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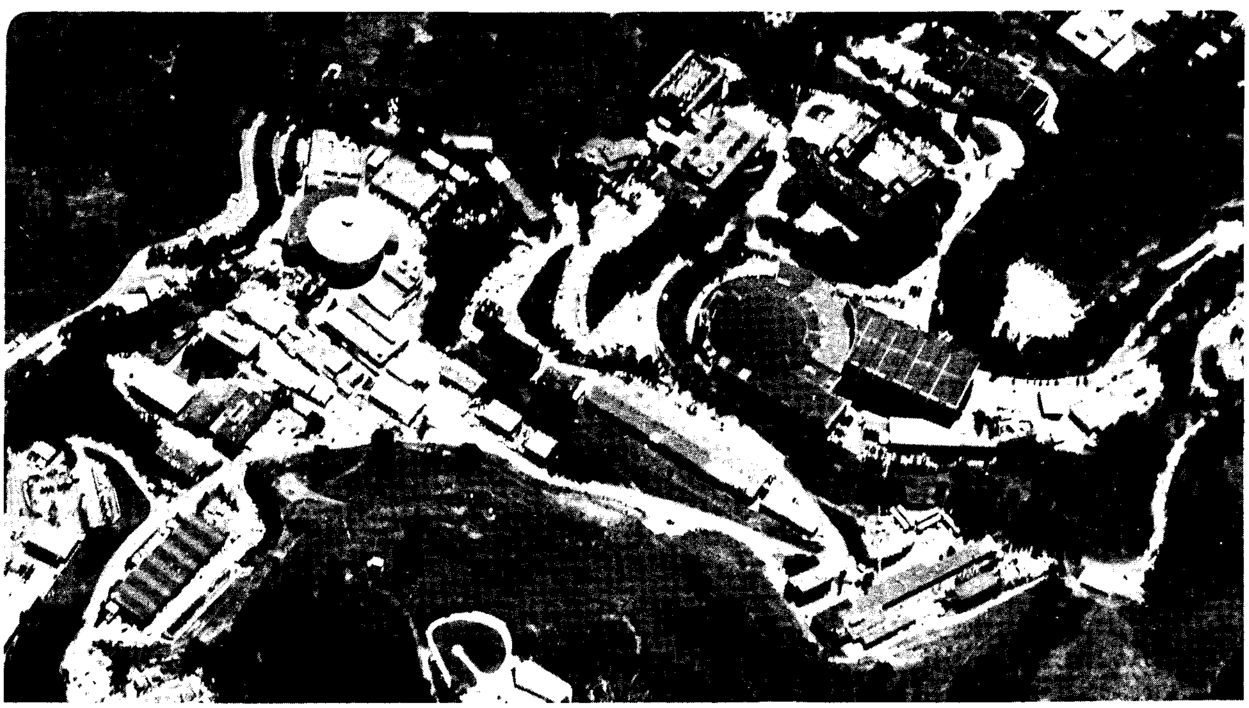

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Transcending Newton's Legacy[1]

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Science can influence our lives in many ways. The influence via technology is evident. But influence through effects on social institutions, such as church and government, can also be important. For example, the purported influence of Newton's idea of "law" upon the U.S. constitution could, in view of the immense influence of government upon our rights and freedoms, and upon our economic environment, be exerting tremendous influence upon our lives. However, more important than than either of these is probably the influence of science upon our idea of what we are; upon our idea of our place in the universe, and our connection to the power that forms it. For our aspirations and values spring, in the end, from our idea of what we are, and nothing is as important in our lives as the character of the ideas that motivate our actions, and the actions of others.

Science was transformed during the twentieth century by three revolutionary developments: the special theory of relativity, the general theory of relativity, and quantum theory. These developments altered not only scientific practice, but also our ideas about the nature of science and the nature of the world itself. I shall discuss here these three developments with regard to both their essential differences from classical Newtonian science, and their potential impact upon the human condition.

Newtonian Science.

Newtonian science must be distinguished from the full thought of Isaac Newton. The former may be characterized by the following three conditions.

1. Absolute Time and Absolute Space. Newton's starting point is the idea of a "true" time and a "true" space. Each is independent of anything external to it, and has an inherent quality of uniformity or homogeneity. These two "absolutes" are contrasted by Newton to their "relative", or "apparent" counterparts, which we can grasp through our senses, and can measure by means of clocks and rulers.

2. Local Ontology. Absolute space is conceived by Newton to be popu-

lated with small bodies or particles, that move with the passage of absolute time.

3. Fixed Laws of Motion. The motions of the particles are governed by "laws". These laws cause the locations and velocities of all particles at *all* times to be determined by the locations and positions of all particles at any *single* time. The world is thus *deterministic*: its condition at one time determines it condition for all time.

These features of Newtonian science give us a picture of the universe called the Mechanical World-View. According to this view the universe consists of nothing but objectively existing particles moving through absolute space in the course of absolute time in a way completely determined by fixed laws of motion.

This picture of the world is mathematical: the objects are described mathematically, by numbers that give the locations and velocities of all the particles. Moreover, the laws that govern these numbers are mathematical. That Newton aspired to the creation of a mathematical picture of Nature is proclaimed by his title: Mathematical Principles of Natural Philosophy.

Three Problems.

Some difficulties with this picture of Nature were evident from the start. I mention three:

(1) Action-at-a-distance

(2) Creation

(3) Freedom

The Problem of Action-at-a-Distance.

The centerpiece of Newton's science is the law of gravity. According to this law, every body in the universe acts instantaneously upon every other one, even though they be separated by astronomical distances. Newton's recognition of a problem with this idea is expressed clearly in his famous assertion: "That one body can act upon another at a distance through the vacuum without the mediation of anything else ... is to me so great an absurdity that I believe no man, who has in philosophical matters a competent faculty of thinking, can ever fall into it"[1].

The ontology set forth in the Principia has, however, nothing to mediate the force of gravity. Newton worked hard to find carrier for gravity compatible with the available empirical evidence, much of which came from his own experiments. Finding in the end nothing that met his standards he declared: "hypothesis non fingo" - I frame no hypothesis.

Two contrasting attitudes toward physical theory can thus be found in Newton's thinking. One attitude reflects his basic overriding commitment to search for truth about Nature. This commitment is massively displayed by his extensive researches into alchemical and theological questions pertaining to the constitution of Nature, by his choice of title mentioned above, and by his careful attention, in the formulation of his principles, to philosophical and ontological details. The second attitude goes with his "hypothesis non fingo". This declaration entails that his theory, as it stood, must, strictly speaking, be construed not as an ontological description of Nature itself, but merely as a codification of connections between measurements. The theory must be viewed as a system of rules that describes how our observations hang together, not as a description of the underlying reality.

These two contrasting attitudes toward physical theories will be the focal point of my discussion of how Newton's ideas fared in the twentieth century. The issue concerns two views of the nature of physical theory. One view holds that basic physical theory ought to provide a description of the real stuff from which the universe is constructed – it should describe the ultimate things-in-themselves. The second view holds that physical theories should deal fundamentally with quantitities that can be measured – they should merely codify the structural features of measurable phenomena.

The Problem of Creation.

The second problem is the problem of creation. Given the Newtonian precepts two questions immediately arise.

1. What fixed the nature of the particles and their laws of interaction?

2. What fixed the initial locations and velocities of the particles in the universe?

Within Newtonian science these two questions are insoluble. Thus from the perspective of the first attitude described above, which holds that basic physical theory should describe the real world, the account provided by Newtonian science is deficient, for it requires something external to the physical world it describes: it needs something to set up the system and fix the undetermined parameters.

From the second point of view, which is that science should merely codify, not explain, this problem of creation might seem to be no problem at all. But the problem is then with the point of view itself, which tends to close off the pursuit of the further knowledge. For, today, within the quantum theoretical framework, physicists are examining theories that purport to answer the first of the questions raised above, just on the basis of self-consistency. Moreover, the second question is moving into science in connection with studies pertaining to the birth of the universe – the big bang. The question is therefore this: To what can science aspire? Can it cope with the problem of creation, or must it remain forever mute on this basic question?

The Problem of Freedom.

Beyond these questions is one far more pressing to man. The mechanistic world-view proclaimed by Newtonian science, and "validated" by its technological success, insists that all creative activity ceased with the birth of the universe. It tells us that we are now living in a "dead" universe that grinds inexorably along a path pre-ordained at the birth of the universe, and held in place by immutable laws of nature. Thus any notion that we can, by our efforts, act to bring into being one state of affairs rather than another is sheer illusion and fantasy. This dreary view is proclaimed in the name of science, and is backed by its authority.

Banished, together with freedom, is any rational notion of human responsibility. For responsibility can be placed only where freedom lies, and according to the precepts of Newtonian science all freedom expired when the universe was born.

I shall return to these questions from the perspective of twentieth century science. But first an essential stepping stone from the ideas of Newton to those of the twentieth century must be described.

Galileo and Lorentz.

The laws of Newton have a simple consequence: given one possible universe, evolving in accordance with Newton's laws, it is possible to construct another in a simple way – just add to every particle in the universe any single common velocity. Then all separations between particles are left unchanged, and, according to Newton's laws, this shifted state of affairs will perpetuate itself through all time. This property is called galilean invariance.

In 1873 James Clark Maxwell proposed a theory of electric and magnetic forces that was wonderfully beautiful and marvelously successful. This theory did for electricity and magnetism what Newton had tried to do for gravity: it explained the forces between charged particles in terms of changes that propagate from point to neighboring point, thus abolishing the need, in electricity and magnetism, for action-at-a-distance. However, the theory of Maxwell was characterized by a certain maximum speed, the velocity of light in vacuum. According to this theory no charged particle could move faster than this maximum speed. Consequently, the property of galilean invariance was lost. However, Maxwell's theory had a substitute, which involved the characteristic maximum speed, the velocity of light. This new property, called Lorentz invariance, was to play a crucial role in what lay ahead.

Absolute Versus Relative in Twentieth Century Science.

The Special Theory of Relativity.

According to Newton's idea of absolute time one can assert that if A and B are two events, each of negligible duration, then either A is earlier than B, or B is earlier than A, or they are simultaneous. The truth of any such assertion, say that "A is earlier than B", is absolute: it does not depend upon anything else.

Consider, however, two such events A and B situated so that nothing can move from either event to the other without traveling faster than light. In this case one cannot determine by direct observation (say the observation of one event from the location of the other) which event occurs earlier than the other. One might expect that such a determination could be achieved by indirect means. However, Einstein showed that if all phenomena in Nature enjoyed the Lorentz invariance property mentioned above then it would be impossible *in principle* to determine from empirical data which of the two events occurred first.

The Lorentz invariance property seemed to hold universally (phenomena associated with gravity excepted, since Newton's theory of gravity needed to be reformulated along the lines of Maxwell's treatment of the electric force). Consequently, Newton's idea of absolute time seemed to bring into physical theory a property that *in principle* could have no correlate in observable phenomena. Einstein therefore proposed that physical theory be based not on absolute time and absolute space, as Newton had proposed, but rather upon a spacetime structure defined by idealized readings of clocks and rulers. The resulting theory is the special theory of relativity. Physicists quickly accepted this idea, which produced economy in notation and conception. Thus they replaced the absolutes of Newton by their relative counterparts.

Quantum Theory.

Quantum theory is another twentieth century development that makes measurements primary. It carries the shift from absolute to relative even further than the special theory of relativity. For, according to the orthodox view of quantum theorists, not only must the underlying spacetime framework be understood in terms of results of possible measurements, but, in fact, the entire mathematical formalism of quantum theory must be interpreted merely as a tool for making predictions about results of measurements.

This view of quantum theory arose from its historical origin and its intrinsic form. But it is sustained by a reason far more compelling than mere "economy": every known ontology that is compatible with the phenomena, as codified by quantum theory, is "grotesque" in some way. Orthodox physicists, reluctant to embrace the grotesque, prefer to adopt a rational stance that separates the predictive mathematical formalism, and the associated scientific practices, from ontological speculations that lack empirical support.

Conversation Between Einstein and Heisenberg.

Werner Heisenberg was the principal creator of the formalism of quantum theory. He has given an account of an interesting encounter with Einstein.[2] He prefaces this account with a brief description of the genesis of quantum theory: he, Heisenberg, reflecting upon Einstein's claim that a physical theory should contain only quantities that can be directly measured, and realizing that orbits of electrons inside atoms cannot be observed, was lead to discover rules that directly connect various measurable quantities pertaining to experiments performed on atomic systems, without ever referring to unobservable orbits.

Early in 1926 Heisenberg described this new quantum theory at a symposium in Berlin attended by Einstein. Later, in private, Einstein objected to the feature that the atomic orbits were left out. For, he argued, the trajectories of electrons in cloud chambers can be observed, so it seems absurd to allow them there but not inside atoms. Heisenberg, citing the nonobservability of orbits inside atoms, pointed out that he was merely following the philosophy that Einstein himself had used. To this Einstein replied: "Perhaps I did use such a philosophy earlier, and even wrote it, but it is nonsense all the same."

Heisenberg was "astonished": Einstein had reversed himself on the idea with which he had revolutionized physics!

To find the probable cause of this "astonishing" reversal it is necessary only to look at what Einstein had done between the 1905 creation of special relativity and the 1925 creation of quantum theory. The special theory holds, as mentioned earlier, only to the extent that the effects of gravity can be ignored. It was necessary to generalize the special theory to the general case by incorporating a reformulation of Newton's theory of gravity along the lines of Maxwell's theory of the electric force.

Einstein undertook this task and in 1915 announced his general theory of relativity. Though this theory was a generalization of the special theory in many ways, it was fundamentally different. The focus was no longer on observers and results of measurements. The theory was about a spacetime structure that exists by itself, governed by its own nature, without relation to anything external. It was about an "absolute" spacetime structure. Einstein was driven during his ten-year search for the general theory not by an effort to codify data. He was driven by demands for rational coherence and by a general principle of equivalence. He sent his work to Born saying that no argument in favor of the theory would be given, since once the theory was understood no such argument would be needed.

Einstein had in this work gone beyond the need for "hypothesis non fingo". He had succeeded in doing what Newton had failed to do. He had discovered a mathematical description of something that could be regarded as Nature itself. The difficulty that defeated Newton, namely the action of gravity at a distance without any carrier, he had resolved by first combining Newton's absolute time and absolute space into an absolute spacetime, next relaxing Newton's demand for uniformity, and finally imposing his mathematical laws in the form of conditions on deviations from uniformity: the presence of matter was represented by departures from uniformity – by distortions of spacetime itself.

An important difference between Einstein's theory and that of Newton is that in Newton's theory time and space are independent of each other, and both are independent of matter. This creates, at least in principle, the possibility of space with nothing in it: an empty arena.

The idea of empty space has puzzled philosphers since antiquity: how can anything be nothing; that is a contradiction in terms. Thus Newton's predecessor Descarte takes extension, hence space, to be something that cannot exist without matter. Newton's contemporary Leibniz takes space to be merely a system of relations. Still, it remains puzzling that so much of the universe can be (almost) empty space if empty space is nothing at all.

Einstein's ontology gives a marvelous solution to this ancient puzzle. Instead of three intrinsically different things – time, space, and matter – whose connection must then, from a logical point of view, be *ad hoc*, hence puzzling, we have only one thing: inhomogenous spacetime.

Considering the direction and achievements of Einstein's general theory of relativity one cannot be surprized that its creator should regard the philosophy of the creator of the special theory of relativity as "nonsense all the same".

The fate in the twentieth century of Newton's two absolutes is then this: the special theory of relativity replaced them by their relative counterparts, but the general theory resurrected them in a combined form that incorporates also the third element of Newton's ontology, matter. However, quantum theory represents a swing from the absolute back to the relative. For, according to the orthodox view, quantum theory must be viewed as codification of connections between measurable, or relative, quantities.

With this background in place I turn now to the question of the impact of twentieth century science upon our ideas about Nature, and upon our ideas about ourselves.

Impact of Quantum Theory Upon the Mechanistic World-View of Newtonian Science.

Quantum theory gives in general only statistical predictions. The question thus arises: Does Nature itself have genuinely stochastic or random elements? Bohr stated the orthodox position: We find, in practice, that even when we prepare an atomic system to the limits of our capabilities there is still a scatter in the results of certain experiments. Quantum theory gives predictions with a matching irreducible scatter. Thus the statistical character of the theory matches the statistical character of the facts. To say more than this is empirically unsupported speculation: quantum theory says nothing about determinism in Nature.

Quantum theory successfully describes and predicts phenomena on the basis of a mathematical description of atoms. Can we conclude that the world is built of atoms?

If one looks at the mathematical representation of these atoms one finds entities that must, according to the orthodox view, be interpreted *only* as parts of a computation of expectations pertaining to results of measurements. Thus the ontological foundation is shifted from the level of the atoms to the level of the devices that record these results, or perhaps even to the level of the observers who use these results to make computations. But the devices and observers are assumed to be built from atoms. So the ontological basis swings back to the atoms, etc.

These examples illustrate the difficulty in trying to draw ontological conclusions from a theory that must be interpreted merely as a tool for making predictions about connections between measurements.

Quantum Theory and Reality.

It is clear to everyone that we cannot pass with certainty from knowledge about the structure of phenomena to knowledge about the structure of the underlying reality. Accordingly, the orthodox interpretation of quantum theory tries to isolate, as far as possible, the mathematical formalism, and the scientific practices associated with it, from more speculative activities: it tries to separate "science" from "natural philosophy". Science is concerned with measurable quantities, and with theoretical structures that codify the observable and testable connections between them. Natural philosophy concerns the conclusions that might reasonably be drawn about the form of the underlying reality on the basis of the evidence provided by science.

The fact that Bohr and Heisenberg adhered to the view that the mathematical formalism of quantum theory should be viewed, strictly speaking, merely as a tool for making predictions pertaining to results of measurements in no way implies that they had no interest in the implications that quantum theory has in the realm of natural philosophy. In fact, each in his own way tried to draw from the data provided by quantum theory insights into the nature of the world that lies behind the phenomena.

Heisenberg's Ontology.

Heisenberg in his book *Physics and Philosophy* in the chapter on the Copenhagen interpretation actually sets forth an ontology[3]. He begins with the words "*If* we want to describe what happens in an atomic event ... ". He then goes on to describe an ontology in which the actual world is formed by "actual events", which occur only at the level of the macroscopic devices. But the objective world contains also something else. It contains "objective potentia". These "objective potentia" are objective tendencies for the actual events to occur. They are associated with the mathematical probabilities that occur in quantum theory.

This ontological substructure gives nothing testable. So it is not "science". But it gives us an informal way of "understanding" quantum theory. It gives us an idea of what is actually going on.

This ontology described by Heisenberg is not the only ontology compatible with the predictions of quantum theory. But it can be said to be the "most orthodox" ontology. Most quantum physicists probably think about quantum phenomena informally in these terms: the quantum probability functions corresponds somehow to the *tendency* for the detector to register a particle, or the *tendency* for a grain in a photographic plate to register the absorption of a photon. The actual things occur only at the macroscopic level.

Heisenberg's ontology cannot be deduced from the phenomena, and is therefore speculative, and to be distinguished from science. However, I do not think it unreasonable to consider it seriously. All creation is certainly not simply a collection of measurements floating on nothing else, even though measurements are of particular interest in science, and are the source of our most precise information about the world.

The reason it is interesting to consider ontologies suggested by the structure of phenomena as codified by quantum theory, and compatible with this structure, is that the conditions thus imposed on ontologies are so restrictive: there is no known ontology that is compatible with the conditions on phenomena imposed by quantum theory that is not "grotesque" in the minds of conservative thinkers. This means that quantum theory has shown us that the world is not at all like what we had previously imagined it to be. It is not at all like the idea of it set forth in the mechanical world-view, formerly promulgated in the name of science, and still largely dominating the prevailing idea of what science tells us. So any curious person must naturally be led to ask: What idea of the world *is* compatible with the data provided by science?

World-View Arising From Heisenberg's Ontology.

Heisenberg's ontology is the most-orthodox, and, in my opinion, the most reasonable, of the known ontologies that are compatible with the predictions of quantum theory. In the remainder of this article I shall describe the principal features of the picture of Nature that arises from this quantum ontology.

1. The World is Nonlocal.

Macroscopically separated parts of the universe are linked together in a way that involves strong faster-than-light connections that do not fall off with increasing spatial separation. This nonlocal aspect is the "grotesque" feature of this ontology that makes it unacceptable to conservative thought.

2. Creation is Distributed Over All Time.

In the quantum ontology the objective potentia are represented by the quantum probability function. At each stage the quantum potentia give tendencies for the next actual event. The occurrence of this next actual event is represented by a "collapse" of the potentia to a new form. The interplay of the Heisenberg uncertainty relations and the Heisenberg equations of motion is such that, even though each successive event effectively closes off certain possibilities, by making fixed and settled things that had formerly been unfixed, still, each event creates new potentialities and possibilities. Consequently, the process of fixing the unspecified degrees of freedom, which in classical physics occurs all at once, at the creation of the universe, is, in the quantum ontology, by virtue of its mathematical structure, a process that can never close off the possibility of its further action. Thus in the quantum ontology, the creative process, in which things formerly unfixed become fixed and settled, does not expire at the birth of the universe, but extends rather over all time.

3. Two Kinds of Time.

The quantum ontology has two different times. The first is Einstein Time, which joins with space to form Einstein's spacetime. The second is Process Time. I shall now explain the difference.

The "numbers" that appeared in Newton's theory, and which described the positions and velocities of the particles, are replaced in quantum theory "operators", which evolve in accordance with equations, called Heisenberg's equations of motion. The evolution of the quantum operators in accordance with Heisenberg's equations of motion is evolution in Einstein time. This evolution generates an association of operators with spacetime points: every spacetime point, from the infinite past to the to the infinite future, is associated with a *fixed* set of operators.

The spacetime structure just described is a structure of quantum operators. To obtain the potentia one must take these operators in conjunction with something called the Heisenberg state vector. The Heisenberg state vector does not depend on spacetime: it refers to all of spacetime. But it combines with the operators associated with any spacetime point to produce numerical potentia associated with that spacetime point.

Each actual event is associated with a "quantum jump" of the Heisenberg state vector. Thus each actual event induces a sudden jump in the potentia. This jump occurs at every spacetime point.

The sequence of quantum jumps defines a time that is different from Einstein time. It is called Process Time. Evolution in process time generates change or evolution of the "actual", whereas evolution in Einstein time generates the evolution of the "potentia". Thus the determinanistic laws of evolution are not binding on our future, for they determine the evolution of the potentialities, not the actual events themselves.

4. Meaning in the Quantum Universe.

The creative process is represented in the quantum ontology by the sequence of jumps in the quantum potentia. These potentia are objective tendencies, which tend to make the statistical predictions of quantum theory hold under appropriate conditions. But the question arises: What determines the actual course of events? That is, what determines, in a given actual instance, whether things will be fixed in one way or another? Heisenberg's ontology leaves that crucial question unanswered. Hence the ontology, as presently understood, is incomplete.

At first, it might seem that, in any case, the choice of what actually happens is either deterministically fixed by what has gone before, or has an element of true randomness or wildness. In either case, the ontology would appear to provide no possibility for a meaningful universe: either we would have simply a new determinism, which would render the universe just as "dead", and devoid of possible meaning, as the world of Newtonian mechanics, or there would be an element of randomness, which could hardly add meaning. Thus we are apparently still trapped between the two horns, determinism or randomness, of the usual dilemma of the impossibility of a meaningful universe.

To have meaning a choice must have intentionality: it must exist in conjunction with an image of the future that it acts to block or bring into being. Any choice that does not refer in this way to the future is a meaningless choice.

In the Newtonian picture the future does not exist in the present, and hence it cannot enter into any present event, or choice. Moreover, the future cannot be changed by any event or choice.

In the quantum ontology the future does exist objectively in the actual present, albeit as potentia. Thus the future can enter into the present event. This event can, moreover, by altering the potentia for the future events, effectively block or bring into being a chosen state of affairs. In this sense a quantum event can have intentionality and meaning.

5. Man in the Quantum Universe.

The role of man in the universe is tied to the mind-body problem. From the perspective of the quantum ontology the brain is a macroscopic system similar to a measuring device. The function of the brain is to organize input, and then make a decision that initiates an appropriate action. According to the brain-device analogy this decision is represented as a quantum jump. Just as in the case of a measuring device, this quantum jump is a macroscopic event: the whole brain, or some macroscopic part of it, is involved.

The problem of understanding, within the framework provided by classical physics, the connection between consciousness and the physics of the brain has been described in some quotations cited by William James:

"The passage from the physics of the brain to the corresponding facts of consciousness is unthinkable. Granted that a definite thought and a definite molecular action in the brain occur simultaneously; we do not possess the intellectual organ, nor apparently any rudiment of the organ, which would enable us to pass, by a process of reasoning, from one to the other." (Tyndall).

Or

"Suppose it to have become quite clear that a shock in consciousness and a molecular action are the subjective and objective faces of the same thing; we continue utterly incapable of uniting the two, so as to conceive that reality of which they are the opposite faces". (Spencer).

The quantum ontology has an analog of the classical motions of molecules moving in accordance with Newton's laws; it is the evolution of the corresponding quantum operators in accordance with Heisenberg's equations. However, the quantum ontology has also something else, which has no counterpart or analog in classical physics: the actual event.

Within the quantum ontology the conscious event and the physical event can be naturally understood as the psychological and physical faces of the same event, namely the event of selecting and initiating a course of action. On the psychological side there is the felt or conscious event of selecting and initiating this action, and on the physical side there is the physical collapse of the potentia, which selects and initiates this action: the physical brain, as represented in quantum mechanics, collapses to a state in which the instructions that inititate the particular course of action are actualized. The connection between these two events is not an *ad hoc* and arbitrary identification of things as totally disparate as, on the one hand, a motion of billions of separate molecules, and, on the other hand, a unified conscious act. It is, rather, the association and identification of the felt event with the physical event that represents, within the quantum ontology, exactly the change that is felt. In this way conscious events become special instances of the actual events that, according to the quantum ontology, form the fabric of the entire actual universe.

Conclusion.

Quantum theory does not *entail* any specific ontology, and it is unreasonable to expect that it should. However, the "most-orthodox", and, I believe, the most reasonable, of all known ontologies compatible with the data provided by quantum theory is Heisenberg's quantum ontology. The chief features of the world that flow naturally from this ontology are:

1. It is nonlocal: there is some sort of nonseparability of spatially separated parts of the universe.

2. It is nondead: the fixing of previously unsettled matters is a continuing process; creativity did not expire with the birth of the universe.

3. It could be complete: no aspect of reality not represented within the quantum ontology seems necessarily required.

4. It allows meaning: choices can have intentionality, hence meaning.

In every one of these essential aspects the world-view provided by the quantum ontology is the reverse of the one provided by pre-twentieth century science. Consequently, modern science provides man with a vision of himself that is altogether different from, and far more inspirational and philosophically fertile then, the one proclaimed in the name of Newtonian science. No longer is he reduced to a cog in a giant machine, an impotent witness to a pre-ordained fate in some senseless charade. Rather, he appears, most naturally, within the framework of present-day science, as an aspect of a fundamentally nonseparable universe that is creation itself, both as noun and verb, a creative process that unites in an intelligible way the mental and physical aspects of Nature, and is moreover endowed in principle with the capacity to suffuse its evolving form with meaning.

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