COMMITTEE II
Synthesis and Relationships in Culture

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THE ROLE OF MATHEMATICS IN SCIENTIFIC SYNTHESIS AND THE INTERPRETATION OF QUANTUM THEORY

by

Luigi Accardi
Professor of Mathematics
University of Rome II
Rome, ITALY

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1.) Synthesis in science.

The notion of cultural synthesis is a crucial one for everybody who believes that the goal of scientific research is not only to make predictions, to prove theorems, to generate technology, but also to contribute to the creation of a global vision of the world in which the various aspects of Nature, necessarily separated by the various sciences, become again united and harmonized.

The notion of "synthesis" presupposes that of "opposites" - a thesis and an antithesis according to Hegel - or that of "distincts" according to the terminology of the italian philosopher Benedetto Croce. A synthesis occurs when the distincts are coordinated to yield something more than their sum or juxtaposition; when a unity is recognized at a deeper level among a multiplicity of a priori distincts objects or individuals or phenomena.

The history of scientific thought provides many examples of synthesis. We can in fact say that the cornerstones of scientific progress can be recognized by the presence of a synthesis.

Maybe the most famous of all scientific synthesis is Newton's theory of gravitation: the anecdote of the falling apple symbolizes exactly Newton's deep intuition of an underlying unity between the forces which cause an apple to fall and the forces which keep together the solar system and, more generally rule the motion of all the celestial bodies.

Another landmark in scientific thought was Maxwell's unification of electric and magnetic forces: it took more than 2.000

years to recognize the unity underlying the phenomena caused by brushing a piece of amber or by bringing together two magnets.

Boltzmann's thought was at the basis of the synthesis between classical mechanics and thermodynamics. An enormous intellectual courage was required to attempt a deduction of the irreversible laws of thermodynamics from the reversible laws of mechanics. The main ideas of this astonishing synthesis were outlined by Boltzmann, but still nowadays the realization of Boltzmann's program is object of interesting and deep researches.

Our century gave birth to two fundamental scientific synthesis: the distinct notions of space and time, of mass and energy were synthetized by special relativity theory. Geometry and gravitations were synthetized by general relativity (geometro-dynamics, in Wheeler's terminology).

Planck's revolutionary discovery of the discrete nature of energy opened the way to Einstein's discovery of the discrete nature of light and, in the converse direction, to de Broglie discovery of the wave nature of matter. All these apparently contradictory aspects were synthetized in the new quantum theory, which constitutes the deepest level of our present understanding of nature.

My talk will be mainly devoted to this last synthesis. I believe that, as usual in science, a deeper analysis of a particular example of synthesis will provide an insight on the general structure of scientific synthesis. Many aspects of this synthesis are in fact common to much more general situations: the presence of apparently opposite attributes for the same entity like 'discrete" and "continuous" for energy of light; "corpuscular" and "ondulatory" for matter or light. The strictly related traumatic breaking of a well established intuition on some familiar notions (light, matter, ...) and the subsequent necessity of educating a new intuition out on higher levels. The role of mathematics, and more generally of the formal and symbolic thinking in the development of our intuition, i.e. of our way of looking at the experiences concerning the physical world and the world of thought. Also the process through which the scientific synthesis becomes cultural synthesis is well illustrated by the historical development of quantum theory: we see in fact that after the initial discovery the technical development is accompanied by a cultural debate on the interpretation of the new theory which becomes wider and wider (both in audience and horizons) till to involve the deepest problems of the theory of knowledge, episthemology and even psychology and religion.... .

I will try to bring, with my paper, a contribution to this debate. In particular I will try to outline the main conceptual points of it without making use of any mathematical formalism. It is in fact my deep conviction that, in the first place, the main ideas in this debate can be clearly explained without appealing to technicalities, in the second place, that the lack of a clear distinction between the mathematical model and the physical properties or entities which are to be described by that model, has been a source of deprecable confusion in this 60 years old debate.

2.) On the role of mathematics.

Before discussing the specific aspects of quantum theory, I want ot say a few words concerning the role of mathematics in scientific synthesis.

A quick overview on the history of scientific development shows a kind of parallelism between the evolution of physical theories and the creation of new branches of mathematics: astronomy and geometry; the rise of modern physics and the development of calculus; the theory of the electro-magnetic field, of heat conduction, of gravitation, ... and the development of the theory of partial differential equations; Blotzmann's synthesis and the developmento fo probability theory; the new geometries and relativity; the rise of functional analysis (from a synthesis of linear algebra with the theory of integral equations) and quantum mechanics; the studies in logic and cybernetic and the computer era; ... .

In fact every scientific synthesis (an by this I mean more than scientific discovery!) has been accompanied by a development in the mathematical thought. The problem wether developments in mathematics have been motivated by developments in other sciences or, on the contrary, made such developments possible, is somewhat like the problem on who came first between the chicken and the egg, and surely not more interesting. What is much more interesting, instead, is to follow the two basic mechanisms through which man can free himself from prejudices about nature, namely experiment and abstraction. In the following I will give a brief outline of how these two mechanisms have worked in the debate on the foundations of quantum theory.

3.) The debate on the interpretation of quantum theory.

The XXth century will be surely remembered for having given rise to many fundamental scientific and technological achievements which, both in potential good or evil, have no precedents in the history of mankind.

But maybe the XXth century will be also remembered as that in which the physicists have stated that "...the objects do not exist as such when nobody looks at them...".

In the following we will often come back on this statement and on the different nuances of meaning it assumed for different schools of thought, however it can be useful to begin since now to illustrate its meaning with a simple example: immagine you take a glass bead, mince it until it is reduced to a very fine powder, and spread this powder around a large flat. Our commonsense is accustomed to make a distinction between the glass bead and the powder - to consider them two different physical systems. Even if the matter from which the two physical systems are composed is the same (say-the glass molecules), in the case of the bead this matter is localized in a well defined space, while the powder is spread throught the whole appartment which is a much larger space. In this sense we might say that, relatively to the bead, the powder is not well localized. Moreover the bead has a well defined form, which cannot be varied very much if we want to keep the denomination "bead", while to the powder we do not attribute any specific configuration, any form.

The "localization" of the glass bead (i.e. the fact that the matter by which it is composed is localized in a very small space), its form, ... are <u>physical properties</u> of the bead:

if we verify (and this can be done experimentally) that such properties do not sussist, then we have the right to say that the bead "does not exist as such". Thus, if somebody claims that a glass bead in a flat, when nobody is looking at it, becomes a glass powder and spreads itself throughout the flat, he is saying that the glass bead does not exist as such when nobody is looking at it.

If instead of glass beads one considers atomic or sub-atomic particles, then it still makes sense to speak of their special localization (in the sense that the matter by which they are composed is concentrated in a relatively small space) and also in this case the localization is a physical property, i.e. something which can be experimentally varified. thus, as for the glass bead, we can say that anyone who claims that an atomic or sub-atomic particle looses (when nobody is looking at it) this physical property of localization, is in fact saying that the particle does not exist as such when nobody is looking at it.

More generally, we will say that a physical system does not exist as such under a particular situation if, in that situation, it looses some of the specific properties used to characterize it (like the space localization in the case of the glass bead).

With this premise, the above mentioned statement "... the objects do not exist as such when nobody is looking at them..." should be interpreted in the sense that "...the objects loose some of their fundamental physical properties when nobody is looking at them...".

It might seem provocative to attribute such statements just to the physicists, who so much contributed to overcome bad methaphysics and ideological dogmatism and to anchor solidly scientific thought to experimental data and to the continual critical confrontation with the outside world. - Somebody might think that, maybe for love of paradox, I am forcing or exagerating a position which can be found in the literature, or that I am attributing to "the physicists" a point of view which in fact belongs to a small minority (quantitatively and qualitatively) of them.

In order to show that this is not the case, and that the above quoted statement expresses faithfully the convictions of an authoritative majority of physicists let us comment briefly upon some statements which can be easily found in the published literature (from proceedings of scientific conferences, to specialized journal, to popularization books, to phylosophical essays,...).

In his beautiful essay "Physics and Philosophy"(1963) W. Heisenberg, Nobel prize for physics and one of the founders of quantum theory, writes: "... let us consider an atom in a closed box, divided by a wall into two equal parts. In the wall there is a very small hole through which the atom can pass. The atom can then find itself, according to classical logic, either in the left half of the box or in the right one. There is no third possibility "tertium non datur". In quantum theory however we must admit - supposing that we want to use the terms "atom" and "box" - that there exist other possibilities which are strangely mixtures of the two first possibilities. This is necessary in order to explain the results of our experiments....". Further, in the same essay, Heisenberg adds ".... the question wether the atom is in the left or in the right (half of the box) is not decided. But the term "not decided" is in no way equivalent to the term "unknown". "Unknown" would mean that the atom is "really" on the right or on the left, only that we do not know where it is. But "undecided" means a different situation, expressible only with a complementary statement....".

The technical term used to describe the "different situation" mentioned by Heisenberg is superposition. If we think to the fact that the atom is on the right or left side of the box as to two mutually exclusive properties, the term "superposition" describes a mixture between these two situations, that is - a situation in which the electron is virtually in both boxes but actually in no one of them. To use again Heisenberg's words: "... so the physicists became accustomed to consider the electronic orbits not as realities but as a kind of potentia ...".

On the other hand every time one makes an experiment to try and see where the electron actually is, one never finds any experimental track of this "potentia" of this "mixture" of this "different situation" alluded by Heisenberg. The experimental results show that always and invariably the electron is found either entirely on the right half of the box or entirely in the left half.

In other words, these superposition states are not experimentally observable quantities: we are obliged to introduce them in order to reconcile some experimental data with some theoretical deductions, but we do not "see" them directly. On the contrary, whenever we devise an experiment to try and look at these superposition states, they misteriously disappear. Thus, if we really want to insist to think to these superpositions or mixtures as to real ways of being of the electron, real physical states, we must admit that such a "physical state" can occur only when nobody is doing an experiment to decide weither it occurs or not. To translate this abstract statement in terms of Heisenberg's esample above: an electron "looked at" always possesses the physical property of being either in the right or in the left half of the box; an electron "not looked at" does not possess this property.

Another Nobel prize for physics and one of the most illustrious living physicists, R. P. Feynman, in his book "The physical law" (1971), describes an experiment in which a beam of particles (nowadays this experiment has been performed by Rauch, Zeilinger and others,... using neutrons) is projected onto a screen on which two slits (called slit 1 and slit 2) have been done. The particles which pass through these holes are then collected onto a second screen, parallel to the former one. According to Feynman the results of this experiment "... contains all the mysteries of Quantum Mechanics ..." so, following Feynman's analysis" ... let us begin to analyze a proposition which we would have believed reasonable, since these objects (i.e. the particles (N. o. A.)) arrive in single units. Since what arrives is always an integral quantity, in this case an electron, it is obvious to suppose that it always passes either through slit 1 or through slit 2; it seems completely evident that it cannot do nothing else, since we are dealing with a single unit. I want to give a name to this statement. I will call it "proposition A".

<u>Proposition A.</u> An electron either passes through slit n. 1 or through slit n. 2.

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We have already in part discussed what happens with Proposition A.: if it were true that an electron passes either through slit n. 1 or slit n. 2 the total number of arrivals would be the sum of the two contributions, i.e. the total number of electrons arriving (on the second screen (N.of A.)) would be equal to the number of those which pass through slit n. 1 plus those which pass through slit n. 2. Since the effective curve cannot be easily expressed as the sum of two pieces, it is obvious that we must conclude that this proposition is false. If it is not true that the electron either passes through one slit or through the other one, it might be that it divides itself temporarily into two halves or that it makes something similar. Therefore logic tells us that Proposition A is false. Unfortunately, or maybe fortunately, we can check logic with experiment. We must find if it is true or not that the electrons pass either through one or the other slit, or if instead they pass through both slits and split temporarily into two. The only thing we must do is to observe them, and for this we need light. Then we put beyond the slits a source of very intense light. The light is scattered by the electrons, i.e. it rebounds on them, so that if it is strong enough one can see the electrons when they pass. We are then there and look if, when an electron is counted, or an instant before it is counted, one sees a flash beyond the slit 1 or the slit 2, or maybe a kind of half a flash in both points contemporarily. Observing we will understand how it works.

We turn the light on, look and see that every time the detector counts there is a flash either beyond the n. 1 or beyond the n. 2. What we see is that the electron passes hundred per cent, full, through either one or the other, when we look. Here we are then to a paradox!....".

Just as in Heisenberg's box: everytime one looks at an electron, one discovers that it always chooses one and only one of the two possible alternatives but, as Feynman says: "... to conclude that the electron passes through one or the other slit when one doesn't look, is equivalent to do an error in the prediction....".

In Heisenber's example the superposition state meant that the "electron not looked at" could not find itself in one and only one of the two halves of the box; in Feynman's example it means that the "electron not looked at" cannot pass through one and only one of the two slits but, in some sense, it must "pass through both". In both cases the specification "not looked at" for the electron, is essential: all the "electrons looked at" are in one and only one half of the box and pass through one and only one of the slits. No follower of Galileo will ever be able to confute experimentally such a statement, because the statement is built up in such a way that it can be true only in no followers of Galileo tries to verify with an experiment if it is true or not.

Can we agree to call "experimental theory" a theory whose interpretation is based on such statements?

On an italian weekly magazine (l'Espresso, June 12, 1983) T. Regge discussed a popularization of a famous argument due to Einstein-Podolsky-Rosen. Let us quote some particularly illuminating pieces of his analysis."...Let us suppose to put in an urn a white ball and a black ball. I put one of these in my pocket without looking at it, a friend of mine makes the same thing with the other one; we then take planes which fly in opposite directions and, one separated, we observe the colour of the ball. If I find a black ball I am sure that the other one has a white ball, and conversely....".

In this case the alternative is: white ball or black ball. The commonsense would that in my pocket there were either a white ball or a black ball. Here too tertium non datur - Regge too, like Feynman, compares this intuition of the common sense with effectively performed experiments and concludes that if the results of such experiments will be confirmed then we will be obliged to conclude that "... a particle is not such until it is not measured .

In the case of the white and black balls, the intuition says that in my pocket there is always a ball of a well determined colour and that the colour "exists" independently on my observation.

In quantum mechanics however one must renounce to this determinism. The black and the white are the result of a measurement and become real only when this measurement is performed (the underlining is mine, N.d.A.). But the act of measurement disturbs the measured system and it is not possible to separate the subject from the object: the electron and the microscope are a unique system. For these reasons one is cautious in speaking of objective reality in the real world...".

Later on Regge adds: "....if I pick out the ball and measure it black I should say that I have created the black by measuring it, that the black became real only in the instant in which I observe it. It follows that also the white in the pocket of my friend is now real, as a consequence of my measure.

Therefore I have created a reality at distance instantaneously, through the simple measurement of a local attribute. Many people find such kind of consequences unacceptable from the philosophical point of view....".

The problem of the acceptability, from the philosophical point of view of statements such as those quoted above, is of course very interesting and instructive. However in the present paper we will limit ourselves to the discussion of another question, namely:

IS IT TRUE THAT THE STRANGE STATEMENT, ACCORDING TO WHICH THE ACT OF OBSERVATION CREATES SOME PHYSICAL PROPERTIES OF THE OBJECTS, IS A NECESSARY CONSEQUENCE OF THE COMPARISON BETWEEN THEORY AND EXPERIMENTAL DATA?

Should the answer to the above stated question be affirmative, then we could nothing but agree with F.J. Dyson's statement (Turbare l'Universo, Boringhieri 1981, pg. 287): "....there is a famous experiment, originally suggested by Einstein, Podolsky and Rosen in 1935 as an ideal experiment to illustrate the difficulties of quantum theory, which proves that the idea that an electron exists in an objective state, independent on the observer is untenable.... .

.....It is a field (microscopic physics (N.of A.)) in which the dogma of Monod "The cornerstone of the scientific method is the postulate that nature is objective" turns out not to be true..".

We will show that the answer to the above stated question is negative, and this will imply that the statements of Dyson, Feynmann, Heisenberg, Regge, ... quoted above are not necessary consequences of the results of the experiments, but depend in a subtle way on an implicit postulate of a purely mathematical nature - a postulate underlying the usual formulation of classical probability theory. This postulate was derived from the experience of the macroscopic world and is perfectly well suited for this level of description of nature. It is from the illegitimate (and implicit) extrapolation of this postulate to physical situations (concerning the microscopic world) in which it cannot be experimentally checked for reasons of principle (i.e. Heisenberg's indeterminacy principle) that the necessity arose of introducing in physics statements which in principle cannot be verified experimentally (such as, for example, that an electron not looked at looses its localization).

Our goal is to expel from physics statements of this kind, and in no way to assert positions of naive "realism" such as the statement that "particles not looked at maintain the same properties they have when we look at them". In fact such a statement is as much unverifiable in principle as its negation. We simply do not care what a particle does when one does not look at it. But at least, from the point of view discussed here no contradiction between theory and experiments will arise if we postulate that particles "not looked at" behave as particles "looked at".

As we will see in the next section, this is already a considerable step forward with respect to the interpretation accepted by the majority of physicists.

4.) The prejudices which lead to the parodoxes of quantum theory

For lack of space we will only outline the main steps of the reasoning whose conclusion is that it is not necessary to introduce in our description of the natural phenomena such strange notions as "non-locality" "collapse (or reduction) of the wave packet", "non separability", ...

Both the reasoning which lead to such strange conclusions and the critiques to it are best explained by the famous "two slit experiment" which, according to R.P. Feynman contains all the mysteries of quantum mechanics. Let us recall the description of this experiment, already outlined in the preceeding section, in order to fix the notations clearly.

A source S emits particles (say-neutrons) towards a screen S_1 with two slits: 1, 2. The particles are collected on another screen S_2 and one counts the number of particles which fall onto a small region X of the screen S_2.

This number is counted under three different physical conditions: (i) both slits are open; (ii) slit 1 is open and slit 2 is closed; (iii) slit 2 is open and slit 1 is closed. Denoting respectively $N(X)$, $N(X|1)$ and $N(X|2)$ these three numbers; if N is the total number of particles collected on the screen S_2, then we introduce the relative frequencies $P(X) = N(X)/N$; $P(X|1) = N(X|1)$; $P(X|2) = N(X|2)$ and call them respectively: the probability that a particle arrives in X ; the probability that a particle arrives in X having passed through slit 1; the probability that the particle arrives in X having passed through slit 2.

Now let us argue as follows:

1) The particle is localized in space, so it either passes through slit 1 or through slit 2, but cannot pass through "both slits".

2) From step (1) and the distributive law of aristotelean logic we deduce that the particle either arrives at X passing through

1 or arrives at X passing through 2, but not both.

3) Step (2) means that the event of arriving at X through 1 (denote it $X \cap 1$) and the event of arriving at X through 2 (denote it $X \cap 2$) are disjoint and their union is X. Thus by the additivity property of probability we must have

$$P(X) = P(X \cap 1) + P(X \cap 2)$$

4) Now we introduce the elementary definition of conditional probability, which can be found in any textbook:

$$P(X|1) = \frac{P(X \cap 1)}{P(1)} \; ; \qquad P(X|2) = \frac{P(X \cap 2)}{P(2)}$$

where P (1) is the probability that a particle passes through hole 1, and similarly for P (2).

5) From step (3) and step (4) we obtain:

$$P(X) = P(1)P(X|1) + P(2)=(X|2)$$

However the experiments show that, whatever (1) and (2) are, one has: $P(X) \neq P(1)P(X|1) + P(2)P(X|2)$

Since our conclusion (step (5)) is contradicted by the experiments, some of the preceeding steps must be false. Which one?

It is interesting to note that all the various interpretations of quantum theory can be classified according to which of the steps of the reasoning above they consider to be falsified by the experiment.

Now: step (5) is a purely mathematical consequence of the preceeding four. Step (3) - i.e. - the additivity of probability of disjoint events - has been questioned by some authors, but at the moment nobody seems to take this possibility seriously.

The negation of Step (1) characterizes the <u>Copenhagen in-</u>

terpretation: this interpretation gives for granted the validity of all the remaining steps of the reasoning and concludes that the final contradiction should be interpreted as an experimental evidence against the belief that a particle is a physical system localized in space.

The negation of Step (2) characterizes the theories called "quantum logics": these theories interpret the above described contradiction between theory and experience as an experimental evidence against the belief that one can apply the usual aristotelic logic (in particular, the distributive law used in Step (2)) to describe the phenomena which occur at the level of the microscopic world.

The negation of Step (4) characterizes the point of view of quantum probability: according to this theory the contradiction between theory and experiments stems from an unjustified application of a mathematical formula of classical probability theory (i.e. the formula defining the conditional probabilities) to a situation in which this formula cannot be experimentally checked.

When there are three different points of view on one and the same problem, it is useful , in order to avoid dogmatic or emotional positions, to examine them comparatively and look at the advantages and the disadvantages of each one of them.

To this goal let us first remark that, as explained by Feynman (for the Copenhagen interpretation, but the argument applies to the quantum logic interpretation as well), the statement that the particle looses its localization (or that to it we cannot apply the usual aristotelic logic) should be referred exclusively to particles "not looked at" since whenever we effectively perform some experiments, we always see that particles are localized and that they obey the usual aristotelic logic.

Thus both the Copenhagen and the quantum logic interpretation force us to introduce in the theory statements of the form: "...there are some statements about a physical system which are always falsified by direct experiments, but such that, if we do not assume that they are true when no experiment is made to verify them, then we arrive to a contradiction....".

On the contrary, any statements of quantum probability concerns only experimentally measurable quantities (transition probabilities, mean values, correlation functions, ...). According to quantum probability, the prejudice at the root of the apparent contradiction in the two slit experiment is related to the use of a mathematical model rather than another and not to misterious, and in principle undescrivable, "physical properties".

Quantum probability does not pretend to say anything on how objects "not looked at" behave, in particular it does not claim that electrons or neutrons are "particle-like", that they possess a trajectory, ... It only claims that to assume that such statements are true does not lead to a contradiction.

If you accept the Copenhagen interpretation, nevertheless you must accept the use of a new probability calculus, because the inadequacy of the Kolmogorovian model to describe some quantum phenomena is not a matter of interpretation, but follows from the experimental data. While if you accept the quantum probability interpretation you can perfectly do without the assumptions of the Copenhagen interpretation on the behaviour of objects "not looked at".

In this way the metaphysical content of notions such as

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"collapse of the wave packet", "non-locality", "non-separability", "states of physical superposition", (and the related paradoxes) is cut away at its very roots by the quantum probabilistic interpretation.

Let us motivate in more detail this last statement.
States of physical superposition: they arise from the attempt to give a physical meaning to a (perfectly well defined) mathematical formula. From a more intuitive point of view we can explain this notion as follows: recall the two slit experiments described above; according to the Copenhagen interpretation, the electron "not looked at" is not localized in space (it passes through "both holes"); how then to describe the physical state of the electron? The orthodox answer is: the electron is virtually everywhere in space, only the act of measurement causes his materialization here or there with different probabilities. This situation is called a state of physical superposition with respect to the position observable (we stress the term physical superposition to distinguish it from mathematical superposition which is a perfectly well defined notion).

Quantum probability does not need to introduce such a notion (it doesn't need to postulate that an electon "not looked at" passes "through both holes"); the formula of mathematical superposition is deduced from basic and physically meaningful postulates and simply considered as a formula for the composition of probabilities in a non-Kolmogorovian model.

Collapse (or Reduction) of the wave packet: once accepted the notion of "physical superposition", that of "collapse of the wave packet" is a necessary consequence. Since the electron "not looked at" is not localized but spread around in the whole space, and since any electron "looked at" is always found localized in a small region of space, it follows that we create the spatial localization of the electron with the act of measurement. This phenomenon (suitably extended also to observables different from the position observable) is called the "collapse of the wave packet. Since quantum probability doesn't need to introduce the notion of "physical superposition" it can also do without the notion of "collapse of the wave packet". The mathematical formula which describes how the object, which in the mathematical model represents the quantum mechanical state of the system, varies under acquisition of some informations on the system, is simply interpreted as the mathematical operation of conditioning in a non-Kolmogorovian model. This operation of conditioning is familiar in classical probability: for example if we throw a fair die then each number from 1 to 6 has probability 1/6; but if somebody tells us that the outcome has been an even number, then the probability of each number becomes zero (for odd numbers) or 1/3 (for even numbers). What happens in this sudden instantaneous change of the way of evaluating the probabilities is qualitatively of the same kind of what happens in the so-called "collpase of the wave packet". The only different thing is the mathematical formula which, in the two cases, gives a quantitative expression to the change of the probabilities.

For the dies we use the usual formula of classical probability (called Bayes formula), while for microscopic particles we use another formula due essentially to von Neumann. Quantum probability explains the use of these different formulas by distinguishing the case in which acquisition of new information is achieved without destroying previously acquired informations, from the case in which this happens.

Non-locality: the "collapse of the wave packet" is a typically non local phenomenon: the particle "not looked at" is virtually spread all over the space; my operation of measurement is well localized in space (this room, this building, ...) however all the points of the universe know instantaneously that the virtual presence of the particle became actual in my room and this first erases instantaneously this virtual presence from any other point of the space. No matter how far from my room. This phenomenon of instantaneous action at distance is called "non locality".

Some scientists have tried to "slow down" this process; they say: "no measurement is really instantaneous. It takes some time (relaxation time). Therefore also this process of localization is not really instantaneous, but smooth .....". But however long this relaxation time might be I can always choose a point so far from the room of the experiment that in this relaxation time non physical signal can arrive from the room to this point. How will then the virtual presence of the particle in that point be annihilated within the relaxation time of the experiment?

This problem does not arise in quantum probability: my information changes through local interactions (measurements); no instantaneous propagation, no collapses, no non-localities, are required to describe this fact.

Non-separability: this is a sophisticated form of non-locality. The typical situation in which it appears is the one described by Bohm's version of the Einstein-Podolsky-Rosen paradox: two particles are related by a conservation law, for example if a physical magnitude relative to particle 1 (call it S_1) has the value +1 then necessarily the corresponding quantity relative to particle 2 (call it S_2) has the value -1. The two particles are prepared initially in a state in which the observables S_1 and S_2 have not a precise value (i.e. the system formed by the particles 1 and 2 is in a state of physical superposition with respect to the observables S_1 and S_2). The system evolves so that the two particles go far apart (as far as we like). If we measure S_1 and find say, +1, then we force istantaneously S_2 to assiùe tje value -1. But the particle 2 can be as far as we want from particle 1, so far that no signal from particle 1 could reach it in the short time in which the measurement of S_1 is accomplished. How can particle 2 know instantaneously that the quantity S_1 has been measured, in a point of space which can be light years apart, and consequently change the value of S_2 from superposition to a well defined value?

This happens because the particles are in a situation of "non separability" claims the orthodox physicist.

No physical change of S_2 occurs for a measure of S_1, says the quantum probabilist: it is my information which changes. This point of view was previously considered in the literature, but was then discarded on the basis of the critique that the formula through which this change of information was quantitatively described, quantitatively lead to contradictions. Quantum probability theory has recognized that these contradictions arise because people were describing the change of probability due to acquisition of new informattion by means of the classical probabilistic formula. Differently from all previous points of view, quantum probability can prove the necessity of its main statement with the technique of the "statistical invarients": this technique allows, given a set of statistical data (transition probabilities, correlation function, mean values, ...) to decide rigorously if these statistical data can be described within the framworks of a single classical probabilistic model. The relevance of this mathematical technique for the foundational problems of quantum mechanics has been explained with the prototypical example of the two slits experiment: the (implicit) application of a formula of classical probability to a set of statistical data collected from different physical experiments lead to a contradiction. To come out from this contradiction people were lead to postulate that objects "not looked at" have some paradoxical properties. From these paradoxical properties all the interpretational problems of quantum theory arose. Quantum probability theory not only indicates a different way out from such contradictions but, for the first time in the history of the interpretational problems of quantum theory, it proves the necessity of its statement.

That the quantum mechanical formalism was a new probabilistic formalism to perform statistical computations was of course clear since the beginning of quantum theory (Born's statistical interpretation is of 1927!). What was not realized in about 60 years of debate on the foundations of quantum theory, and what constitutes the main contribution of quantum probability to the foundational problem, is that this new probability calculus is the mathematical expression of different probabilistic axioms, in particular of the axioms which describe how our probability evaluations change under the acquisition of new information on the system.

It is very natural that this change of point of view was motivated by quantum theory, in fact it is only with Heisenberg indeterminacy principle that we began to realize that acquisition of new information on a system requires physical interaction with it and hence possible destruction of previously acquired information. The prejudice about the uniqueness of the classical Kolmogorovian model was underlying most of the debate on the foundations of quantum theory. In the last years the existence of a <u>single</u> classical probabilistic model for a given set of statistical data (correlations, transition, probabilities, ...) was even tacitly identified with the existence of a deterministic model for the quantum phenomena (hidden variables theories).

For example, in a new famous paper, Bell remarked that certain correlation functions arising in connection with Bohm's version of the Einstein-Podolsky-Rosen paradox cannot be described within a <u>single</u> probability space. Bell however (and many others) did not realize that such examples were known in the debate on the interpretation of quantum theory, at least since 1927. Bell attributed particular importance to the fact that his example concerned <u>two</u> different particles widely separated in space, and the fact that certain six observables (3 for particle 1, 3 for particle 2) cannot be represented by six random variables (assuming the same values as the observables) in a <u>single</u> probability space, was called by him <u>non-locality</u> (other people say "non-separability").

The quantum probabilistic analysis shows that the old arguments of the Copenhagen school and Bell's argument are based exactly on the same scheme: one shows that certain statistical data cannot be described within a single classical probabilistic model; one (implicitly) postulates that this can happen only if the system we are dealing with has some strange physical property, one then tries to describe this physical property. According to quantum probability theory, there is no priori reason why some statistical data, collected with different (and mutually incompatible - in Heisenberg's or Bohm's sense) experiments should be described within a single classical probabilistic model. This is a property which should be checked case by case using the theory of the statistical invariants. The point of view of classical determinism only requires the existance of a space S (space of the classical states of the system) such that all the observables of the systems can be represented mathematically as functions on S. But nothing in the deterministic point of view requires that a family of statistical data derived from a set of different experiments should be described by a single probability measure (maybe not unique, but this has little importance).

Both the Copenhagen school and Bell's followers make this assumption implicitely. Both do not realize that all the apparent paradoxes are consequence only of this physically unjustified mathematical assumption, and not of strange (because valid only for ojects "not looked at") physical properties.

So the original antithesis of the interpretation of quantum theory, i.e. determinism - indeterminism, has gradually evolved into another antithesis, more precise mathematically hence more restricted phylosophically, concerning the use of classical or non classical probabilistic models in the description of nature. The synthesis - quantum (or more generally - non Kolmogorovian) probability theory - arose form the overcoming of a secular prejudice and opened a new and exciting field of investigation.

The problem of how, with which mechanisms and in which times, the cultural synthesis will become also a social synthesis, i. e. accepted, recognized and effectively used to close the debate on the old problems and to orient it towards the new ones, will intrigue still for a long time the sociologists and the historians of science . I hope that with this paper I offered to them some material for reflection.