference frame. If this background space is not found or shown to exist via solid theoretical exposition, then the property of position needs to be thought in purely relative terms, where it would make sense to

[3]Where $h' = h(y)$ and $h = max(h(y))$.

speak of the position of an object only relative to a reference frame. Thus, position is a relative property of a classical system if we do not assume the existence of a space container. In our example, the choice of the ground as a reference frame is as valid as any other (the top of the cliff, Alpha Centauri, etc.). Yet some choices are more natural and more effective for calculating and considering an event than others. Since the position of the bottom of the cliff will become the likely resting place of the entity (or what is left of it), then it is a natural choice for a reference frame. In sum, it is meaningless to speak of the position of the entity without reference to a frame from which to assert that the entity has a position relative to it. Unless, of course, we were to assume the existence of an absolute reference frame or background from which we could absolutely determine the state of the entity.

2.2 Relative vs. Relational in Classical Mechanics

The relative state of properties of motion and the system are natural consequences of classical mechanics when the notion of a fixed background of space and time, as an absolute frame of reference, is not assumed. A relational system entails that the properties of the system express a relation between two interacting systems in addition to the relative state view that we need a separate frame of reference to speak meaningfully of properties of motion. The difference between relative and relational is a conceptual distinction I introduce to clarify the role of interactions between systems and the role of reference frames. A main difference between the relative and the relational is that the relative is primarily epistemological while the relational is primarily ontological. By relational we mean that the reference frame is not solely an epistemic tool for being able to talk meaningfully of or measure position, velocity, or energy, but rather that the reference frame has some ontological significance for the account of the properties of the system and, of course, the system itself. This means that the system, to be a system, needs another system to interact or relate. A system needs boundaries, and the boundaries of a system are provided by other system(s). The relational account takes the boundaries to imply an interaction between the original entity with another system or entity. In our example, the car's energy is in relation (potentially albeit) with the ground and the car's energy (and thus the system) is thus defined as being in that relation. The system's energy depends on the possible interaction (which may become real) with the ground.

To become clear on this difference an examination ensues to show that, like position, velocity is a relative property of bodies, but it is not relational. In the example, the velocity of the car depends on the reference frame of the ground, but any other reference frame would serve. We could have chosen the reference frame of

Alpha Centauri or the Eiffel Tower. The property of velocity is relative to the choice of reference frame and that choice is arbitrary. Yet, clearly, some choices of reference frames may be preferred over others in some circumstances, since we often want to know the velocity of bodies with respect with frames of reference that are in or may potentially be in interaction.[4] The choice of the ground for our reference frame is made because of the anticipated interaction of the car with the ground. We presume that someone in the car would care to know that information about the velocity of the car with respect to the ground rather than with respect to Alpha Centauri. This preference is due to the relation or potential relation between the body and the ground, however, one can still meaningfully ask about the velocity of the car from the reference frame of Alpha Centauri. There is no reference frame for velocity that is absolute, truer, or ontologically more fundamental so the choice of reference frame is arbitrary.

Since kinetic energy is proportional to the product of mass and velocity squared, $T = \frac{1}{2}mv^2$, it is a property of a system relative to the reference frame chosen. From the reference frame of the body, the kinetic energy is zero at all times, since no object moves with reference to itself. There is no intrinsic velocity and, therefore, no intrinsic kinetic energy.[5] In the example, the kinetic energy of the car from the car itself is as valid as the kinetic energy consideration from the frame of reference of the ground. The difference lies in that the former tell us little of the coming interaction while the latter is setup with the interaction in mind. We choose the ground as our reference frame since we were particularly interested in finding the state of the energy upon impact. Hence, the choice of reference frame for determining the kinetic energy is modulated by the fact that we anticipate an interaction, in this case, with the boundary which hosts the chosen reference frame. Although we could chose any reference frame we wanted to determine the kinetic energy of a system, often our choice is dependent on the information we want to draw from a given interaction. In this case, we want to know the dynamics of interaction between the car and the

[4]This potential of interaction is what curtails the limitless choices of reference frames into a smaller subgroup of reference frames. This smaller subgroup are local reference frames that may interact with the body. This is what I will describe shortly as relational. What is local, of course, varies on the scale of our system, so Alpha Centauri may turn out to be a local reference frame in some circumstances. The idea of potential interaction harbors a notion of time-space scale, since anything within the range of present and future light-cones can become potential interactions. Wait long enough and the car may be in interaction with a body now far away.

[5]Jeremy Butterfield, in a recent article "Against *Pointillisme* about Mechanics", argues against the idea that velocity can be intrinsic and points to the fundamental physical fact of the necessity of an outside reference frame to speak meaningfully of motion. It is true that we can speak of a body's velocity from its own reference frame, but clearly this carries little explanatory power or physical significance since it will always be null.

ground boundary.

Since the potential energy is dependent on the position and the position is relative, then the potential energy is also relative to the chosen reference frame. From the reference frame of the car, the potential energy would be zero at all times as well since the distance the body travels with reference to itself is always null. Thus the total mechanical energy of a body in reference to itself is zero. The energy can become non-zero only when assessed from an outside reference frame, i.e., the reference frame of the ground as per our example. Obviously, there is no dynamics of an entity measured from its own reference frame, so to do dynamics we must determine the state of the system from a reference frame outside of it.[6] Since the potential energy exists by virtue of the reference frame-boundary outside of the entity, the potential energy is also relational. The preference of treating the ground as a 'preferred' reference frame lies in the interaction that will occur between car and ground. Consider now the following situation so we can understand the meaning of potential energy of the system in terms of a future interaction. Imagine that as the car begins to fall we remove a fake ground and reveal the true ground level 50 meters below. What happens to the potential energy? The potential energy was measured to be mgh and now is measured at $mg(h+50)$. Changing the system (by moving the point of impact, the frame of reference) changes the potential energy. The potential energy will vary depending on the reference frame we choose to measure the system. We can still speak of the potential energy at a distance h, but that would constitute a partial account of the mechanical potential of the system. The full potential occurs how at $h+50$.

Imagine further that we make the cliff to be excessively large, $h \to \infty$. The potential energy of the system becomes infinite large and, hence, the total energy becomes infinitely large. In the absence of physical boundaries, or when the reference frame is infinitely far away, the potential energy becomes infinite and the system is then ill defined. Thus, the potential energy of a system is relational since it only makes sense to speak of a system's energy, or to speak of a system altogether, in the presence of some boundary. Changing the boundaries of the system also affect the final kinetic energy of the system, and, obviously, the final energy of the system. The energy of a system is relative to the reference frame chosen (like velocity), but is also dependent on the boundaries chosen for the system. The energy is relational to the choice of boundary of the system, that is, the energy of an entity is relative to the

[6]Often, by the system a theorist entails the body being measured, the reference frame outside of the body from which we measure its dynamics, and the boundaries of the system, which often, but not always, host the reference frame. In our example, the system was the car, the reference frame of the ground, and the boundaries of the system which include the ground.

frame of reference from which we consider the physical situation. In the first scenario, the system was the car-entity as referenced by the cliff and the ground at a distance h. In the second scenario, the system was the car-entity, the cliff and the ground at a distance $h + 50$. The energy of a system is relative to the choice of reference frame but some reference frames will be preferred over than others because of the possible interaction. This interaction is a relation between entities (the car and the ground). Although the choice for a reference frame for position and velocity is purely relative, the relational nature of energy ensures that some reference frames, those that contain a present or future interaction, will be preferred. In the example, the choice of car and cliff as the system is altered when the ground is removed to reveal the new ground 50 meters below. It turns out that our system was slightly different than anticipated, and the energy of the system varies according to its boundaries.

Since Hamiltonian and Lagrangian formulations tell us that we can speak of the system as the Hamiltonian-Energy and the laws of motion, then since the energy of a system is relative to the choice of reference frame, the state of the system is obviously also relative. The state-energy of the system is then relational to the choice of the system and its boundaries from which it will experience an interaction. The relational aspect of classical mechanics is subdued since we can treat the interaction of the systems boundaries to be minimal or negligible. That is, that we can accurately enough treat the system as closed. Still, saying that the entity has energy is meaningless if a reference frame is not specified.[7] A system is made by the interaction of the entity and its boundaries. So, when we speak of an entity, we necessarily pick a reference frame or boundary of interaction from which we can then meaningfully describe it as a system. The system does not exist prior to the assignment of a boundary.

3 Relational Quantum Mechanics

Since its early years, quantum mechanics has struggled to account for how systems come into interaction. The mathematical formalism describes the state of a system as the addition or superposition of its possible states, yet the interaction of measuring the system reveals it as being in only one of these states. This problem, often referred as the measurement problem or the problem of the collapse of the wave function, has received much attention and many possible solutions, or dissolutions in some cases, exist.

[7] We ignore for the moment the more complex question of the internal energy, but the quantum mechanics examination should help elucidate this.

The traditional or Copenhagen interpretation, which is so widespread that practioners often just equate it to quantum mechanics, indicate that somehow some type of interactions, measurements with macroscopic devices, will collapse or select one of the possible values of the state of the system. (Bohr 1935) Other interpretations have included the attempt to claim that quantum mechanics is incomplete (Einstein 1932, Bohm 1952) since the formalism gives a state of the system that is not accurately representing what we obtain when we measure. The Many-Worlds interpretation, which postulates that there is no collapse of the wave function or state of the system, and rather, at the moment of measurement, a new universe is opened for each of the possible states of the system (Everett 1957, Dewitt 1973). There is also Decoherence (Zeh 1970, Omnès 1994), Transactional interpretation (Cramer 1986), Modal Interpretations (Shimony 1969, van Fraassen1991), and more.

In 1996 Carlo Rovelli published Relational Quantum Mechanics (Rovelli 1996) where he proposed a new account of quantum mechanics and a novel way to examine the interactions between systems. Rovelli argues that there is a seeming contradiction on how quantum mechanics treats the interactions of systems. Although Rovelli was not the first to propose such a relational view of the state of the system, he was the first one to carry out the physical, conceptual, and initial philosophical consequences of treating systems relationally. As Rovelli acknowledges, Zurek, in 1982, and Kuchan, in 1979, proposed similar accounts of the state of the system and its relation to other measuring systems.

Rovelli begins his argument for the need of a relational account of the measurement problem in quantum mechanics by considering a simple general system with two discrete possible values or eigenstates. Here I follow the spirit of the illustration of Rovelli, but expanded to be able to examine it critically later in the paper. Consider the following example from elementary quantum mechanics.

Imagine the state of a system ψ , with two possible eigenstates $\uparrow$ or $\downarrow$.

$$|\psi\rangle = a|\uparrow\rangle \; + b|\downarrow\rangle \tag{1}$$

When the state ψ is measured, it will be found in only one of the two possible eigenstates $\uparrow$ or $\downarrow$. The formalism of quantum mechanics predicts this result and experiments confirm it. Associated with the possible states are the eigenvalues, a and b, of $\uparrow$ or $\downarrow$, respectively. The square of the absolute value of the eigenvalues gives the probability of finding the system in such a state upon measurement. The probability of finding the system in the state $\uparrow$ is given by $P(\psi,\uparrow)$ is

$$P(\psi,\uparrow) = |a|^2$$

and similarly

$$P(\psi, \downarrow) = |b|^2$$

where

$$|a|^2 + |b|^2 = 1$$

if we have the eigenstates normalized. This indicates that the square of the absolute value of these eigenvalues values, assuming that the eigenstates are normalized, can range in value from 0 to 1 and their sum must add to 1.

A specific example of such a system that would fit the above mathematical description would be the spin state of one electron. The formalism of quantum mechanics tells us that the spin state ψ can be written as the sum of the projection states that span the Hilbert space, $\uparrow$ and $\downarrow$.

For instance, if there was a 50% chance to find the state of the electron upon measurement in the state $\uparrow$ or $\downarrow$, then

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle \; + |\downarrow\rangle)$$

where

$$a = b = \frac{1}{\sqrt{2}}$$

and therefore

$$|a|^2 + |b|^2 = \frac{1}{2} + \frac{1}{2} = 1$$

Consider now the situation where a system ϕ comes into interaction with system ψ at time t_1. We can consider that this system measures and reports at a short interval later at t_1 the value found for the spin of ψ. It reports one of the two possible eigenstates of the spin of the electron. For instance, $\uparrow$. Prior to measurement, at t_0, ϕ has not come to interaction with system ψ, but it can report on the state of ψ

At t_0, system ϕ reports:

$$|\psi\rangle = a|\uparrow\rangle \; + b|\downarrow\rangle \tag{2}$$

At t_1, system ϕ reports:

$$|\psi\rangle = |\uparrow\rangle \tag{3}$$

Imagine that a third system ξ was nearby at t_1 but not interacting with either ψ or ϕ. Yet at t_2 it interacts with the combination state ψ and ϕ.

At t_0, system ξ reports:

$$|\psi\rangle = a|\uparrow\rangle \ + b|\downarrow\rangle \tag{4}$$

and

$$|\phi\rangle = |\phi_{initial}\rangle \tag{5}$$

At t_1, system ξ reports:

$$|\psi\rangle \otimes |\phi\rangle = (a|\uparrow\rangle \ + b|\downarrow\rangle) \otimes (|\phi_{\uparrow}\rangle + |\phi_{\downarrow}\rangle) = a|\uparrow\rangle \otimes |\phi_{\uparrow}\rangle + b|\downarrow\rangle \otimes |\phi_{\downarrow}\rangle \tag{6}$$

At t_2, system ξ reports:

$$|\psi\rangle \otimes |\phi\rangle = a|\uparrow\rangle \otimes |\phi_{\uparrow}\rangle \tag{7}$$

Where $|\phi_{\uparrow}\rangle$ is the eigenstate of the interacting system ϕ when it correlates to the state $|\uparrow\rangle$ and $|\phi_{\downarrow}\rangle$ is the eigenstate of the interacting system ϕ when it correlates to the state $|\downarrow\rangle$. Notice that the non-correlated terms vanish.

Rovelli points out that here we have a situation where, at t_1, measuring system ϕ reports that the state of ψ is $\uparrow$, but for system ξ (although it has yet to measure the combined system ψ and ϕ) the state of ψ is entangled in a superposition with state ϕ. Rovelli claims "[i]n quantum mechanics different observers may give different accounts of the same sequence of events." (Rovelli 1996, 4) In short, one system accounts for a collapse of the state of possibilities of ψ as being $\uparrow$, while another system ξ reports no collapse and the state of the combined system ψ and ϕ is in a state of superposition. It follows then that a quantum mechanical description of the state of a system (state and/or values of physical quantities) cannot be taken as an absolute (observer independent) description of reality, but rather as a formalization, or codification, of properties of a system relative to a given observer. (Rovelli 1996, 6) This move should not be confused, Rovelli warns us, as a loss of descriptive power about the system or systems. If the notion of observer-independent description of the world is unphysical, a complete description of the world is exhausted by the relevant information that systems have about each other. (Rovelli 1996, 7) The relation between the accounts of different measuring systems must be treated as a quantum mechanical interaction as well.

A critique of Rovelli's account may center on questioning, first, how (3) and (6) can be both the state of the system ψ and second, how (7) will be the case and not

$$|\psi\rangle \otimes |\phi\rangle = a|\downarrow\rangle \otimes |\phi_{\downarrow}\rangle \tag{8}$$

In the first problem we need to clarify that the difference between equation (3) and (6) could be taken to be solely an epistemic difference, meaning that (3) is the state of ψ from the reference frame of ϕ and (6) is the state of ψ from the reference frame of ξ. From this epistemic consideration both accounts of the state of ψ are valid in that they illustrate the knowledge that ϕ and ξ have of ψ and nothing more. If this was the case, however, then quantum mechanics would be a theory about a system's knowledge of the quantum world and not of the quantum world itself or simply an incomplete theory of phenomena. Besides, it appears that we would have two incompatible accounts of the system ψ from two different reference frames. If we take into consideration the analysis of classical mechanics, the energy state of the system is relative to the reference frame and in relation to the boundaries of interactions. From the reference frame of ϕ, ψ is in a state of possibility represented by (2) and upon interaction in state (3). The state ϕ is now entangled with ψ, but it does not enter explicitly into its account of ψ in (3). It is no surprise, then, to have another system, ξ report that entanglement in (6). The surprising bit comes from the report of (6) that there is no collapse, but it is consistent with traditional quantum mechanical accounts of the postulate of measurement in that the actualization does not occur unless there is an interaction. From the reference frame of ξ, ψ and ϕ constitute a single system $\psi \otimes \phi$ which is in a superposition of states until measurement. However, this is only problem if we insist to hold on to a non-relative view of a system or state. This view conflicts with the way we have been doing mechanics since Galileo. The challenge here is to understand that relativity of states does not imply loss of objectivity. Rather objectivity needs to be disassociated from the notion that an absolute reference frame exists. The relativity of motion is objective in that a particular reference frame will report a unique value in classical mechanics and a set of possibilities in the more fundamental account of QM.

An ontological reading would claim that the state at t_1 of ψ is both (3) and (6). As in the epistemic case the state of the system differs from system to system and there is no absolute state of the system. But notice what happens when ξ finally interacts with ψ (which is entangled with ϕ) as depicted in (7), which brings us to the second problem. It reveals the state collapsed into one of its possible values as in (3). But how come we expect to find it $\uparrow$ and not $\downarrow$? One response would be to appeal to Luder's rule and claim that if t_2 occurs right after t_1 we will expect the state of ψ and its entanglement with ϕ to remain $\uparrow$ when interacted by ξ. But this response would seem to avoid the real problem raised in that (8) is as good an answer as (7) unless we assume that there is an absolute, already given, state for ψ ($\uparrow$ in our example). From the simple lesson of classical mechanics we know that the state of the system depends on the anticipated interaction. In quantum mechanics this still holds true and the state of ψ depends on boundaries given by other systems. In (3) the boundary of ψ is ϕ while in (6) the boundary of ψ (entangled with ϕ) is ξ. Since the boundaries of the systems change, we should expect a different account, in the same way we expect (3) (at t_2 albeit) and (7) to be distinct. The state of the system ψ depends on the interactions it experiences and those interactions will be different for different systems.

The further problem in QM, unlike classical mechanics, is the existence of the state of superposition, as in (4) and (6). How can it be that ψ is both an actual state and a superposition of states, at the same time? This seemingly contradiction at an ontological level is similar to the epistemic question we raised in the previous paragraph. In the ontological account it appears that the collapsed state of ψ can only occur when interacted by a system. Since the system can be chosen to have any boundaries, the entangled stated of ψ and ϕ is not collapsed until a external system, ξ, interacts with the entangled state. Rovelli does not expose the nature of interaction and how it produces such a change in the state.[8] In classical mechanics the interaction seems clear, as when the car hits the ground. But in the quantum realm, what constitutes and interaction or measurement is still subject to debate and seems crucial for understanding precisely how Rovelli's relational account would work. His proposal to understand interaction as information has possibilities, but leaves some of the conceptual questions still open.

Despite the difficulty of ascertaining what constitutes measurement or interaction the ontological account, the state of a system ψ depends on the system or reference frame and that the system requires another system to create its boundaries. When a system interacts with another system, then the possibilities become actualized, but only from the reference frame of the external system, in our example ϕ and later ξ. What a system is depends on the system that is interacting with it. In Rovelli's example, we assumed that there was nothing interacting with ψ and it was in a state

[8]Rovelli is aware of the main problem in QM, the measurement problem. He mentions that the solution probably lies in a combination of the interpretations, but he does not specify what the solution is in full, but that it may disappear given his relational account. Rovelli recognizes that more work would need to be done in RQM to show this is the case, possibly with the complicity of other interpretations

of superposition. Once ϕ interacted, then the state of ψ changed into one of its possibilities, but for ξ, ψ was entangled with ϕ in a state of possibilities.

3.1 Ontological Picture that Emerges from RQM

David Bohm and others have already hinted at the role of external systems in determining the nature of a quantum mechanical system. Bohm declares:

> Thus, under all circumstances, we picture the electron as something that is itself not very definite in nature but that is continually producing effects which, whether they are actually observed by any human observers or not, call for the interpretation that the electron has a nature that varies in response to the environment." (Bohm 1951, 610)

This variation of the state of the system in relation to the environment could often be ignored for practical purposes in classical mechanics, but it creates a conceptual vacuum in QM if ignored. QM is relational and the entities described by the theory can only be understood in relation to other entities. Without boundaries or other systems to interact, the electron vanishes. With set boundaries the electron develops its properties and certain types of interactions can render this properties of the entity actualized. The sacrifice is that other possible properties of the entity are lost. Rovelli's argument for a relative and relational quantum physics adds another aspect to the understanding of an entity in QM. A system's state will vary depending on what system is reporting (relative) and that difference depends on the type of interaction (relational) the systems have.

For Rovelli, however, the difference between Galilean relativity and relationism lies in that relationism refers to the relativity of any kind of motion and not just inertial motions. This distinction is a good start for generalizing the relativity of motion and towards a more robust ontological account of GR, yet the problem with it is that relationism taken in this sense would simply be a more general epistemological form of relativity like the one we obtain in SR and GR. It is the case the Galilean relativity is superseded by the more comprehensive account of motion given the special relativistic treatment of frames of reference and in turn, GR gives an even more general account of the relativity of frames of reference with respect to the gravitational field. But if this was just the only improvement that relativity offered the Galilean-Newtonian account, that we could conceive and describe it as a more general type of relativity of motion, then we would miss the deeper lesson. The deeper lesson occurs at an ontological level in that the theory demands a reference frames to have ontological significance in that they carry the possibility, at least, of interaction of their gravitational fields, in GR, and with other systems, in QM. To speak of the motion or being of an entity or system demands that we specify a reference frame first. This is what should properly be referred as relationism.[9] Without the interaction, and not just a mere epistemic reference frame, the entity in QM (and GR) does not have a status. From this we abandon, at Rovelli's suggestion the notion of absolute state of physical systems, but also we demand that to speak of the existence of a physical system we need to specify another physical system of interaction.

Rovelli makes a declarations on this issue, but does not stress the ontological significance of interaction sufficiently:

> Physics is concerned with relations between physical systems. In particular, it is concerned with the description that physical systems give of other physical systems.

(Rovelli 1996, 10)

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[9] In fact, that is how Rovelli uses the term in his account of relationism in quantum mechanics.

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