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Night thoughts of a quantum physicist

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1.1 Introduction

As the twenty-first century begins, theoretical physics is in a situation that, at least in recent history, is most unusual: there is no generally accepted authority. Each research programme has very widely respected leaders, but every programme is controversial. After a period of extraordinary successes, broadly stretching from the 1900s through to the early 1980s, there have been few dramatic new experimental results in the last fifteen years, with the important exception of cosmology. All the most interesting theoretical ideas have run into serious difficulties and it is not completely obvious that any of them is heading in the right direction. So to speak, some impressively large and well-organised expeditionary parties have been formed and are faithfully heading towards imagined destinations; other smaller and less cohesive bands of physicists are heading in quite different directions. However, we really are all in the dark. Possibly none of us will get anywhere much until the next fortuitous break in the clouds.

I will try to sketch briefly how it is that we have reached this state and then suggest some new directions in which progress might eventually be possible. However, my first duty is to stress that what follow are simply my personal views. These lie somewhere between the heretical and the mainstream at the moment. Some of the best physicists of the twentieth century, would, I think, have been at least in partial sympathy.[1] However, most leading present-day physicists would emphasise different problems; some would query whether physicists can sensibly say anything at all on the topics I will discuss.

I think we can, of course. It seems to me that the problems are as sharply defined as those we have overcome in the past: it just happens that we have not properly tackled them yet. They would be quite untouched – would remain deep unsolved problems – even if what is usually meant by a 'theory of everything' were discovered. Solving them may need further radical changes in our world view, but I suspect that in the end we will find there is no way around them.

1.2 Physics in 1999

The great discoveries of twentieth-century physics have sunk so deeply into the general consciousness that it now takes an effort of will to stand back and try to see them afresh. We should nonetheless try, just as we should try to look at the night sky and at life on earth with childlike eyes from time to time. In appreciating just how completely and how amazingly our understanding of the world has been transformed, we recapture a sense of awe and wonder in the universe and its beauty.[2]

So recall that, in 1900, the existence of atoms was a controversial hypothesis. Matter and light were, as far as we knew, qualitatively different. The known laws of nature were deterministic and relied on absolute notions of space and time that seemed not only natural and common sense but also so firmly embedded in our understanding of nature as to be beyond serious question. The propagation of life and the functioning of the mind remained so mysterious that it was easy to imagine that their understanding might require quite new physical principles. Nothing much resembling modern cosmology existed.

Einstein, of course, taught us to see space and time as different facets of a single geometry. Then, still more astonishingly and beautifully, he

[1] In any case, I am greatly indebted to Schrödinger and Bell's lucid scepticism and to Feynman's compelling explanations of the scientific need to keep alternative ideas in mind if they are even partially successful, as expressed in, for example, Schrödinger (1954), Bell (1987) and Feynman (1965).

[2] We owe this, of course, not to nature – which gives a very good impression of not caring either way – but to ourselves. Though we forget it too easily, that sense is precious to us.

taught us that the geometry of space–time is nonlinear, that matter is guided by the geometry and at the same time shapes it, so that gravity is understood as the mutual action of matter on matter through the curvature of space–time.

The first experiments confirming an important prediction of general relativity – that light is indeed deflected by the solar gravitational field – took place in 1917: still within living memory. Subsequent experimental tests have confirmed general relativity with increasingly impressive accuracy. It is consistent with our understanding of cosmology, insofar as it can be – that is, insofar as quantum effects are negligible. At the moment it has no remotely serious competitor: we have no other picture of the macroscopic world that makes sense and fits the data.

Had theorists been more timid, particle physics experiments and astronomical observations would almost certainly eventually have given us enough clues to make the development of special and general relativity inevitable. As it happens, though, Einstein was only partially guided by experiment. The development of the theories of relativity relied on his extraordinary genius for seeing through to new conceptual frameworks underlying known physics. To Einstein and many of his contemporaries, the gain in elegance and simplicity was so great that it seemed the new theories almost had to be correct.

While the development of quantum theory too relied on brilliant intuitions and syntheses, it was much more driven by experiment. Data – the blackbody radiation spectrum, the photo-electric effect, crystalline diffraction, atomic spectra – more or less forced the new theory on us, first in *ad hoc* forms and then, by 1926, synthesised. It seems unlikely that anyone would ever have found their way through to quantum theory unaided by the data. Certainly, no one has ever found a convincing conceptual framework that explains to us why something like quantum theory should be true. It just is. Neither has anyone, even after the event, come up with a truly satisfactory explanation of what precisely quantum theory tells us about nature. We know that all our pre-1900 intuitions, based as they are on the physics of the world we see around us every day, are quite inadequate. We know that microscopic systems behave in a qualitatively different way, that there is apparently an intrinsic randomness in the way they interact with the devices we use to probe them. Much more impressively, for any given experiment we carry out on microscopic systems, we know how to list the possible outcomes and calculate the probabilities of each, at least to a very good approximation. What we do not fully understand is why those calculations work: we have, for example, no firmly established picture of what (if anything) is going on when we are not looking.

Quantum theory as it was originally formulated was inconsistent with special relativity. Partly for this reason, it did not properly describe the interactions between light and matter either. Solving these problems took several further steps and in time led to a relatively systematic – though still today incomplete – understanding of how to build relativistic quantum theories of fields and, eventually, to the conclusion that the electromagnetic force and the two nuclear forces could be combined into a single field theory. As yet, though, we do not know how to do that very elegantly and almost everyone suspects that a grander and more elegant unified theory of those three forces awaits us. Neither can we truly say that we fully understand quantum field theory, or even that the theories we use are entirely internally consistent. They resemble recipes for calculation, together with only partial, though tantalisingly suggestive, explanations of why they work. Most theorists believe that a deeper explanation requires a better theory, which has perhaps yet to be discovered.

Superstring theory, which many physicists hope might provide a complete theory of gravity as well as the other forces – a 'theory of everything' – is currently the most popular candidate. Though no one doubts its mathematical beauty, it is generally agreed that so far superstring theory has two rather serious problems. Conceptually, we do not know how to make sense of superstrings as a theory of matter plus space–time. Neither can we extract any very interesting correct predictions from the theory – for example, the properties of the known forces, the masses of the known particles, or the apparent four-dimensionality of space–time – in any convincing way.

Opinions differ sharply on whether those problems are likely to be resolved and hence on whether superstring theory is likelier to be a theory of everything or of nothing: time will tell. Almost everyone agrees, though, that reconciling gravity and quantum theory is one of the deepest problems facing modern physics. Quantum theory and general relativity, each brilliantly successful in its own domain, rest on very different principles and give highly divergent pictures of nature. According to general relativity, the world is deterministic, the fundamental equations of nature are nonlinear and the correct picture of nature is, at bottom, geometrical. According to quantum theory, there is an intrinsic randomness in nature, its fundamental equations are linear and the correct language in which to describe nature seems to be closer to abstract algebra than to geometry. Something has to give somewhere, but at the moment we do not know for sure where to begin in trying to combine these pictures: we do not know how to alter either in the direction of the other without breaking it totally.

However, I would like here to try to look a bit beyond the current conventional wisdom. There is always a danger that attention clusters around some admittedly deep problems while neglecting others, simply through convention, habit, or sheer comfort in numbers. Like any other subject, theoretical physics is quite capable of forming intellectual taboos: topics that almost all sensible people avoid. They often have good reason, of course, but I suspect that the most strongly held taboos sometimes resemble a sort of unconscious tribute. Mental blocks can form because a question carries the potential for revolution, in that addressing it thoughtfully would raise the possibility that our present understanding could, in important ways, be quite inadequate: in other words, they can be unconscious defences against too great a sense of insecurity. Just possibly, our best hope of saying something about future revolutions in physics might lie in looking into interesting questions that current theory evades. I will look at two here: the problem of measurement in quantum theory and the mind–body problem.

1.3 Quantum Theory and the Measurement Problem

As we have already seen, quantum theory was not originally inspired by some parsimonious set of principles applied to sparse data. Physicists were led to it, often without seeing a clear way ahead, in stages and by a variety of accumulating data. The founders of quantum theory were thus immediately faced with the problem of explaining precisely what the theory actually tells us about nature. On this they were never able to agree. However, an effective-enough consensus, led by Bohr, was forged. Precisely what Bohr actually believed (and why) remains obscure to many commentators, but for most practical purposes it has hardly mattered. Physicists found that they could condense Bohr's 'Copenhagen interpretation' into a few working rules that explain what can usefully be calculated. Alongside these, a sort of working metaphysical picture – if that is not a contradiction in terms – also emerged. C. P. Snow captures this conventional wisdom well in his semi-autobiographical novel *The Search* (Snow 1934):

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> Suddenly, I heard one of the greatest mathematical physicists say, with complete simplicity: 'Of course, the fundamental laws of physics and chemistry are laid down for ever. The details have got to be filled up: we don't know anything of the nucleus; but the fundamental laws are there. In a sense, physics and chemistry are finished sciences'.
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> The nucleus and life: those were the harder problems: in everything else, in the whole of chemistry and physics, *we were in sight of the end*. The framework was laid down; they had put the boundaries round the pebbles which we could pick up.
>
> It struck me how impossible it would have been to say this a few years before. Before 1926 no one could have said it, unless he were a megalomaniac or knew no science. And now two years later the most detached scientific figure of our time announced it casually in the course of conversation.
>
> It is rather difficult to put the importance of this revolution into words. [. . .] However, it is something like this. Science starts with facts chosen from the external world. The relation between the choice, the chooser, the external world and the fact produced is a complicated one [. . .] but one gets through in the end [. . .] to an agreement upon 'scientific facts'. You can call them 'pointer-readings' as Eddington does, if you like. They are lines on a photographic plate, marks on a screen, all the 'pointer-readings' which are the end of the skill, precautions, inventions, of the laboratory. They are the end of the manual process, the beginning of the scientific. For from these 'pointer-readings', these scientific facts, the process of scientific reasoning begins: and it comes back to them to prove itself right or wrong. For the scientific process is nothing more nor less than a hiatus between 'pointer-readings': one takes some pointer-readings, makes a mental construction from them in order to predict some more.
>
> The pointer-readings which have been predicted are then measured: and if the prediction turns out to be right, the mental construction is, for the moment, a good one. If it is wrong, another mental construction has to be tried. That is all. And you take your choice where you put the word 'reality': you can find your total reality either in the pointer-readings or in the mental construction or, if you have a taste for compromise, in a mixture of both.

In other words, in this conventional view, quantum theory teaches us something deep and revolutionary about the nature of reality. It teaches us that it is a mistake to try to build a picture of the world that includes every aspect of an experiment – the preparation of the apparatus and the system being experimented on, their behaviours during the experiment and the

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observation of the results – in one smooth and coherent description. All we need to do science (and all we can apparently manage) is to find a way of extrapolating predictions – which, as it happens, turn out generally to be probabilistic rather than deterministic – about the final results from a description of the initial preparation. To ask what went on in between is, by definition, to ask about something we did not observe: it is to ask in the abstract a question that we have not asked nature in the concrete. According to the Copenhagen view, it is a profound feature of our situation in the world that we cannot separate the abstract and the concrete in this way. If we did not actually carry out the relevant observation, we did not ask the question in the only way that causes nature to supply an answer, so there need not be any meaningful answer at all.

We are in sight of the end. Quantum theory teaches us the necessary limits of science. But are we? Does it? Need quantum theory be understood only as a mere device for extrapolating pointer-readings from pointer-readings? *Can* quantum theory be satisfactorily understood in this way? After all, as we understand it, a pointer is no more than a collection of atoms following quantum laws. If the atoms and the quantum laws are ultimately just mental constructions, is not the pointer too? Is not everything?

Landau and Lifshitz, giving a precise and apparently not intentionally critical description of the orthodox view in a classic 1974 textbook on quantum theory, still seem to hint at some disquiet here:

> Quantum mechanics occupies a very unusual place among physical theories: it contains classical mechanics as a limiting case, yet at the same time requires this limiting case for its own formulation.

This is the difficulty. The classical world – the world of the laboratory – must be external to the theory for us to make sense of it; yet it is also supposed to be contained within the theory. Furthermore, since the same objects play this dual role, we have no clear division between the microscopic quantum and the macroscopic classical. It follows that we cannot legitimately derive from quantum theory the predictions we believe the theory actually makes. If a pointer is only a mental construction, we cannot meaningfully ask what state it is in or where it points; so we cannot make meaningful predictions about its behaviour at the end of an experiment. If it is a real object independent of the quantum realm, then we cannot explain it – or, presumably, the rest of the macroscopic world around us – in terms of quantum theory. Either way, if the Copenhagen interpretation is right, a crucial component in our understanding of the world cannot be theoretically justified.

However, we now know that Bohr, the Copenhagen school and most of the pioneers of quantum theory were unnecessarily dogmatic. We are not forced to adopt the Copenhagen interpretation either by the mathematics of quantum theory or by empirical evidence. Neither is it the only serious possibility available. As we now understand, it is just one of several possible views of quantum theory, each of which has advantages and difficulties. It has not yet been superseded: there is no clear consensus now regarding which view is correct. However, it seems unlikely that it will ever again be generally accepted as the one true orthodoxy.

What are the alternatives? The most interesting, I think, is a simple yet potentially revolutionary idea originally set out by Ghirardi, Rimini and Weber (GRW) in 1986, and later developed further by these authors, Pearle, Gisin and several others. According to their model, quantum mechanics has a piece missing. We can fix all its problems by adding rules to say exactly how and when the quantum dice are rolled. This is done by taking the collapse of the wave function to be an objective, observer-independent phenomenon, with small localisations or 'mini-collapses' constantly taking place. This entails altering the dynamics by adding a correction to the Schrödinger equation. If this is done in the way GRW propose, the predictions for experiments carried out on microscopic systems are almost precisely the same, so that none of the successes of quantum theory in this realm is lost. However, large systems deviate more significantly from the predictions of quantum theory. Those deviations are still quite subtle and very hard to detect or exclude experimentally at present, but they are unambiguously there in the equations. Experimentalists will one day be able to tell us for sure whether or not they are there in nature.

By making this modification, we turn quantum theory into a theory that describes objective events continually taking place in a real external world, irrespective of whether any experiment is taking place and whether anyone is watching. If this picture is right, it solves the problem of measurement: we have a single set of equations that gives a unified description of microscopic and macroscopic physics and we can sensibly talk about the behaviours of unobserved systems, irrespective of whether they are microscopic electrons or macroscopic pointers. The pointer of an apparatus probing a quantum system takes up a definite position – and does so very quickly, not through any *ad hoc* postulate, but in a way that follows directly from the fundamental equations of the theory.

The GRW theory is probably completely wrong in detail. There are certainly serious difficulties in making it compatible with relativity – though recent research gives some grounds for optimism here. Nonetheless, GRW's essential idea has, I think, a fair chance of being right. Before 1986, few people believed that any tinkering with quantum theory was possible: it seemed that any change must so completely alter the structure of the theory as to violate some already-tested prediction. However, we now know that it is possible to make relatively tiny changes that cause no conflict with experiment and that by doing so we can solve the deep conceptual and interpretational problems of quantum theory. We know too that the modified theory makes new experimental predictions in an entirely unexpected physical regime. The crucial tests, if and when we can carry them out, will be made not by probing deeper into the nucleus or by building higher-energy accelerators, but by keeping relatively large systems under careful enough control for quantum effects to be observable. New physics could come directly from the large-scale and the complex; frontiers we thought long ago closed.

1.4 Physics and consciousness

Kieślowski's remarkable film series *Dekalog* begins with the story of a computer scientist and his son who share a joy in calculating and predicting, in using the computer to give some small measure of additional control over their lives. Before going skating, the son obtains weather reports for the last three days from the meteorological bureau and together they run a program to infer the thickness of the ice and deduce that it can easily bear his weight. Tragically, however, they neglect the fire a homeless man keeps burning at the lakeside. Literally, of course, they make a simple mistake: the right calculation would have taken account of the fire, corrected the local temperature and shown the actual thickness of the ice. Metaphorically, the story seems to say that the error is neglecting the spiritual, not only in life, but perhaps even in physical predictions.

I do not myself share Kieślowki's religious worldview and I certainly do not mean to start a religious discussion here. However, there is an underlying scientific question, which can be motivated without referring to pre-scientific systems of belief and is crucial to our understanding of the world and our place in it, which I think is still surprisingly neglected. So, to use more scientifically respectable language, I would like to take a fresh look at the problem of consciousness in physics, where by 'consciousness' I mean the perceptions, sensations, thoughts and emotions that constitute our experience.

There has been a significant revival of interest in consciousness lately, but it still receives relatively little attention from physicists. Most physicists believe that, if consciousness poses any problems at all, they are problems outside their province.[3] After all, the argument runs, biology is pretty much reducible to chemistry, which is reducible to known physical laws. Nothing in our current understanding suggests that there is anything physically distinctive about living beings, or brains. On the contrary, neurophysiology, experimental psychology and evolutionary and molecular biology have all advanced with great success, based firmly on the hypothesis that there is not. Of course, no one can exclude the possibility that our current understanding could turn out to be wrong – but, in the absence of any reason to think so, there seems nothing useful for physicists to say.

I largely agree with this view. It *is* very hard to see how any novel physics associated with consciousness could fit with what we already know. Speculating about such ideas *does* seem fruitless in the absence of data. Nonetheless, I think we can say something. There is a basic point about the connection between consciousness and physics that ought to be made, yet seems never to have been clearly stated and suggests that our present understanding almost cannot be complete.

The argument for this goes in three steps. First, let us assume, as physicists quite commonly do, that any natural phenomenon can be described mathematically. Consciousness is a natural phenomenon and at least some aspects of consciousness – for example, the number of symbols we can simultaneously keep in mind – are quantifiable. On the other hand we have no mathematical theory even of these aspects of consciousness. This would not matter if we could at least sketch a path by which statements about consciousness could be reduced to well-understood phenomena. After all, no one worries that we have no mathematical theory of digestion, because we believe that we understand in principle how to rewrite any physical statement concerning digestion as a statement about the local

[3] Penrose is the best-known exception: space does not permit discussion of his rather different arguments here, but see Penrose (1989, 1994).