

Mental and Physical Objects in Quantum Mechanics: Any Lessons for Other Disciplines?

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Abstract: The standard formulation of Quantum Mechanics has raised from its beginning animated discussions about the interpretation of the counterintuitive properties of mental objects (wave functions or Schrödinger waves) introduced to represent the properties of the physical objects. Two questions have since then been formulated to which a universally accepted answer is still lacking. The first one (Bohr, von Neumann) concerns the ontological nature of physical reality (the existence of classical objects) and the role of the observer (wave packet collapse) in assessing it. The second one is the non local character of quantum physical quantities (Einstein Podolski Rosen [EPR] long distance correlation of particles). An alternative formulation of Quantum Mechanics, originally proposed in 1932 by Eugene Wigner, taken up by Richard Feynman in 1987, and reelaborated by myself in the years from 1998 to 2003, is possible. The mental objects of standard Quantum Mechanics (Schrödinger waves) no longer appear in this new formulation and are replaced by new ones (Wigner functions) which do not show any more the puzzling properties which worried Einstein. My conclusion from the preceding discussion is that different explanations of a given set of experimental data may be derived according to the different nature of the mental objects introduced to represent the properties of the physical objects involved. The confusion between these two kind of objects may be, however, very misleading. I will finally discuss two examples of this conclusion from Biology and Economics

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1. Introduction

1.1. Already 2500 years ago the Greek philosophers proposed two conflicting views of reality:

a) Nothing changes (Parmenides)

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Reality is only a poor and imperfect copy of eternal ideas (Plato's cavern)

b) Everything changes (Eraclitus)

Ideas are artefacts of man's mind obtained by abstracting concepts, categories, relations from phenomena (Aristoteles).

Scientists are still faced with the problem of choosing whether one stands on one side or the other one. This choice has to be done before starting doing science in any particular domain.

Mathematics "works" in describing reality not because reality is made of "real" mathematical objects. It "works" because we construct mental objects – reciprocally connected through logical relations - by selecting those aspects of reality which our experience indicates as more fundamental and general, and neglecting those which appear to us unimportant and contingent (us means a given human community in a given historical stage of civilization or culture).

Ex. If we believe in continuity we discard the discrete aspects of phenomena and we invent differential calculus to describe their form and their temporal evolution, and if we believe in discontinuity we focus on abrupt changes and sudden variations and invent fractals and numerical algorithms to represent them.

I will try to show how these two ways of looking at reality still provide the bases for the construction of scientific knowledge in many disciplines, from basic physics to biology and economics.

1.2. The first step of my talk is to recall that the standard formulation of Quantum Mechanics has raised from its beginning animated discussions about the interpretation of the counterintuitive properties of mental objects (wave functions or Schrödinger waves) introduced to represent the properties of the physical objects (Jammer 1974)

Two questions have since then been formulated to which a universally accepted answer is still lacking. The first one concerns the ontological nature of physical reality and the role of the observer (wave packet collapse) in assessing it (Bohr 1958a).

The second one is the non local character of quantum physical quantities (Einstein, Podolski Rosen, 1935, Bohr 1958b) shown by long distance correlation of particles. From his thought experiment Einstein concluded that Quantum Mechanics does not describe completely and fully the real microscopic world.

The debate on Einstein's conclusion has gone on for almost fifty years and led Alain Aspect (Aspect, Dalibard, Roger 1982) to perform the experiment suggested by Bell (Bell 1964) to test Einstein's claim. Its result has been almost unanimously interpreted as a proof that Einstein was wrong and that the physical objects do have the queer properties of the mental objects of Quantum Mechanics.

1.3. This is not, however, the end of the story. In fact the second step of this talk is to show that an alternative formulation of Quantum Mechanics, originally proposed by Eugene Wigner (Wigner 1932), taken up by Richard Feynman (Feynman 1987), and reelaborated by myself (Cini 1999, Cini 2003, Cini 2006) is possible.

The mental objects of standard Quantum Mechanics (Schrödinger waves) no longer appear in this new formulation and are replaced by new ones (Wigner functions) which do

not show any more the puzzling properties which worried Einstein.

Whether this is the final solution of the debate which animated the physicist's community for more than seventy years is however not yet clear.

Undoubtedly, however, the adoption of this approach has the advantage that Wigner functions provide directly all the measurable statistical factors (mean values, mean square deviations, correlations) of actual experiments without introducing ambiguities about the properties of physical objects.

1.4. The final step of my talk will consist in trying to draw a methodological lesson from the history of Quantum Mechanics. My conclusion from the preceding discussion is in fact that different explanations of a given set of facts may be derived according to the different nature of the mental objects introduced to represent the properties of the real objects involved. The confusion between these two kind of objects may be, however, very misleading.

I will finally discuss two examples of this conclusion from Biology (Gould 2002) and Economics (Ormerod 1998)

2. The Wavelike Behavior of Particles

2.1 The Two Slit Experiment

The whole edifice of the standard formalism of Quantum Mechanics can be built on an experiment (Davisson & Germer 1926) which shows that a beam of particles (electrons) behaves as a wave under suitable conditions. Its scheme goes as follows.

The beam impinges on a screen with two slits F_1 and F_2 through which the particles pass and fall on a photographic plate parallel to the screen which detects them.

The black spots produced on the plate by the random impact of each particle form a pattern (interference pattern) made of many lines parallel to the slits of different intensity extending also in the regions of the shadows of the screen. This pattern is characteristic of the propagation of any wave (sound, surface, electromagnetic waves) through the slits of the screen.

The pattern has a strong maximum at the center when the distance between the slits is of the order of the wavelength and gradually builds up the two expected classical images in correspondence with the slits as their distance becomes very large.

This result conflicts with the expectation that the pattern obtained in the setup with the two slits simultaneously open should be equal to the result of adding the patterns obtained by allowing alternatively the particles to pass with certainty through F_1 (with F_2 closed) and F_2 (with F_1 closed).

The pattern obtained when both slits are open can therefore only be interpreted as a consequence of the fact that it is impossible to assess whether each particle has actually passed through F_1 or F_2 .

Furthermore this pattern does not depend on the intensity of the beam. Even if the particles pass one at a time, they gradually accumulate randomly to build the same final

interference pattern. It appears gradually as if the motion of each particle is guided by the propagation of the same single wave.

2.2 The Interference Pattern

In order to explain this wavelike behavior of particles, Quantum Mechanics introduces, by analogy with the standard representation of other physical waves a mental object called wave function $\psi(x, t)$, representing the amplitude and phase of this new (Schrödinger) wave at each point of space x at any time t .

Again following the analogy with other waves, the intensity $P(x, t)$ of the wave is assumed to be

$$P(x, t) = [\psi(x, t)]^2 \quad (1)$$

The explanation of the interference pattern follows easily from Eq. (1). If we call $\psi_1(x, t)$ and $\psi_2(x, t)$ the waves which pass through F_1 and F_2 respectively, we can write

$$\psi(x, t) = \psi_1(x, t) + \psi_2(x, t) \quad (2)$$

and from (1) (2)

$$P(x, t) = [\psi_1(x, t)]^2 + [\psi_2(x, t)]^2 + 2\psi_1(x, t)\psi_2(x, t) \quad (3)$$

The first two terms are the intensities one would expect for classical particles travelling along straight trajectories. The third is due to the interference of the two waves.

Eq.(3) explains why the intensity on the plate when both slits are open is not the sum of the intensities obtained when one is open and the other one is closed.

The interference term in fact may be positive or negative. At the points x_0 of the plate where $\psi_1(x_0, t) = -\psi_2(x_0, t)$ the intensity is in fact zero, while at points x_m where $\psi_1(x_m, t) = \psi_2(x_m, t)$ the intensity is four times as much.

The alternating black and white lines (maximal and zero intensities) which form the interference pattern are therefore simply explained as the loci where the waves going through the two slits add up constructively or subtract each other destructively.

The presence of the interference term implies that the two alternatives “the particle has passed through F_1 ” and “the particle has passed through F_2 ” are not mutually exclusive, because their probabilities do not add.

2.3 The Wave/Particle Duality

The wavelike behavior of particles revealed by the interference pattern solved also the puzzle of the discrete structure of electronic orbits in atoms, which explains, according to Bohr’s theory, the lines in the spectra of emission and absorption of electromagnetic radiation when the electron jumps from one orbit to another one.

In fact Bohr’s rule for the existence of a stationary orbit is given by the relation

$$2\pi r p = n h \quad (n = 1, 2, 3, \dots) \quad (4)$$

where r is the orbit radius, p is the electron momentum and h is Planck's constant. Now, if λ is the wavelength of the stationary wave associated with the orbit the condition for a stationary wave is that the length of the orbit $2\pi r$ should be an integer multiple of its wavelength.

Eq. (4) gives therefore the fundamental relation (postulated in 1924 by Louis de Broglie)

$$p = h/\lambda \quad (5)$$

which connects the particle's kinetic momentum with the propagation length of its wave.

2.4 The Heisenberg Uncertainty Relation

The wavelike behavior of a particle is also at the origin of the famous Heisenberg uncertainty principle.

In the setup with both slits open, the uncertainty of the electron position along the screen Δx is the distance d between the slits. On the other hand the uncertainty of its momentum is at least $\Delta p = \alpha p$ where α is the angle under which the two slits are seen from the central line of the interference pattern. Considering that the path leading from one slit to the central line differs by one wavelength from the path leading to the next interference line, (namely that $\lambda = \alpha d$) one finds, by using (5)

$$\Delta x \Delta p \geq d \alpha p = d [(h/p)/d] p = h \quad (6)$$

The meaning of (6) is that the concept of geometrical trajectory of a particle should be abandoned. In fact, the more precisely definite is its position, the less precisely definite is its momentum, and viceversa. Position and momentum are incompatible variables. Other incompatible couples of variables are the angular momentum and the angle, or, in quantum field theory, the number of quanta and the field phase.

3. How real are Quantum particles?

3.1 Probability waves

The attempts to interpret a wave function as a physical wave propagating in ordinary space failed because the extension from single particles (electrons) to compound systems (atoms with many electrons) needed the use of a wave function $\psi(x_1, x_2, \dots, t)$ dependent on the coordinates of all the components. This wave function cannot be a wave in ordinary three dimensional space.

The solution, found in 1927 by Max Born, was to interpret the wave function ψ as a probability wave, and its amplitude's squared $P(x, t) = [\psi(x, t)]^2$ as the probability that the particle is at the point x at time t . The probability for any other physical quantity G having a well determined value g is similarly obtained by squaring a corresponding probability amplitude $\alpha(g, t)$ by means of the same rule $P(g, t) = [\alpha(g, t)]^2$ The physical

nature of a probability amplitude is the open question of the standard formulation of Quantum Mechanics. In fact the problem is that it is not a concept related to either the observed object or to the observer subject, but it refers to the relationship between the two. This leads to two main paradoxical features of quantum objects.

3.2 The Role of the Observer

“With the Heisenberg uncertainty principle – wrote W. Pauli - the initial phase of the theory came to the end. The solution is obtained at the cost of abandoning the classical causal description of nature in space-time which depends essentially on our capacity of separating uniquely the observer and the observed object.”

It should be emphasized at this stage that the impossibility of separating uniquely the observer and the observed object is a typical quantum effect which is often mistakenly considered to be analogous to the phenomenon, well known in social sciences, of the influence exerted on the behavior of people by their knowledge of being observed. Electrons do not have consciousness and this should not be forgotten.

To understand Pauli’s statement it should be pointed out that the same uncertainty found before about which slit has the particle passed through, arises also when the one particle probability wave $\psi(x, t)$ is the sum (eq.(3)) of wave functions $\psi_n(x, t)$ corresponding to any set of different alternatives.

Assume that each one describes a state of the particle in which the physical quantity \mathbf{G} has with certainty a definite value g_n :

$$\psi(x, t) = \sum_n \psi_n(x, t) \quad (7)$$

Also in this case the presence of interference terms will make the space probability pattern $P(x, t)$ different from the sum $\sum_n [\psi_n(x, t)]^2$, expected for a statistical mixture in which each term represents the contribution of particles with \mathbf{G} having with certainty the value g_n .

On the other hand if, as we did by closing one or the other slit, we measure the physical quantity \mathbf{G} obtaining a definite value g_i the space pattern becomes suddenly $[\psi_j(x, t)]^2$, which implies that $\psi(x, t)$ becomes suddenly $\psi_i(x, t)$. This jump is called wave function collapse.

The question therefore arises (Wheeler J., Zurek W. 1983): Is this sudden jump due to the knowledge acquired by the observer that the particle had already a value g_i of \mathbf{G} before the measurement, or is it due to the sudden acquisition by the particle of the value g_i of \mathbf{G} during the act of measurement?

3.3 The Bohr/von Neumann Debate

The first alternative, is untenable. In fact, if we had in mind to measure another physical quantity \mathbf{F} incompatible with \mathbf{G} , the same initial wave function $\psi(x, t)$ should have been

written:

$$\psi(x, t) = \sum_n \phi_n(x, t) \quad (8)$$

($\phi_n(x, t)$ being the wave function corresponding to \mathbf{F} having the value f_n). The same reasoning as before implies however that, if we measure \mathbf{F} and obtain the value f_j the wave function $\psi(x, t)$ must become suddenly $\phi_j(x, t)$. However, since \mathbf{F} and \mathbf{G} are incompatible, the assumption that they had simultaneously well defined values before being measured is incompatible with the presence of different interference terms in the two cases of the space probability pattern before the measurement.

The second alternative however, as we shall see in a moment, runs into other difficulties. A solution of this kind was indeed proposed by Niels Bohr, based on the assumption that the measuring instruments are classical, namely that all their variables have always sharp values.

This implied that a quantum variable, whose value is in general uncertain, acquires a sharp value only when the object interacts with the instrument designed for its measurement. Since no instrument can simultaneously measure two incompatible variables, no contradiction arises with the uncertainty principle.

Bohr's solution, however, was not universally accepted: The double nature of the macroscopic apparatus (on the one hand a classical object and on the other hand obeying quantum mechanical laws) – wrote Max Jammer in 19 - remained a somewhat questionable or at least obscure feature in Bohr's conception of quantum mechanical measurements.

In fact, John von Neumann argued, against Bohr, that, if the laws of Quantum Mechanics are universal and represent the ultimate nature of matter, it is not allowed to assume that classical objects (the instruments) exist not submitted to Heisenberg's principle. This means that, in principle, the physical quantities of the instrument cannot be more objectively real than those of the particle. The only non physical entity capable of producing the wave function collapse, is, therefore, according to him, the observer's mind.

3.4 The existence of classical objects

I disagree completely with Von Neumann's argument, which started, in my opinion, a flood of nonsensical publications about the role of the observer's consciousness in creating physical reality which went on for many decades. The developments of the latest twenty years show however that Bohr's solution was appropriate at that time and was consistent with the view that reality exists independently of human mind.

My answer to the question "How and when does the collapse of the wave function happen?" is the same as Bohr's This answer accepts that real microscopical objects with a definite mass, spin and charge never possess simultaneously the kinematic properties which would allow to describe their motion along a trajectory in space. Their properties are therefore context dependent.

It implies for example, that if a particle interacts with a photographic plate we can "objectively describe" the system after the interaction as made of a photographic plate with a black spot and the quanton with a sharp position located where the black spot is. It

implies furthermore that an analogous but complementary objective description of reality can be made when (a beam of) particles interact(s) with a diffraction grating.

The difference with Bohr is that it becomes now necessary to prove that the existence of macroscopic pieces of matter with context independent properties is not a postulate but follows from the equations of Quantum Mechanics themselves. This question was investigated and answered by my group in Rome twenty five years ago (Cini M., De Maria M., Mattioli G., Nicolò F., 1979; Cini M. 1983; Cini M. and Serva M. 1990; Cini M. and Serva M. 1992). In these papers we proved that macroscopic aggregates of particles in normal conditions never exhibit quantum behavior because the phase relations of their microscopic constituent's wave functions are completely destroyed.

We did in fact prove that the effects of quantum interference (the wavelike behavior) tend to zero for a sum of two macroscopically different wave functions of a macroscopic object. This implies that when a quantum particle P in a given state interacts with a suitable instrument S_q made of N quantum particles, the difference between the probabilistic predictions of Quantum Mechanics and the predictions of classical statistical mechanics with a classical instrument S_c replacing S_q tends to vanish when N becomes very large ($\gg 1$). This means that, after all, Bohr was right in assuming that classical bodies exist.

3.5 The Nature of Reality

This solution is a good example of the a priori difference between a neoplatonist approach and a neoaristotelian one. If one insists that the presence of interference terms, however small may they be for macroscopic bodies, implies that the wave function never collapses, then one concludes that only mathematical entities (wave functions) exist and that reality is a creation of our mind.

On the other hand if one believes, as I do, that one should not attribute unphysical properties to mathematical objects created by our mind, then the conclusion that classical objects practically exist for all purposes avoids talking about metaphysical phantasies.

In addition, it allows to predict that, under suitable conditions to be invented, they might show some experimentally detectable quantum properties certainly not in contradiction with the principle that reality is not created by the human mind. In fact experiments on the phenomenon called Macroscopic Quantum Coherence are under way which seem to confirm that Quantum Mechanics works well also for macroscopic objects.

4. Quantum Nonlocality

4.1 The Bohr Einstein Debate

The EPR argument is based on a reality criterion formulated as follows: In a seminal paper of 1935 Einstein, Podolski and Rosen (EPR) challenged the accepted interpretation of Quantum Mechanics by proposing a thought experiment which kept physicists discussing for almost fifty years. If, without in any way disturbing a system, we can predict

with certainty the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.

Their thought experiment considers a two particle system in a state in which their distance $x_1 - x_2 = d$ and their total momentum $p_1 + p_2 = p$ are given. Therefore, if one measures x_1 and finds a value a it becomes possible to deduce, without disturbing particle 2, that its position x_2 is $a + b$.

This means that its position was an element of reality even before measuring the position of particle 1.

We might have chosen, however, to measure the momentum p_1 of particle 1, obtaining the value q . Once more we would have deduced, without disturbing particle 2, that the value of p_2 was $p - q$ even before measuring p_1 .

This implies that both the position and the momentum of particle 2 were elements of reality before performing any measurement on particle 1.

The final conclusion of EPR was therefore that Quantum Mechanics, which holds that incompatible variables do not have objectively real values at the same time, is incomplete. Bohr objected: From our point of view we now see that the wording of the above mentioned criterion of physical reality proposed by EPR contains an ambiguity as regards the meaning of the expression “without in any way disturbing a system”. The conditions which define the possible types of predictions regarding the future behaviour of the system.. constitute an inherent element of the description of any phenomenon to which the term “physical reality” can be properly attached. [Therefore] the argumentation of the mentioned authors does not justify their conclusion that quantum-mechanical description is essentially incomplete.

4.2 The Long Distance Quantum Correlations

The argument of EPR had two drawbacks. One is that the condition that the distance d between the two particles should be given could only be ensured by introducing an additional physical constraint (e.g. a screen with two holes) which would imply a disturbance on both particles. The second one was that there was no actual experiment which could decide whether it was Einstein or Bohr who was right.

The first one was eliminated by David Bohm who proposed to consider the measurement of two other incompatible variables rather than position and momentum. These variables are any two of the three components (along the space directions x,y,z) of the individual angular momentum (spin) of each particle, say $\sigma_x^{(1)}, \sigma_z^{(1)}$, (or $\sigma_x^{(2)}, \sigma_z^{(2)}$) which, according to the Heisenberg principle cannot have simultaneously a given value. However, when the total angular momentum of the system is zero, its three components are also simultaneously zero.

In this case the law of conservation of the total angular momentum guarantees that all of them maintain the initial value zero even when the distance between the particles increases indefinitely. The EPR argument can therefore be carried on without any further objection.

The second drawback was overcome by John Bell, who eliminated the pointless discussion about the legitimacy of attributing a value to a variable without measuring it, by proposing an actual experiment in which the correlation coefficient $C(a, b)$ between the measurements of the spin component of particle 1 along a direction a and of the spin component of particle 2 along a different direction b . The correlation $C(a, b)$ is obtained by performing a series of measurements on a great number N of pairs of particles with total spin zero.

Bell showed that the dependence of $C(a, b)$ on the angle θ between a and b predicted by Quantum Mechanics is different from the one obtained by assuming the validity of Einstein's reality criterium.

As stated at the beginning, in 1982 Alain Aspect performed the actual experiment envisaged by Bell and showed that Einstein's criterion was wrong. The interpretation of this result is that Quantum Mechanics is right in predicting that the physical objects do have the queer properties of the mental objects introduced in the standard formulation of the theory.

4.3 The Nature Of Quantum Correlations

The strange quantum behavior of two particles whose variables remain correlated even after having been separated spatially, is not that they remain correlated also when they are far away. This happens also to a pair of classical particles. Take for example an object with zero total angular momentum which is split in two parts which fly away in opposite directions. The conservation of angular momentum implies that any component of the angular momentum of one part is always equal and opposite to the same component of the other part. What is paradoxical is that this behavior persists also in Quantum Mechanics in spite of the fact that in principle only one component of a particle's spin can have at a given time a sharp value.

We ask therefore: how is it possible that, when the particle 1 acquires a sharp value of its spin component during the interaction with its instrument, the far away particle comes to "know" that it should acquire the same and opposite value of its own spin component? Furthermore, is this value acquired instantaneously at the very moment of the first measurement or is it delayed to a later moment, when the far away particle 2 interacts at its turn with its own instrument?

People tend to answer to both questions by invoking a spooky action-at-a-distance responsible for this apparent instantaneous transfer of information from one particle to the other.

One can not explain however in this way this counterintuitive behavior, because this difference has its roots in the ontological (or irreducible) - not epistemical (or due to imperfect knowledge) - nature of the randomness of quantum events.

One has in fact to accept that physical laws do not formulate detailed prescriptions, enforced by concrete physical entities, about all that must happen in the world, but only provide constraints and express prohibitions about what may happen. Random events

just happen, provided they comply to these constraints and do not violate these prohibitions.

The far away particle, once the first one has acquired a sharp value of its angular momentum component, has to acquire an equal and opposite sharp value for the same component of its own angular momentum, because, should it not behave this way, it would violate the law of conservation of angular momentum.

The quantity total angular momentum is itself, by definition, a non-local quantity. In fact, the two instruments are not two uncorrelated pieces of matter: they are two rigidly connected parts of one single piece of matter which measures this quantity. The non local constraint is therefore provided by the nature of the macroscopic instrument. Non locality therefore needs not to be enforced by a mysterious action-at-a-distance.

This entails that, once the quantum randomness has produced the first partial sharp result, there is no freedom left for the result of the final stage of the interaction: there is no source of angular momentum available to produce any other result except the equal and opposite sharp value needed to add up to zero for the total momentum.

5. Quantum Mechanics in Phase Space

5.1 The Wigner Quasiprobabilities

If chance has an irreducible origin the fundamental laws should allow for the occurrence of different events under equal conditions. The language of probability seems therefore to be the only language capable of expressing this fundamental role of chance. The proper framework in which a solution of the conceptual problems discussed above should be looked for is the birthplace of the quantum of action, namely phase space, where no probability amplitudes exist. It is in fact clear that joint probabilities for both position and momentum having sharp given values cannot exist in phase space, because they would contradict the uncertainty principle.

Wigner (1932) however, introduced the functions $W(x, p, t)$ called after his name, which, in spite of the fact that they do not satisfy the requirement for probabilities of being nonnegative, may be used to represent Quantum Mechanics in phase space and showed that one can use them as normal probabilities to compute any physically meaningful statistical property of quantum states.

This can be done by means of a suitable representation $\mathbf{G}(x, p)$ of the required property in phase space through the usual expression for its average value:

$$\langle G \rangle = \int \int dx dp W(x, p, t) G(x, p) \quad (9)$$

It seems reasonable therefore to consider the Wigner functions as a framework for looking at Quantum Mechanics from a different point of view.

Their physical meaning is well clarified by Feynman's (1987) words: It is that a situation for which a negative probability is calculated is impossible, not in the sense that the chance for its happening is zero, but rather in the sense that the assumed conditions of

preparation or verification are experimentally unattainable.

The road is therefore open for a new reformulation of Quantum Mechanics, in which the concept of probability waves is eliminated from the beginning. After all, particles and waves do not stand on the same footing as far as their practical detection is concerned. The position of a particle assumes a sharp value as a consequence of a single interaction with a suitable detector, but we never detect waves: we only infer their existence by detecting a large number of particles.

5.2 The Elimination of Probability Waves

This program has been recently carried on (Cini 1999) by generalizing the formalism of classical statistical mechanics in phase space with the introduction of Planck's quantum postulate, namely the discreteness of the values of the action variable of oscillators. The whole structure of Quantum Mechanics in phase space is therefore deduced from a single quantum postulate without ever introducing wave functions or probability amplitudes. The elimination of probability amplitudes from quantum theory is coherent with the method inaugurated by Einstein with the elimination of the ether in the theory of electromagnetism. Also in that case people discussed for many years about the strange properties of this mental object, which should have been at the same time perfectly transparent and infinitely rigid. Special relativity got rid of it and no one speaks of the ether any more.

The elimination of Schrödinger wave functions has the advantage that the paradoxes typical of the wave-particle duality disappear. On the one hand, the long time debated question about the meaning of the wave functions of macroscopic objects and the related question of wave function collapse may be set aside as baseless.

The Wigner function of a macroscopic body (Cini 1999) tends in fact to the corresponding non-negative probability distribution in phase space of classical statistical mechanics. Therefore the statistical predictions of Quantum Mechanics for the outcomes of the measurement of a physical quantum property tend to those of the classical statistical mechanics of an ensemble of classical instruments triggered by the occurrence of random quantum events.

On the other hand, as already shown by Feynman, it becomes possible to express the correlations between two distant particles in terms of the product of two pseudoprobabilities independent from each other. All the speculations on the nature of an hypothetical superluminal signal between them becomes equally meaningless.

6. Some Methodological Conclusions

6.1 The Analogies with Other Disciplines

We should be very careful in asking whether we can draw any lessons from the history of Quantum Mechanics which may be useful for clarifying controversial issues in other

disciplines.

The first thing to do is in fact to emphasize that a deep gulf separates the world of quantum particles from the macroscopic world, and even more from the world of living matter, let alone the world of human beings. All the fairy tales about possible connections between human mind and Quantum Mechanics are meaningless babbles.

This is why I already stressed before that the problem of separating uniquely the observer and the observed object in Quantum Mechanics has nothing to do with the phenomenon, well known in social sciences, of the influence exerted on the behavior of people by their knowledge of being observed. Electrons do not have consciousness and this should not be forgotten. The only useful suggestions one can draw by comparing two different disciplines do not therefore concern their different phenomenological domains but the higher methodological and epistemological metalevels.

Different disciplines share in fact at a given time the same cultural, economic and social context, with its conflicting different ways of looking at the surrounding world, each one based on a coherent set of conceptual premises and frames of reference. It is this common *Zeitgeist* which projects its features on the conceptual frameworks adopted by the different scientific communities in order to construct an adequate representation of the phenomena investigated.

I wish therefore to draw from the preceding discussion on the interpretations of Quantum Mechanics the conclusion that different explanations of a set of actual experiments may be derived according to the different nature of the mental objects introduced to represent the properties of the real objects involved.

I will therefore, from an outsider's point of view, try to show by means of two examples, one from biology and another from economics, how the confusion between these two kind of objects, may lead to the same difficulties which have for such a long time, worried the physicist's community.

6.2 First Example: Evolutionary Theory

My first example is the controversy on the interpretation of Darwinism and of its developments which opposed for decades Stephen J. Gould, author of a great number of popular books on evolutionary theory, culminated with the publication, shortly before his untimely death, of the highly professional book *The Structure Of Evolutionary Theory*, and Richard Dawkins, author of the worldwide bestseller *The selfish gene*.

Their views differ radically on many aspects of the contemporary Theory of Evolution. I only mention some of them. Dawkins thinks that the large scale features of the natural world may be extrapolated from the microevolutionary dynamics of genes, while Gould denies this possibility. Dawkins believes in a gradual and uniform pace of change in the evolution of species, in contrast with Gould's vision of speciation as characterized by sudden changes separated by long periods of equilibrium. Gould stresses the importance of internal constraints in limiting natural selection, while Dawkins considers them irrelevant. Finally, last but not least, Dawkins holds that genes are the fundamental units of

selection while Gould draws a picture of evolution as the result of a multiplicity of levels and units of selection.

I will limit myself to illustrate this last point with two quotations.

I must argue – Dawkins wrote – for my belief that the best way to look at evolution is in terms of selection occurring at the lowest level of all. . . I shall argue that the fundamental unit of selection, and therefore of self-interest, is not the species, nor the group, nor even, strictly, the individual. It is the gene, the unit of heredity.

Richard – reacted Gould - has displaced the level of explication at the lowest step: it is not the organisms but the genes who fight for survival. But he is wrong. Only if organisms could be defined as a cumulative sum of the actions of mutually independent genes would it be possible to reduce the properties of the former to the behavior of the latter. But this is not the case, because organisms have myriads of emergent characteristics. In other words, genes interact nonlinearly between themselves: it is this interaction which defines the organism's identity.

The comparison shows that we are here again in presence of two conflicting views of reality which lead to the introduction of different mental objects. The purpose of Dawkins is to define genes in order to explain reality in terms of their properties, at the price of forcing reality to fit into the rigid framework built on the assumption that the physical objects existing in nature coincide with his mental objects. He wants to explain processes in terms of an elementary structure (reductionist and neoplatonic approach). On the other hand Gould is willing to accept a multilevel vision of reality, each level being defined by its constraints and its units of selection, with contingency as a basic factor of evolution (*Wonderful Life*: if you rewind the tape of evolution and play it again you will get a completely different pattern). His mental objects are derived from physical objects, rather than the opposite.

6.3 Second Example: Economy at the Edge Of Chaos

In the preface to his book *Butterfly Economics* Paul Ormerod wrote:

Conventional Economics is wrong in considering economy and society as sorts of complicated machineries which can, after all, be predicted and governed. Human society resembles much more closely a living organism, whose behavior may be understood only by examining the complex interactions between its different parts.

In orthodox economic theory it is not allowed to individuals to influence each other directly. This approach leads, under special circumstances, to a satisfactory explanation of facts. More often, however, it happens that individuals and enterprises are directly influenced by the actions of others. This leads to a much more complex, but also more realistic model, and I am convinced that economy, together with other social sciences, will adopt it soon.

Both the title of Ormerod's book and the expression *At the Edge of Chaos* are taken from the language of the community built around the Santa Fé interdisciplinary Institute for the Study of Complexity.

It was the economist Brian Arthur who opened the road of this approach in economics with a seminal paper published 1989 (rejected for five years by the leading economic journals) entitled *Competing rechnologies, increasing returns*, and lock-in by historical events. His theory, known as QWERTY theory (from the first six letters of the English clavier of typewriters) is based on the crucial hypothesis that if the number of individuals who buy a product A in competition with another product B exceeds the number of those who buy B, the probability that successive buyers decide to buy B becomes higher. This model shows how can it happen that a technology may expel from the market a better one, disproving therefore the predictions of the orthodox consumer's theory.

The theory of Ormerod belongs to the same area of thought but takes as a model the behavior of a population of ants. His approach is based on the belief that the behavior of individual ants, their direct influence on the choices of other ants, and the consequences of the interaction between them on the entire anthill, provide a general description – a model – of a wide range of economic and social phenomena. Many of them in fact show the same fundamental properties that characterize the behavior of ants: they are unpredictable in the short period, but in the long period a sort of regularity takes over, giving origin to complex systems, poised at the edge of chaos.

As an outsider I am not in a position of being involved in discussions with experts on the merit of this approach. My task is only to point out that here again, in spite of the enormous differences between the nature of the objects involved in the different fields of investigation, we assist to a confrontation between the same two different ways of looking at changing reality. One is based on the assumption that change is apparent, a mere necessary consequence of simple mechanical principles; while the other one follows from the assumption that the unpredictable emergence of new properties is an essential and irreducible feature of complex objects.

Perhaps J.R. Oppenheimer was right in saying:

These two ways of thinking, the one which is based on time and history, and the one which is based on eternity and timelessness, are two components of man's effort to understand the world in which he lives. Neither is capable of including the other one, nor can they be reduced one to the other, because they are both insufficient to describe everything.

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