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Peter Gibbins

Excerpt

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## 1

## Meta-physics

Metaphysics in the grand style, the product of a philosopher of genius working out from scratch and from his armchair a new conception of ultimate reality, has been out of fashion for a hundred years or so. This is not only because the results of this activity have so often been absurd. It is partly because other disciplines, such as physics, have developed remarkable and puzzling pictures of bits of the world, pictures that are at least as interesting as, at least as 'deep' as, and much more reliable than those of the armchair metaphysician.

Unlike armchair metaphysics, the theories of physics are the results of the efforts of many minds. They are also tested against the world in experiment and are continuously applied in technological devices and in weaponry. We take them seriously. Just why, and in precisely what respects, we should take them seriously is a problem for the philosophy of science. But we do, and if we were asked what is our best account of the way the world is, most of us would cite the fundamental theories of physics.

If armchair metaphysics is out of date, a new kind of metaphysics, scientific metaphysics, has come into fashion. The new metaphysician asks: what is there in the physical world, and what is true of what there is in the physical world? The answers are provided by the philosophy of physics, a subject whose metaphysical part sets out to tell us the way the world is, if physics is true.

Granted that there is a subject called the philosophy of physics, or, as one might say, *meta-physics*, why is there a subject called *the philosophy of quantum mechanics*? And why does it have so much metaphysical interest?

One must of course admit that through nuclear weaponry, the transistor, and now the microchip, our system of communication, indeed our technoculture as a whole, has come to be based on and threatened by an ultimately quantum-mechanical technology. But the importance of

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quantum mechanics in our scientific and technical culture is not sufficient to generate a *philosophy* of quantum mechanics.

Nor is it sufficient that quantum mechanics is a *fundamental* theory of physics which, incidentally, in its nonrelativistic form it certainly isn't. It is true that quantum mechanics in its nonrelativistic form is our best theory of atoms, molecules, and the solid state, and in relativistic forms, of subatomic particles and matter in the plasma state. Maxwell's electromagnetic theory is a fundamental theory of physics. Yet no one speaks of 'the philosophy of electromagnetism'. Classical mechanics has its philosophy, and important figures in the history of the philosophy of science, philosopher-physicists like Mach and Hertz, have made contributions to it. But 'the philosophy of classical mechanics' has lost much of its significance now that classical mechanics has come to be seen as less than fundamental.

The fact that there is a philosophy of quantum mechanics does not imply the *truth* of quantum mechanics. One cannot say that the quantum theories are known to be true, whereas other less philosophically interesting theories of physics are known to be false. Quantum mechanics is not known to be true. It is a truism of the philosophy of science that no generally applicable physical theory ever could be. In fact one can be sceptical of the truth of quantum mechanics and still be interested in the philosophy of quantum mechanics. One might even have more confidence in the truth of Maxwell's theory than in the truth of quantum mechanics and still think that there needs to be a philosophy of quantum mechanics but no philosophy of electromagnetism.

So why the interest in the philosophy of quantum mechanics?

From the point of view of the natural philosopher, to use an old name for the new metaphysician, today's hybrid of physicist and metaphysician, the most significant difference between the classical and quantum theories is this: quantum mechanics, like electromagnetic theory, is enormously successful in explaining the structure and properties of matter but, unlike electromagnetic theory, it is *deeply* mysterious. It is mysterious because it subverts the classical picture of the world, of which classical mechanics and electromagnetic theory are refinements.

Just how far quantum mechanics subverts the classical picture of the world – which is, crudely, the synthesis of classical mechanics and electromagnetic theory – is a matter of controversy. It is also the subject of this book. Determining just how far quantum mechanics subverts the classical picture of the world is an important part of the philosophy of quantum mechanics. Quantum mechanics seems to contradict atomism, which is strange indeed. It seems to show that things which we think of as separate are in fact not, to show that the world is neither determined

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nor, perhaps, even determinate. Some physicists and philosophers think that quantum mechanics is so paradoxical to the classical mind that it shows that this is an *illogical world*. This idea – the idea that quantum mechanics has a logic of its own which, if the theory is true, is also the *logic of the world* – is what will concern us most.

The most surprising ideas of contemporary metaphysics have their origin and justification in theoretical physics. This explains why metaphysics is so interesting. The most surprising, maybe the wildest of these ideas are to be found in quantum mechanics. No theory of physics has greater metaphysical interest than quantum mechanics, not even the theories of relativity. No theory has had a more devastating impact on our world-picture. No idea in the philosophy of quantum mechanics is more deeply metaphysical than the idea that the world has a logic and that the logic of the world is quantum logic and not classical logic.

### The classical world picture

To fill out the claim that quantum mechanics is fundamental to our metaphysics we should begin by contrasting the world pictures we inherit from classical physics – the physics of Newton and Maxwell above all – with the description of the world that makes up the settled part of contemporary physics.

The *Newtonian world picture*, a refinement of Democritean atomism, is now the common sense of (and so part of the subconscious metaphysics of) most educated laymen and therefore of most professional philosophers. Both materialism and mechanism are embedded in the Newtonian world picture and few ideas can have had greater philosophical influence. The great success of Newtonian mechanics in describing the motions of the planets, the tides, and the behaviour of things on the surface of the Earth in the years following the publication of the *Principia Mathematica* in 1687, gave Newton and his corpuscular philosophy immense prestige.

The corpuscular ontology of Robert Boyle and John Locke, both contemporaries of Newton, was materialist at least as far as the *physical* world was concerned. As a theory about the physical world, it was also mechanistic and deterministic. Newton added forces to this purely corpuscular ontology. God also had a part to play, though Newton's account of it is unlikely to impress us nowadays. Forces enabled Newton to develop his dynamics but only at the cost of admitting what seemed to both Boyle and to Locke along with conventional opinion to be the 'occult'. Newton himself had doubts about forces, doubts which he ex-

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pressed in the General Solum of Book III of *Principia*, and at the end of Book III of *The Opticks*.

Of course, no intellectual revolution goes smoothly and it wasn't all plain sailing for Newton. One caricatures the development of the classical world picture if one ignores the opposed views of the Cartesians, of Leibniz, of philosophical (and theological) critics like Berkeley and, later, of the alternative tradition of German idealism. That is, if one ignores the history of philosophy. But the corpuscular philosophy did come to dominate the popular metaphysical outlook of the nineteenth century, and Newton's own theological conjectures came to be viewed as an aberrant and antiquated appendage to it.

In the materialist, mechanistic world view which Newtonian physics thus inspired, the physical world was thought of as consisting of enduring particles each of which had determined properties: mass, position and velocity in Absolute Space, that all-pervading medium which defined absolute acceleration and which was perhaps the visual field of the Deity (who unlike us sees things as they are, immediately, without perspective, without time, rather in the way that Cubist painters tried to capture). The force laws which operated between the corpuscles in a system isolated from outside influences specified for that system an unique evolution in time.

The materialism of the Newtonian picture (together with some typically Newtonian theology) is summed up in this delightful and famous passage from Newton's *Opticks*, the book in which his corpuscular philosophy is most clearly expounded.

All these things being consider'd, it seems probable to me, that God in the Beginning form'd Matter in solid, massy, hard, impenetrable, moveable Particles, of such Sizes and Figures, and with such other Properties, and in Proportion to Space, as most conduced to the End for which he form'd them: and that these primitive Particles being Solids, are incomparably harder than any porous Bodies compounded of them: even so very hard, as never to wear or break in pieces; no ordinary Power being able to divide what God himself made one in the first Creation . . . And therefore that Nature may be lasting, the Changes of corporeal Things are to be placed only in the various Separations and new Associations and Motions of the permanent Particles.<sup>1</sup>

The world view which classical mechanics, as Newtonian mechanics in its nineteenth-century form came to be called, was both materialist and determinist and at least potentially a-theist. The most famous expression of the thesis of universal determinism is to be found in the second chapter of the *Philosophical Essay on Probabilities* written by the Marquis de Laplace in 1816:

We ought then to regard the present state of the universe as the effect of its anterior state and as the cause of the one that is to follow. Given for one instant

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an intelligence which could comprehend all the forces by which nature is animated and the respective situation of all the beings who compose it – an intelligence sufficiently vast to submit these data to analysis – it would embrace in the same formula the movements of the greatest bodies of the universe and those of the lightest atom; for it, nothing would be uncertain and the future, as the past, would be present to its eyes. The human mind offers, in the perfection which it has been able to give to astronomy, a feeble idea of this intelligence. Its discoveries in mechanics and geometry, added to that of universal gravity, have enabled it to comprehend in the same analytical expressions the past and the future states of the world.<sup>2</sup>

In what we shall call *classical metaphysics* – the metaphysics naturally appended to classical mechanics – the physical world is *determinate*: things consist of separate corpuscles each of which endures through time, the variable physical quantities or *dynamical variables* used to describe bodies – energy, momentum, angular momentum – all take a continuous range of possible values, each possible value being definite, a point on the real line, or a point vector in a three-dimensional space. The machinery of the physical world operates on these corpuscles through the iron laws of conservation of energy, momentum, and angular momentum.

The world picture of classical physics in its late nineteenth-century form superimposed on this Newtonian ontology something undreamt of in Newton's time – the electromagnetic field and the aether in which it inhered. The aether in itself was nothing new. In one form or another it appears in the metaphysics of René Descartes and Giordano Bruno and others. But James Clerk Maxwell's electromagnetic field theory, set out in his treatise of 1873, added the *field* to matter and the aether. Physics became dualist. The electromagnetic field explained the apparent *action-at-a-distance* of electricity and magnetism. Solutions to Maxwell's equations showed that the electromagnetic field propagated through space with a fixed speed as radiation in the form of waves. Maxwell had shown that light was nothing more than electromagnetic radiation of a particular range of wavelengths.

A medium to support this wave motion had to be invented. After all, waves have to be waves *in* something. The *aether* supported electromagnetic waves and was perhaps to be identified with Newton's Absolute Space. But this neat encapsulation of mechanics and electricity and magnetism concealed a fundamental tension.

Given the aether hypothesis, the speed of light is its speed relative to the aether. Therefore Maxwell's equations, which contain a constant referring to the speed of light, must lack the universality of Newton's laws of motion, for these were held to be true in all unaccelerated frames of reference and not just those at rest with respect to the aether. The dualism of field and particle was unsettling in itself. Particles are highly

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localized and impenetrable. Fields and waves in fields are extended in space. Waves can be superposed on one another and even made to self-interfere. Consequently, the prevailing physical picture of the world embodied in the physics of the late nineteenth century was essentially Newtonian but it had, rather untidily, to incorporate a field. Soon the field was to threaten the Newtonian ontology in a fundamental way.

The tension between Newtonian mechanics and Maxwellian electromagnetism produced an unexpected outcome in the special theory of relativity. It was Newtonian mechanics that gave way to electromagnetism. Einstein dropped the aether hypothesis. Maxwell's equations acquired full generality. The Newtonian equations were seen to be mere limits of the relativistic equations (as the speed of light is allowed to go to infinity). Furthermore, the speed of light was seen to be a constant in all allowed frames of reference.

Through the theories of relativity – the special theory of 1905 and the general theory of 1915 – theoretical physics revolutionized our ideas of space and time. These are now thought of as aspects of a single entity called *space-time*, the arena of physical happenings. An oddness of the relativistic picture of the world is that space and time do not fall out of space-time in a unique way. They fall out differently for relatively moving observers. General relativity tells us that space-time is not only an unity but also that it is warped. But deep though the philosophical impact of relativity is, the impact of quantum mechanics is even greater.

In special relativity space-time takes over from space and time is perhaps the aether but in a new guise. In general relativity space-time is warped and this generates what appears to us as the force of gravity. *Relativity – special and general – preserves the determinateness of reality.* In comparison with quantum theory, relativistic physics seems merely neoclassical.

### Quantum metaphysics

One should mention the impact that relativity has had on our conception of the world for the following reason. With quantum mechanics we meet something entirely new, something much more subversive of the classical picture of the world even than relativity. Again the revolution took time to unfold. In a first phase, which takes up the period from Planck's explanation of black-body radiation in 1900, through Einstein's explanation of the photoelectric effect in 1905, the Bohr theory of the hydrogen atom in 1913, the Bohr-Sommerfeld theory of the atom of 1916, and the work of the spectroscopists up to 1925, the *old quantum theory* quantized the classical ontology.

But in a second phase, beginning with Heisenberg's matrix mechanics and Schrödinger's wave mechanics in 1925, the classical ontology was swept away. The mathematical formalism of quantum mechanics, the quantum theory of this second period, was developed long before its interpretation was decided. Indeed, one should say that it never has been decided. There is a philosophy of quantum mechanics precisely because there is no agreement as to what the theory tells us about the world.

In what philosophers habitually call 'the philosophy of quantum mechanics' we pursue quantum physics to 1930 or so, up to the time at which the formalism had been unified by the Hungarian mathematician von Neumann, the indeterminacy relations derived and discussed, prior to most of the early work on quantum electrodynamics and quantum field theory.

Why do we say nothing about those relativistic theories, quantum electrodynamics, quantum field theory, and fundamental particle physics which paint pictures of the deepest and most fundamental ontology of physics, if there is such a thing? Why do we limit ourselves to the nonrelativistic quantum mechanics of sixty odd years ago, physics which is surely old hat by now?

First, the essentially quantal aspects of all these theories – like the superposition principle, the indeterminacy relations, complementarity – already appear with quantum mechanics.

Second, although quantum mechanics cannot be true strictly speaking since it is a nonrelativistic theory, quantum field theory contains inconsistencies and there is much greater uncertainty as to its correct formulation than is the case for quantum mechanics.

And third, the philosophy of elementary nonrelativistic quantum mechanics is hard enough already. In fact philosophers are only now beginning to seriously examine quantum field theory.<sup>3</sup>

So we filter out as far as possible the electromagnetic and relativistic aspects of the quantum theories, much as a nineteenth-century philosopher of science like Ernst Mach might filter out electromagnetism and its field from his philosophy of classical mechanics.

What then are the problems that the philosophy of quantum mechanics confronts?

Unlike classical mechanics, quantum mechanics is at least *prima facie* a *fundamentally statistical* theory, a fact on which much turns. Quantum mechanics yields probabilities. Only in special cases can it make determinate nonstatistical predictions. Contrast classical particle mechanics. Every particle in a system described by that theory has a determinate position and momentum at any given time. The force laws

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that operate on the particles determine the way these positions and momenta change with time. When the number of particles is large – in fact when the particles interact any number greater than two is large – the physicist must fall back on a statistical description of the system. The stock example is provided by the kinetic theory of gases. One can treat a sample of a gas as a collection of classical particles and one can predict its gross behaviour even though one cannot in fact predict the behaviour of any particle in the sample. One says that one predicts the behaviour of each particle *in principle* though not in fact since one knows the force law governing the interactions and one knows that these fix a unique evolution in time for the position and momentum of each particle.

Probability – as it appears via the Maxwellian distribution function for particle speeds in a gas – arises because of our *ignorance* of the state of each particle in the sample of gas. It is the same throughout statistical mechanics and throughout classical physics generally. The classical world picture has it that the physical world is determinate and determined and that probability is not a feature of the world but arises because of our ignorance and so is a feature of us, or of the relation in which we stand to the world as knowing subjects.

If the probability in statistical mechanics arises because of ignorance, then one must ask: what do probability statements mean? What do we mean when we say that the most probable speed for a nitrogen molecule in a sample of air at room temperature is 420 meters per second?

The standard interpretation of probability in physics has it that probability deals with *relative frequencies within an ensemble*. The probability that our molecule has its speed within a given range is then just the fraction of molecules having speed in that range in the appropriate ensemble. The appropriate ensemble might be just the actual collection of nitrogen molecules in the sample of air. Understood this way probability has nothing to do with the individual molecule but is simply a property of the ensemble. When we say that the probability that a particular molecule has its speed in such-and-such a range is  $p$  we can legitimately mean only that the fraction of molecules in our chosen ensemble having speeds in that range is  $p$ . We reduce probability statements about the molecules in a gas to statements about relative frequencies in ensembles, all the while conceding that the motion of each individual molecule is determinate and rigidly determined by the laws of classical mechanics.

But quantum mechanics is, or at least seems to be, irreducibly statistical. What does this mean? It means that quantum mechanics is unlike statistical mechanics in that it is not and cannot be based on, under-



pinned by, a deeper nonstatistical mechanics. So should we say that quantum mechanics *does not describe individual quantum systems at all* but describes *mere ensembles* of quantum systems because probability refers to ensembles? Should we say that the quantum theories fail in their duty to provide a determinate and deterministic underpinning to the probability statements they issue?

Einstein thought so. He became a critic of the orthodox interpretation – the Copenhagen interpretation – of quantum mechanics as it developed and took hold in the late 1920s, somewhat ironically since Einstein was one of the founders of the old quantum theory and even received his Nobel Prize not for relativity but for his work on the photoelectric effect. According to the Copenhagen interpretation quantum mechanics exhaustively describes the individual quantum system, the individual electron, proton, photon. Einstein, on the other hand, held that quantum mechanics does not describe the individual quantum system for which variables ‘hidden’ from quantum mechanics would be required, though it does describe the gross statistical behaviour of ensembles.

The hidden-variables idea has it that there really is a (presumably deterministic) underpinning of quantum mechanics analogous to the underpinning of classical statistical mechanics by classical mechanics. The ensemble view of quantum mechanics seems to leave open the route to a hidden-variables theory. It views quantum mechanics as a new and generalized statistical mechanics.

From the fact that quantum mechanics is a statistical theory and from the relative frequency interpretation of probability arise two of the most fundamental questions in the philosophy of quantum mechanics: *Does quantum mechanics describe only ensembles or does it describe the individual quantum system? Can there be a hidden-variables underpinning of quantum mechanics?*

Taken together these questions form the problem of the *completeness* of quantum mechanics. An ensemble interpretation which is sympathetic to the idea of hidden variables (like Einstein’s) will view quantum mechanics as incomplete. An individual-system interpretation (like Heisenberg’s) which rejects the possibility of a hidden-variables underpinning will view quantum mechanics as either complete or at least as complete as it is possible for a fundamental theory of physics to be. The dispute between the two interpretations has philosophical significance not merely for the philosophy of physics but in philosophy generally. For in defending the maximal completeness of quantum mechanics one can be led, as Bohr was, to develop a rudimentary philosophy of the limits of explanation and even of the limits of language. The dispute has extraphilosophical significance since someone who rejects the pos-

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sibility of hidden-variables theories will frown on research into such theories while his opponents will try to encourage it.

Several questions related to completeness arise immediately. There is the question of the meaning of the Heisenberg uncertainty principle – or as we say more neutrally, *the indeterminacy relations*. These tell us about a trade-off between ‘indeterminacies’ in (for example) position and momentum. Do the indeterminacy relations apply to the individual system or must they be interpreted, perhaps like probabilities, as referring only to ensembles?

Assuming an individual system interpretation, the indeterminacy relation

$$\delta X \delta P_x \geq \frac{1}{2} \hbar$$

tells us that the product of the ‘uncertainties’ in the position (in the  $X$ -direction) and momentum (in the  $X$ -direction) of a quantum system must be greater than or equal to a minimum whose value depends on  $\hbar$ , Planck’s constant. Yet it is not clear what ‘uncertainty’ is supposed to mean.

Reinterpreting the indeterminacy relation, the ensemble interpreter might say this. Imagine a beam of particles, all prepared by the same process to have their momenta restricted to a narrow range. Imagine for example a beam of nuclei emerging from a mass spectrometer. When you measure the positions of some of the particles and the momenta of some others as they emerge from the preparing apparatus you will find that they have minimum spreads in their positions and momenta such that the product of these spreads will always satisfy the indeterminacy relation for position and momentum. This says nothing at all about whether each individual nucleus has simultaneous determinate position and momentum. Indeterminacy is demystified but at the cost of limiting the scope of quantum mechanics. If one goes on to insist that each individual nucleus has simultaneous determinate position and momentum then one has an *epistemic* interpretation of the indeterminacy relation. Indeterminacy expresses a limitation on our *knowledge* of an unfuzzy Nature.

In individual-system interpretations, like the Copenhagen interpretation as presented by Heisenberg, the indeterminacy relations present more of a problem. They can be thought to express a real fuzziness in Nature: the *ontic* interpretation, asserting a *de re* indeterminacy, an indeterminacy of things not of knowledge; or, alternatively, a limitation on the simultaneous definability of dual or conjugate concepts like position and momentum: asserting a *de dicto* indeterminacy, an inevitable indeterminacy of concepts rather than of things.