The Crisis of Intelligibility in Physics and the Prospects of a New Form of Scientific Rationality

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1. G. H. von Wright and the crises of reason and intelligibility

The Finnish philosopher Georg Henrik von Wright's (1916-2003) book *Vetenskapen och förnuftet – ett försök till orientering* (*Science and reason – an attempt to orientation*), first published in 1986, gave rise to an intense debate in both Finland and Sweden about the pros and cons of science and technology. The book was an expanded version of a paper "Images of science and forms of rationality" which he had delivered in Colmar in April 1985, at a European Science Foundation colloquium (von Wright 1989). The book had two underlying motivations. One of these was von Wright's aspiration to understand the basic features of the world-view that modern science provides us with. Another was his desire to evaluate the effects that science has had upon our lives, through technology and the industrial form of production. He describes this kind of exploration as follows:

> It is becoming increasingly obvious … that the transformations of life effected by science and technology are not exclusively beneficial. … These worries … have challenged reflective minds to question the impact of scientific technology on life, and therewith also the value of the type of rationality which science represents." (von Wright 1989, 11).

The adverse effects of science and technology are well known – they include pollution, overpopulation, alienation and stress, as well as the threat of nuclear war. Von Wright characterizes the situation as a *crisis of reason* that, for one thing, expresses itself in various anti-rationalist protests and an increased interest in magic, the supernatural and various "wisdom doctrines" based on Eastern religion, sometimes relying on recent scientific advances. Another aspect of the crisis is that intellectuals have felt the need to explore the nature of scientific rationality, which has resulted in a rational debate about rationality. It could be the case that science and technology are neutral and that the problem is merely the way human beings use them. But it might also be the case that there is something about the very nature of the prevailing scientific rationality which makes it especially prone to bring about the adverse effects of science and technology.

Von Wright notes that a main contribution to this debate has been Adorno and Horkheimer's notion of the "dialectics of the Enlightenment", according to which the prevailing kind of rationality involves above all the use of means to achieve various ends. It is an instrumental, technical and goal-oriented rationality that enables a better efficiency in the production of goods and in the organization of services. But such technical rationality is helpless when it comes to finding and articulating the values that legitimate the aims. (von Wright 1986, 17-18).

Habermas proposed that there could be a different, communicative rationality that is based on language and our ability to exchange thoughts freely. However, von Wright did not think that Habermas's approach could tackle the inevitable course of the "negative dialectic" of progress and enlightenment. Instead, he felt that we should explore the deep relationship that exists between the form of the scientific rationality of a given age and the nature of the scientific world-view of that age. But this requires that we understand the basic features of the relevant scientific world-views. Thus, a considerable part of *Science and reason* is dedicated to an attempt to explicate the development of scientific word-views from ancient Greek science to the present time.

Von Wright notes that during the transition from the Middle Ages to the Modern era great changes took place in our view of the structure of the universe and the laws that determine the course of natural processes. A new world-view was born which during many centuries was to dominate people's view of the world and of their possibilities to carry out their lives. He says that this world-view was based upon certain vague ideas about the *comprehensibility* or *intelligibility* of reality. Over the centuries, leading philosophers and scientists made an attempt to articulate these ideas in more exact terms. To put it in general terms, von Wright says that the world-view that was being constructed was *deterministic* and *mechanistic*. (Ibid, 9-10).

He then points out that the foundations of this mechanistic-deterministic world-view were shaken and partly deteriorated during the 20th century. This process began with a crisis in the conceptual framework of physics that is still going on. He calls this the *crisis of intelligibility*. He adds that certain developments in biology (e.g. ethology, ecology and the theory of evolution) have contributed to the transformation. The mechanistic patterns of thought have become less dominant and have given room for holistic ways of thinking. (Ibid, 10). However, he notes that these new ways of thinking do not yet amount to a coherent, commonly accepted world-view, comparable to the old mechanistic-deterministic one.

Von Wright's main concern is to try to understand how science, via technology, has influenced the living conditions of humanity. He says that this can also been seen an attempt to understand one's own time, adding that to understand the present involves tracking down and interpreting the tendencies that point towards the future:

> It is about getting a grip on the question "Where are we heading for?" The idea is not to predict how the future turns out to *be*, but rather how it *may* turn out to be, if one projects the trends that are salient in the present. The trends can be broken and the very insight into them can become a force that contributes to the change. (Ibid, 11-12).

This underlines the potentially important role that philosophy may have in society. For von Wright philosophy is not merely an intellectual exercise that is irrelevant to the surrounding world; on the contrary he implies that philosophical insight may awaken humanity to become better aware of potential disasters it is heading towards, and even change its course.

Von Wright further notes that his attempts to orient himself in the present, with the future in view, have always searched for starting points in the past. Not only has he been seeking in the past the source of the forces that are now driving the development, he has also tried to discover alternatives to our own form of life (as an example, he characterizes ancient Greek science as a "rational search for the reasonable", in contrast to our present more technically oriented science). For him such an approach is justified primarily because it might help us to understand ourselves better. (Ibid, 12).

Von Wright emphasizes that his work is an *attempt* toward orientation. He understands those who might think that the attempt has failed. He himself has found "the world-view of science" to be fragmented and confused, and he does not want to take a stand on the question of whether the impact of technology upon our lives has been more negative than positive. He thinks that perhaps the best result that an attempt to orient oneself can give is a strengthened critical and skeptical attitude towards reality. (Ibid, 12-13).

While von Wright is very cautious and somewhat pessimistic regarding his "attempt", he also saw some signs of hope. We already saw above that he thought that an insight into present trends might contribute to changing them.

But he also felt there was some reason for optimism in the holistic ways of thinking that have emerged in 20th century physics and biology:

> …it is interesting to note the similarity of trends in microphysics … and macrobiology … towards new ideals of scientific intelligibility. … Would such a holistic world-view, if it were to emerge, represent a new form of rationality? Perhaps in the sense that it would have a less close tie to the goal-directed, managerial rationality of control and prediction. Its technical pay-off would presumably be smaller than that of science of Bacon and Descartes. But it may instead encourage a shift in the view of the man-nature relationship from an idea of *domination* to one of *co-evolution* – and this may be to the advantage of the adaptation of industrial society to the biological conditions of its survival. (von Wright 1989, 24).

I find von Wright's attempt highly relevant today, as it is clear that humanity has not been able to solve the kinds of problems that he drew attention to. The list of most salient problems may perhaps have changed somewhat in the thirty years since the publication of *Science and reason*, as we now worry about things like global warming, terrorism, the Syrian crisis, many other conflicts and the associated refugee problems, the new tension between Russia and the rest of Europe, and various economical crises. Yet we seem to be quite helpless regarding how to approach the root of such problems that often involve science and technology in subtle ways. Von Wright proposed that the prevailing goal-directed scientific rationality (and its underlying dualistic and mechanistic-deterministic world view) is likely to be an important contributing factor behind many of our problems. At the same time he speculated that science itself might hold a key to their solution in the sense that certain new, more holistic developments in science may facilitate a transformation of scientific rationality into a more harmonious direction.

In the light of the above it is understandable that a major part of *Science and reason* is a description of the development of the Western scientific world-view, focusing on those features that are relevant to shaping the form of scientific rationality. In particular, von Wright brings out the main features of the mechanistic-deterministic world-view of the 16th and 17th centuries, making clear how some of its features naturally enable a goal-oriented, technical rationality. But he also shows how developments in quantum physics radically violated many of the basic principles of this world-view in the early 20th century, creating a crisis of intelligibility. The key question for him is whether a more harmonious form of scientific rationality could arise from the holistic new categories that seem to be required to make sense of the new developments in physics and biology.

In this paper I will revisit von Wright's discussion. I will first summarize his overview of the mechanistic world-view (sections 2 and 3). I will then describe – often in more detail than von Wright himself - the developments in quantum physics which challenged the mechanistic world-view (section 4). I will next consider, in the light of von Wright's discussion, one of the key attempts to resolve the crisis of intelligibility in physics, namely David Bohm's "hidden variable" or "ontological" interpretation of quantum theory" (section 5). Finally, I will briefly consider von Wright's idea that a new form of scientific rationality and world-view, emerging from physics and biology, might help to meet the problems of our times. As an example of an attempt toward this direction I will mention Bohm's work on communication and a new form of dialogue (section 6).

2. The intelligibility of nature as the rational foundation of science

As we mentioned above, von Wright proposed that there might something about the prevailing form of scientific rationality (and its underlying scientific world-view) that plays a role in bringing about the adverse effects of science and technology. This led him to examine various forms of rationality, such as the goal-directed use of reason involved in the early development of agriculture; the rational search for the reasonable in ancient Greek science; the "magical science" of Middle Ages Arabic culture that in its own way aimed to control and master the forces of nature; the dualistic, mechanistic-deterministic and experimental rationality that arose in the scientific revolution of the 16th and 17th centuries; the technological and managerial means-ends rationality that became dominant with the industrial revolution; and finally, the new kind of holistic rationality that might arise if we manage to make sense of the new phenomena revealed in modern physics and biology. One of von Wright's central focuses in this discussion is intelligibility:

> The mental attitude underlying Greek science and speculation is a belief that the human mind is capable, on its own, of deciphering the *logos* of things – just as the Renaissance pioneers of modern science were convinced that 'the book of nature' lay open to be read and understood by human beings. One could call this a belief in the *intelligibility* of the natural order of things. It is … the common rational foundation of anything which is properly called 'science', whether in the Greek or in the Western sense. (von Wright 1989, 12).

The above helps to understand why it was so shocking to the entire scientific enterprise when physics encountered the mysterious relativistic and quantum phenomena in the early 20th century. For if von Wright is correct, such a crisis of intelligibility in fundamental physics shook the very rational foundations of science as this has been traditionally understood.

To bring out the nature of intelligibility characteristic of Western science, von Wright discusses in some detail the scientific revolution of the sixteenth and the seventeenth centuries, which amounted to a creation of a new world-picture. This was based on the breakthrough of heliocentric astronomy, great advances in mathematics and the acquisition of an entirely new conceptual framework for mechanics (von Wright 1986, 15). He is particularly concerned with the underlying methodology and the *new demands of intelligibility* of the new science, and with this concern in mind presents some basic features of this new way of thinking, which we will briefly report in the following.

The first of these has to with *a new view of the relationship between human beings and nature* that can also be called a *new conception of nature*. The basic idea is that nature is object and a human being is subject. A human being faces nature partly as a detached observer and partly as a manipulator. Von Wright characterizes this as a *dualistic* conception of reality, with roots not only in Descartes and some of his contemporaries but also in a long tradition before them. For one thing, the objectification of nature led to a sharp distinction between facts and values. Unlike with the ancient Greek science, it was no longer thought to be possible to find values through studying the order of nature. (Ibid, 45).

Von Wright notes that a common feature of both ancient and modern science is the conception of nature as *lawful order*. In the course of the scientific revolution this conception became *strictly deterministic* and *mechanistic*. Determinism here amounted to a belief that everything that happens has a cause in something that has happened earlier and can be predicted if one knows the law according to which the cause operates. To say that this determinism is mechanistic means that all natural processes can in the end be reduced to the motion of bodies. This mechanistic determinism gave rise to the problem of freedom and determinism: if all movements of the body are governed by the laws of nature, how then could the individual with her free will actively interfere in the course of physical processes? Connected to the Cartesian conception of reality there is, of course, also the general mind-body problem concerning how the body and the mind are related to each other. (ibid, 46-7).

Von Wright moves on to discuss another significant feature of the way of thinking advocated by the new science, namely the relation of a whole to its parts. The basic idea in this regard is that material bodies and natural processes can be analysed or divided into elementary component parts, whose properties and manner of influence determine the whole. The whole can be grasped on the basis of the parts, but the reverse does not hold, i.e. one cannot grasp the parts on the basis of the whole. The wholes that can be understood in this way are called meristic or mereological. A meristic view of the relation between the whole and the parts is also called atomistic. The division into component parts is analysis, while the construction of the whole from the parts is synthesis. (Ibid, 48).

Von Wright notes that the new mathematical physics came to be the paradigmatic example of a mechanistic-deterministic and atomistic-meristic science. This example has been an important normative factor for the development of not only the natural sciences but also the social sciences and humanities, such as Comte's sociology and the classical associationist psychology. (Ibid, 49). He also notes that the opposite of a meristic methodology is a holistic one. To adopt a holistic view of a whole (a system, a totality) is to grasp the properties and way of functioning of the parts in terms of laws that apply to the whole. The whole, as it were, is prior to the parts. It is interesting to note here that some contemporary social scientists, such as Alexander Wendt (2015), are today making use of the holistic features of quantum theory as they are trying to develop a more holistic framework for the social sciences.

The third main feature of the rationality of the new science was the role of experiment in the endeavor of trying to understand nature. This required that one adopt a *manipulative* approach to nature. The object of study is isolated from the environment and one tries to control and vary the factors that are assumed to influence the outcome of the experiment. The idea is that experiments ought to be repeatable and that one can *predict* and *control* the results of one's intervention. Such manipulative approach was foreign to ancient Greek science where one typically respected and studied the natural course of events (ibid, 50-1).

3. Intelligibility vs. mathematical precision in classical physics

Von Wright notes that already early on it became doubtful whether the new physics of Galileo et al. could satisfy all criteria of intelligibility that are demanded by the very nature of scientific rationality (von Wright 1986, 88). According to him the most passionate effort toward clarity and concrete comprehensibility in the history of scientific literature is Descartes' *Principia philosophiae* (1644); von Wright sees it as a most remarkable attempt toward an explanation of nature. He notes that in his search for intelligibility Descartes was led to speculate how things might happen in levels and contexts that in his time were beyond experimentation and observation. Descartes made no use of the mathematical models he himself had developed; his system did not make predictions that could have been tested; and it gave rise to no technical applications. Von Wright then notes with great insight that Descartes's "failure" raises the question of whether mathematical precision in the description of nature can be fully reconciled with reasonable demands of rational comprehensibility. (Ibid, 88-9). As we will see later, this question becomes particularly relevant in the context of quantum theory, where we have a mathematics that allows for prediction and control, but where it has traditionally been seen as very difficult, if not impossible, to provide an intelligible physical description of physical processes. For example, some physicists have tried to explain quantum processes in terms of a sub-quantum fluid, which can be seen as attempt to satisfy Cartesian criteria of intelligibility in quantum theory. In recent years this kind of approach has received new attention via Couder's "bouncing droplet" model, a classical system that can in a truly fascinating way reproduce some quantum behavior (Couder and Fort 2006). However, it is important to bear in mind that this model has serious limitations and cannot reproduce some important quantum phenomena such as non-locality and aspects of many-body behavior.

Let us return to consider the problems of intelligibility in classical physics. Most notably, Descartes could only comprehend an influence that is transmitted via a material medium: there must be a direct contact between things that influence each other. Newton's law of gravitation was not consistent with this requirement, as it postulated action at a distance. Von Wright points out that such an influence would have been totally incomprehensible for Descartes – a relapse into an intellectual "Middle Ages barbarism" that Descartes thought he had eliminated (Ibid, 89).

We might note here that the Newtonian action at a distance was, however, not a big problem for the *consistency* of classical physics. When action at a distance - or non-locality - reappears in quantum theory in the 1930s things are different, however. This is because the special theory of relativity holds that signals cannot be transmitted faster than the speed of light. While it is usually thought that one cannot send signals via non-local quantum influences, there is nevertheless a serious tension between relativity and quantum non-locality (for an interesting recent attempt to reconcile the problem, see Walleczek and Grössing 2016). We will discuss quantum non-locality in more detail below.

Another difficulty for thought had to do with the two rival theories about the nature of light that arose in the late 17th century. According to Newton light was made of particles while Huyghens proposed that light was a form of wave motion in a medium that was called the lumineferous ether. In the early 19th century the experiments by Young and Fresnel demonstrated that light had wave properties such as diffraction and interference, and thus Huyghens' theory was thought to have won. However, the ether hypothesis in its classical form was strongly challenged by the Michelson-Morley experiment in the later 19th century. Von Wright notes that with the failure of the ether hypothesis the ideals of comprehensibility of the new science had entered into a danger zone. The classical era of physics was coming toward its end and physics was at the edge of something essentially new. A crisis of intelligibility was soon to erupt. The transition to a new era was marked by what von Wright considers to be two of the greatest achievements in the history of science: the birth of the theory of relativity and quantum theory. (Ibid, 90-1).

4. Quantum theory and the crisis of intelligibility

Let us focus on quantum theory (here we will go into some more detail than von Wright in his review in *Science and reason*). We noted above that it had been established by Young's interference experiments that light has a wave nature. However, to explain the photoelectric effect (in which light transmits energy to matter) Einstein was led to postulate in 1905 that light consists of small particle-like packets or quanta of energy, photons. This did not, however, mean that the wave nature of light that had been experimentally detected was given up. On the contrary, the energy of a "particle" of light was given by Einstein's famous equation $E = hf$, where h is Planck's constant and f is the frequency of the light. Thus, the energy of a *particle* of light depends on the frequency of the *wave aspect* of the same light. Light thus has *both* wave and particle properties, and this somewhat paradoxical feature is called wave-particle duality. For something to be both a particle and a wave at a same time is thought to be paradoxical, because traditionally in physics wave and particle were thought to be mutually exclusive categories: a wave is typically spread out in space, while a particle is localized. Something is either a wave or a particle, but not both.

In the meantime Niels Bohr was working on the atomic structure of matter and came up with a model where the atom was visualized as a miniature solar system, where electrons go around a nucleus, somewhat like the planets go around the sun. To explain the atomic spectra (the discrete frequencies of light emitted by a gas of, say, hydrogen), Bohr postulated that only certain discrete energy levels were possible for the electrons, and also that there was a lowest level, thus explaining the stability of matter. The electron could then make discrete "quantum jumps" from one allowed energy level to another. When it moved from a state of higher to a lower energy, it emitted one quantum of light with a frequency $E = hf$. And in order to jump to a higher level of energy it needed to absorb a quantum of a suitable energy. However, Bohr was not able to explain *why* the discrete energy levels and the lowest level existed; he just postulated them in order for the model to predict the observed results.

An important further step in the development of quantum theory was taken by Louis de Broglie, who was inspired by the notion of symmetry in his research. If electromagnetic radiation (such as light) has both wave and particle properties, could it be the case that matter, too, exhibits these two properties? Thus, de Broglie postulated in 1924 boldly that a material particle such as an electron is associated with a wave property. Such a wave-property of electrons was soon detected in Davisson and Germer's experiment in 1927, where they observed wave-like interference patterns produced by electrons. De Broglie's idea could also be used to better explain some puzzling features of Bohr's early atomic model. It was known already in classical physics that waves in enclosures vibrate in discrete frequencies (e.g. the harmonic overtones of a vibrating guitar string). If an electron has a wave associated with it, and if such an electron wave is "enclosed" within an atom, then it would be natural for it to vibrate with discrete frequencies, giving rise to the observed discrete energy levels for the electron (if we also assume that the Einstein equation $E = hf$ holds for electron waves).

Von Wright raises the question of whether the apparently mutually exclusive wave and particle pictures of matter and energy imply that there is a *contradiction* in the conceptual structure of physics. He notes that the question has not yet been answered, but refers to Bohr's notion of complementarity as an attempt to reconcile the wave and particle pictures. Notice that when we say that two pictures are "complementary" in Bohr's sense, this cannot be understood in the sense of two parts of a single picture. Rather, we have here two *incompatible* pictures that, however, both give information about the object. Bohr (1949) says that "…only the totality of the phenomena exhausts the possible information about the objects". But this totality includes mutually exclusive phenomena. Bohr's notion of complementarity is thus very subtle, involving the necessity to combine incompatible viewpoints. Arkady Plotnitsky (2010, xvi) provides a succinct summary of this difficult concept (see also Pylkkänen 2015):

> …complementarity is defined by (a) a mutual exclusivity of certain phenomena, entities, or conceptions; and yet (b) the possibility of applying each one of them separately at any given point; and (c) the necessity of using all of them at different moments for a comprehensive account of the totality of phenomena that we must consider.

Von Wright notes that Bohr's approach implies a radical violation of the criteria of intelligibility of classical physics:

> …the so-called Copenhagen Interpretation … is in substance an acknowledgement of the fact that a self-consistent and complete theory of the microworld which satisfies the requirement of classical physics simply cannot be provided. (von Wright 1989, 21).

Von Wright then moves on to discuss Heisenberg's uncertainty principle, according to which it is not possible to measure accurately both the momentum and the position of a particle at the same time. This is so because the observation disturbs the system in a certain way (we might add here that this is Heisenberg's early idea; Bohr had a more subtle view of the situation, see Plotnitsky 2010). The more precisely one measures the momentum, the more indeterminate becomes the position and vice versa. Von Wright (1986, 95) notes that it is not clear how one ought to interpret the situation: "Is it just a question of a limit to our possibilities to *know* where a microparticle is located and how fast it moves – or is it so that an electron in fact *has* no well-defined position and velocity?" Regardless of how we answer this question, it is clear that we can no longer assume that the observed object is independent of observing subject (or her measuring apparatus) in the same way as in classical physics. Von Wright also notes that Heisenberg's uncertainty principle calls into question traditional views about causality in nature. Could it be the case that natural processes, instead of being strictly determined by laws of nature, are rather governed by probabilities, which allow for exceptions? (Ibid, 96).

Von Wright acknowledges that while it is possible that people will gradually get intellectually used to the idea complementarity, it feels for the time being unsatisfactory to the demands of thought. He notes that inspired by Einstein there have been attempts to develop "hidden variable" theories in quantum mechanics. The aim of this endeavour is to obtain a more unified theory of the microworld than the Copenhagen interpretation has provided, yet not necessarily a deterministic theory in the classical sense (Ibid, 97-8). We might mention here as an example that David Bohm's hidden variable approach (which we will discuss in more detail in a later section) includes both deterministic (Bohm 1952; Bohm and Hiley 1987) and stochastic (Bohm and Vigier 1954; Bohm and Hiley 1989) versions; see also Nelson (1966).

Von Wright next considers the thought experiment of Einstein, Podolsky and Rosen (EPR) that they presented in 1935. We shall here describe the experiment in some more detail than von Wright does. Bohr had said that because of the limitations described by Heisenberg's uncertainty principle it is meaningless to talk about an electron as if this had simultaneously a well-defined momentum and position. However, quantum mechanics implies that there are situations where two systems that interact with each other can become entangled. EPR pointed out if two such entangled systems are separated from each other, their properties remain correlated in such a way that by measuring the position of a particle A one can obtain information about the position of particle B, and the same for momentum – and according to them this happens "without in any way directly influencing B". But surely, argued EPR, the particle B must have both a well-defined position and a well-defined momentum already prior to measurement, if an experimenter can choose which one of these she wants to measure (i.e., an experimenter can choose to measure either the position or the momentum of particle A, and in this way (without disturbing B) get information about either the position or the momentum of particle B; surely particle B must have these properties well-defined, waiting to be revealed).

Bohr's reply to EPR emphasizes the new feature of quantum wholeness and complementarity. To measure the position requires a certain form of the experimental-set up, which is incompatible with the set-up required to measure the momentum. Bohr implied that when we change the experimental set-up there is an "…influence on the very conditions which define the possible types of prediction regarding the future behavior of the system" (Bohr 1935, 700). Thus when we choose to measure the position of A, we need an experimental set-up which influences the conditions which define our predictions concerning B; in this set-up only predictions concerning the position of B are meaningful. And the situation is analogous for a momentum measurement. So Bohr was implying that when deciding which property of A we measure, we are influencing the properties of B in the sense that our experimental set-up for A determines what we can find out from B. However, Bohr's reply was very cryptic, and the nature of the influence upon B was left quite vague.

However, when we examine the EPR situation more realistically (as von Wright does in his short description) we encounter a difficulty somewhat similar to the difficulty with the notion of action at a distance in Newton's theory of gravitation. For it seems that with entangled quantum systems, experimental interventions at subsystem A appear to influence subsystem B instantaneously, without any mediating local contact between them. This challenges traditional notions of cause of effect, insofar as one assumes that signals cannot be transmitted from one location to another faster than the speed of light (which latter would violate the theory of relativity). Von Wright then writes:

> An imaginative and interesting attempt to resolve the difficulty has been made by the American-English physicist David Bohm. Bohm's idea is that the microphysical system in question is a whole (his term is "unbroken wholeness") in which the relationship of the parts to each other is determined by overarching laws in such a way that a change in one location (immediately) "corresponds" to a change at another location, according to the demands of order within the system. The idea blatantly contradicts the meristic postulate of Cartesian intelligibility. The relationship of the parts must by understood on the basis of an

> ordering principle for the whole. Such a way of thinking is *holistic*. (von Wright 1986, 99).

Bohm's proposal is an example of the kind of holistic thinking that von Wright sees characteristic of the attempts to develop a world-view that can deal with quantum and relativistic phenomena. We also mentioned above that von Wright thought that a new form of rationality might emerge from such thinking. Let us thus, in the next section, examine in more detail Bohm's attempts to make sense of quantum theory.

5. David Bohm and the search of an intelligible explanation of quantum phenomena

We have already above seen examples of Bohm's work that are relevant to the question about the crisis of intelligibility in physics. For one thing, Bohm was one of the main proponents of a "hidden variable" theory that attempted to go beyond the limits set by the Copenhagen interpretation. But since the 1960s he was also working toward a more general way of describing relativistic and quantum phenomena, which he characterizes as a "new order" for physics, namely the "implicate order" (Bohm 1980; this is the notion that von Wright's refers to in the above quote where he mentions Bohm's explanation of the EPR experiment). We will here focus on Bohm's (1952) "hidden variable" approach, which later developed into an "ontological interpretation" of quantum theory (Bohm and Hiley 1993; see also Goldstein 2013). This approach is particularly relevant to von Wright's discussion that we have reported above, because Bohm was – at least initially – trying to explain quantum phenomena in many ways according to classical demands of intelligibility. However, it turns out that the Bohm theory – especially under its later formulation due to Bohm and Hiley - goes radically beyond the mechanistic materialism of classical physics. This gives us one way of understanding how quantum phenomena call for new criteria of intelligibility. We may even be able to get a glimpse of a new form of rationality, something that von Wright speculated might arise if we manage to make sense of the new physics.

Bohm encountered the crisis of intelligibility in quantum theory early on in his career. Richard Feynman (1965) famously said "I think I can safely say no-one understands quantum mechanics", and this was probably a fairly common sentiment among ordinary physicists in the 1940s, regardless of Bohr's "Copenhagen interpretation". Bohm was particularly troubled by this situation. He felt that the teaching of quantum theory typically involved a one-sided emphasis on mathematics. Not enough attention was given to the physical meaning of the theory, and to how the need for the theory arose from certain problems in classical physics. I recall Bohm telling me in discussion that he was so frustrated by the prevailing attitude in physics in the 1940s that he considered giving it up and doing something else (discussion between Bohm and PP, Joensuu, Finland, August 1987). Unable to find a meaningful alternative for himself he however decided to stay in physics and write a textbook on quantum theory that would try to remedy the situation as much possible. His book *Quantum theory* came out in 1951, and is considered to be one of the best textbooks of its time, and is still a valuable resource (Bohm 1951). The book contains a number of new ideas that try to make sense of quantum phenomena in physical and philosophical terms, along with a detailed mathematical exposition. There was even a discussion of analogies between quantum processes and thought (see Pylkkänen 2014).

When Bohm had finished his textbook he was still not satisfied. Something was missing: quantum theory did not provide a coherent ontology. These feelings became stronger when Einstein, having read Bohm's book, contacted him and wanted to discuss with him (both of them were in Princeton at the time). The discussions with Einstein convinced Bohm of the need to look for a realistic and causal extension of quantum theory.

Bohm's search was successful. He considered a certain approximation (WKB) that is used to discuss the transition from quantum theory to classical theory. From the philosophical point of view, by making the approximation one slips from "no well-defined ontology" (quantum theory) to the well-defined ontology of classical physics (i.e. particles moving along trajectories under the influence of potentials). It is as if an ontology suddenly appears from a mysterious “non-ontology, if one just approximates away, or *removes* something from this quantum “non-ontology”. Bohm then asked himself what would happen if one did not make the approximation, and saw that there was actually a new kind of well-defined ontology hiding in the Schrödinger equation when this latter was rewritten in another form. The term that one usually approximated away could now be seen as a new kind of “quantum potential” which has the dimensions of energy and which acts on the electron, besides other potentials such as the electromagnetic. Bohm had independently rediscovered a model that de Broglie had presented in the 1927 Solvay conference, but had soon abandoned due to criticisms. Bohm was able to answer some of these criticisms and in this way gave a new life to this approach. (Bohm 1987).

Bohm’s theory is extremely important for von Wright’s discussion of the crisis of intelligibility in modern physics. For it appears at first sight that the theory restores at least some aspects of *classical intelligibility* in quantum physics. An electron is not ambiguously a particle OR a wave, but rather it is always a particle AND a wave. Moreover, individual quantum processes (e.g. the motion of a quantum particle) can be understood as being causally determined, instead being inherently indeterministic as in the usual interpretation of quantum theory. At the same time Bohm’s theory also made the holistic features of quantum phenomena very explicit, and in this sense it differed radically ~~for~~ from the mereological character of classical physics.

Let us briefly explore some features of Bohm’s model. The wave gives rise to a quantum potential that affects the particle over and above classical potentials. The quantum potential thus accounts for the difference between classical and quantum behavior. For example, if one examines the famous two-slit experiment, Bohm’s theory makes the hypothesis that the particle goes through one of the slits while the associated quantum wave goes through both slits. After passing the slits the wave interferes with itself, which gives rise to a complex quantum potential that profoundly affects the behavior of the particle. The quantum potential “bunches” the possible particle trajectories in such a way that when a large number of particles are passed one by one through the system, we observe an interference pattern emerging "spot by spot" at the screen. This way we can *explain* or *make intelligible* what happens in the two-slit experiment. The electrons are particle-like because they move along trajectories and give rise to localized spots; and they also exhibit wave-like behavior because they are affected by the quantum potential arising from the quantum wave.

However, in typical circumstances at the large-sale level, the quantum potential has a negligible effect and classical physics provides a good approximation. The Bohm theory thus provides not only an explanation of quantum behavior (such as particle interference) but also a clear answer to the notorious problem of how the quantum and classical levels are related. This is in contrast to the Copenhagen interpretation that on the one hand presupposes the classical level, while on the other hand it also admits that in some sense the classical level consists of quantum objects (see Bohm 1951, ch23).

Have we thus been able to transcend the limits of the Copenhagen interpretation? Unfortunately, the restoration of intelligibility in the Bohm theory does not come without a price. While the theory is logically consistent, there are some puzzling features. For one thing, the theory is non-local. This is perhaps the main reason why Einstein did not accept it. However, it was precisely the non-locality of the Bohm theory which made John Bell to ask more general questions about hidden variable theories, which in turn led to the famous Bell's theorem. Bohm had already in his 1951 textbook formulated the EPR thought experiment in a form that could be tested experimentally. Bell's work gave new impetus to these type of experiments, and as is well know, the results of the experiments are consistent with quantum theory and thus also with Bohm's theory (see Bricmont 2016). It would have been very interesting to see Einstein's reaction to Bell's theorem and the results of the experiments testing it.

Another puzzling feature of the Bohm theory is the space in which the new kind of quantum wave (mathematically described by the wave function psi) lives. For a single particle it looks as if the wave lives in a 3-dimensional space (so that we can, for example, imagine the wave going through both slits in a two-slit experiment, which would satisfy Cartesian demands of intelligibility). However, it is characteristic of quantum theory that when two quantum objects interact they form an entangled state. Such an entangled state is described by a wave function that is a superposition of states. One cannot express such a wave function in a 3-dimensional space, but rather has to use a 3N-dimensional configuration space (where N is the number of particles; so that for 2 particles the space is 6-dimensional). This means that the quantum field in Bohm's theory is different from, say, the electromagnetic field. In Bohr's Copenhagen interpretation one is not trying to give an ontological interpretation to the quantum wave function, but sees it as a part of a mathematical algorithm one~~s~~ uses to calculate probabilities. The multi-dimensionality of the many-body wave-function is thus not a serious ontological puzzle. However, in an ontological approach such as Bohm's one typically assumes that the quantum wave describes an objectively existing, real field. But for a many-body system this field lives in a multi-dimensional configuration space, and it is difficult to understand what this could mean physically. Thus the crisis of intelligibility characteristic of quantum phenomena ~~thus~~ persists even in the Bohm model.

Yet another feature of the theory that Bohm himself initially thought to be "strange and arbitrary" is the mathematical form of the quantum potential. Classical potentials are proportional to the size or amplitude of the fields that underlie them. But the quantum potential depends only upon the form (second spatial derivative) of the quantum field.

Bohm himself suggested a way to resolve some of these difficulties only when he began to re-examine his 1952 model in the mid 1970s. But as we will see, his new modifications imply the need to say farewell to traditional materialism. Bohm realized that the form-dependence of the quantum potential might reveal an entirely new feature in fundamental physics. In classical physics the effect of a wave upon a particle depends on the amplitude of the wave – the bigger the wave, the more energy it transmits, as our every-day experience with, say, water waves testifies. But we are also familiar with situations where it is only the form of the wave that matters. Think of a ship guided by a radar wave. The radar waves are not pushing and pulling the ship, but it is the form of the wave that in-forms the much greater energy of the ship. Analogously, Bohm proposed that it is the form of the quantum wave that literally in-forms the energy of the particle. Note that this is information for the electron, not information for us (Bohm is thus assuming that information is an objective commodity that can guide processes in the objective world). Also, if we assume that the quantum field is essentially a field of information, this might help to make sense of the multidimensionality of the many-body wave function, for it is common to assume that information can be organized multi-dimensionally.

Yet another feature of the Bohm theory is that the form of the quantum wave and thus the quantum potential reflects the form of the entire experimental environment, so that the particle can be influenced by distant features of the environment. We saw above that Niels Bohr used to emphasize the crucial role of the whole experimental context for the results of measurement, and Bohm's new hypothesis makes such a role more intelligible. The Bohm theory also underlines the participatory nature of measurement at the quantum level. During the measurement, the observed system and the observing apparatus form an undivided whole, and measurement typically does not reveal a property that a particle had prior to measurement. Such a participatory nature of the measurement differs radically from classical physics, where it is assumed that one is able to reduce the disturbance caused by the observing apparatus to the observed system without limit.

Bohm also reflected upon the broader philosophical implications of his theory. For one thing he felt that the introduction of objective and active information at the quantum level could alleviate the strict separation of mind and matter in Western science and philosophy. If we allow that Bohmian quantum information can be seen as a primitive mind-like property of elementary particles, this might make features such as mental causation more intelligible (Bohm 1990; Hiley and Pylkkänen 2005; Pylkkänen 2007). This is yet another way in which quantum theory might challenge the Cartesian philosophy, in this case undermining its strict dualism.

While von Wright had respect for the richness of Bohm's knowledge and his creative phantasy, he also felt that Bohm's philosophical attempts were clumsy (von Wright, 1986, 102n). However, he expressed to me in person that he was genuinely interested in Bohm's mind-matter theory and invited me to present a paper in his legendary research seminar in the spring of 1993 (Pylkkänen 1995). When commenting on my paper "Mental causation and quantum ontology", von Wright told the seminar participants that *if* Bohm's proposal were correct it would be truly significant; he added, however, that he does not think it likely that it is correct.

It is interesting to note that while Bohm's theory was initially proposed as a materialistic picture of the physical world, the difficulties in the model prompted him later to modify this materialistic starting point, suggesting instead - in a somewhat panpsychist vein - that information (understood as a primitive mind-like quality) is a fundamental feature of elementary particles. This may be telling us something about the nature of quantum phenomena. If we want to say something about quantum reality, at the very least we seem forced to give up classical mechanistic materialism. However, the nature of quantum reality is still a genuinely open question; and there are even those like Plotnitsky (2010: 9) who argue radically, in the spirit of Niels Bohr, that we cannot even *conceive* of quantum objects beyond assuming that they exist. This is an extension and radicalization of a Kantian viewpoint.

One should also note that a number of physicists think that Bohm's theory can be interpreted without such exotic postulates as "active information" (see Goldstein 2013, which also includes a discussion of various criticisms of the Bohm theory; see also Bricmont 2016). This seems to be another case of the tension between intelligibility and mathematical precision that we saw already when considering Newtonian gravity in relation to Cartesian demands of intelligibility. Bohm himself was seeking for an intelligible explanation and this led him to the exotic proposal of quantum theoretical active information; some other "Bohmians" find this unpalatable, and prefer to stick to the equations of "Bohmian mechanics", without too much interpretative and metaphysical baggage (see also Pylkkänen, Hiley and Pättiniemi 2016).

6. Conclusion: toward a new form of scientific rationality?

We have seen that where the mechanistic world-view emphasizes the separation of subject and object, as well as atomism and determinism, quantum theory typically characterizes the relation of observing apparatus and object as mutual participation; emphasizes that the behavior of a system cannot be understood merely in terms of its parts and their relationships; and holds that individual quantum processes are typically incontrollable and unpredictable, even if a kind of statistical causality prevails. It seems clear that the mechanistic world-view is limited, but there does not yet exist a commonly accepted coherent new world-view that could replace it (for a recent "structuralist realist" attempt, see Ladyman and Ross 2007).

In *Science and reason* von Wright draws attention to the new holistic ways of thinking in physics. He also notes how many physicists have seen analogies between features of quantum theory and traditional myths and religions, regarding the existence of a mind in nature, as well non-deterministic and non-mechanical relationships. He comments as follows:

> One must remain critical toward such speculations. They are neither "physics" nor "philosophy" in a strict sense. If they were merely an expression for conceptual confusion, they would not be … interesting. But they are also an expression for a so far diffuse search after new basic models for scientific understanding. Thinking is freeing itself from the meristic and reifying view of nature and is moving toward a holistic approach, in which the gap between the object and the subject no longer splits reality into two essentially separate parts. (von Wright 1986, 100).

As we mentioned in the introduction, von Wright thought that this search might even play a role in resolving the crisis of reason:

> The world-view that is slowly emerging will perhaps turn out to less devoted to legitimizing science as a productive factor in the

> industrial process. The scientific search for truth may again be valued for the orientation it provides for our striving toward a reasonable life style, and not only for the power it gives to direct and manipulate the natural conditions.
>
> In the changes which the scientific world-view is undergoing – under the influence of [developments in physics and biology] – I have recognized a beginning of such a re-evaluation. (von Wright 1986, 153).

The question is whether science could again become a "rational search for the reasonable", and in this way contribute better to solving the problems of our time, instead of making them worse. Von Wright ends his book with characteristic pessimism and caution:

> I do not want to predict how these tendencies are going to develop and which role they are going to play in history. I have no strong belief in the "triumph of reason". But perhaps my attitude can be called a *commitment* to reason as a *hope* for humanity. (Ibid, 154).

Von Wright's speculations are bold – could it really be the case that a form of holistic scientific rationality that arises from modern physics and biology can help humanity to solve its many problems? Bohm, too, was concerned with the various problems of humanity. He felt that a major problem is the tendency of human thought to fragment reality into independent parts, somewhat in the spirit of the mechanistic world-view; and he also felt that the holistic developments in physics could help thought to transcend such fragmentary habits of thinking (Bohm 1980, ch1). However, while von Wright's approach was historical, Bohm (who initially was a Marxist dialectical materialist) came to emphasize the role of psychological and social factors. Inspired by many discussions with the Indian thinker J. Krishnamurti he advocated the need for a "change of consciousness" (Bohm and Edwards 1991). Later, he came to emphasize the importance of communication and dialogue, perhaps somewhat similar to Habermas's approach (Bohm 1996; Kakkuri-Knuuttila 2015). Not only did Bohm theorize, he also actively initiated and engaged in various concrete large-group (30-40 participants) dialogue experiments. The idea was that a new mode of large-group communication, collective intelligence and "impersonal friendship" at the grass-roots level would spread throughout the society.

We do not know which, if any, of these approaches will succeed in the long run. But it is the great legacy of von Wright's work that an important task of philosophy and science is to reflect upon the deeper roots of the urgent problems facing our time.

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