Primas, Emergence and Worlds

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1 The Mechanistic Dream

Since the very beginnings of human thought it has been noticed that the world is made of more or less complicated things which have smaller parts (which themselves have yet smaller parts) and that the properties of the wholes depend on the properties, arrangement and interactions of the parts. This pervasive if at first doubtlessly inchoate line of thought began to be codified and made more precise just as soon as humans began to develop the intellectual apparatus required for theoretical engagement with the world.

Doctrines of atomism go back thousands of years in both Western and Eastern traditions, most especially in ancient Greece and India (see e.g. Gregory (1931), Pyle (1997), Gangopadhyaya (1981)). Of course, ancient thinkers did not have a very well worked out idea of mechanism, perhaps because they lacked the rich set of technological examples, such as the pendulum clock, which enriched the thinking of the early scientists of the 17th century (see Berryman (2009)[1]). But the ancients certainly advanced the common sense observation of how appropriately arranged parts generate more complex structures and behaviours to a new theoretical and at least quasi-scientific viewpoint.

The development of modern science allowed for a more precise statement of the mechanical world view in terms of mathematical laws governing the interaction of material objects (e.g. particles). For example, the law of conservation of energy permitted the strict deduction of the outcome of particle collisions, given their initial velocities. It began to seem that nature might be nothing more than a gigantic, and gigantically complicated, pinball machine, an idea that was famously expressed by Pierre Laplace:

> An intelligence that, at a given instant, could comprehend all the forces by which nature is animated and the respective situation of the beings that make it up, if moreover it were vast enough to submit these data to analysis, would encompass in the same formula the movements of the greatest bodies of the universe and those of the lightest atoms. For such an intelligence nothing would be uncertain, and the future, like the past, would be open to its eyes Laplace (1825/2012).

This quotation is usually presented in a discussion of determinism but here the important point is the implicit idea that the world can be resolved into the 'lightest atoms' and com-

[1] The mechanical ingenuity of the ancients should not be underestimated however, as the discovery and eventual decoding of the Antikythera illustrates (see Freeth *et al.* (2006)).

pletely understood in terms of their interactions as determined by 'all the forces that animate nature'.

In its purest form, mechanism would endorse only a set of atomic[2] particles which interact solely by elastic collisions. An extremely precise and austere formulation of the mechanistic ideal was presented much later by C. D. Broad. He writes that

> ... the essence of Pure Mechanism is:
>
> (a) a single kind of stuff, all of whose parts are exactly alike except for differences of position and motion;
>
> (b) a single fundamental kind of change, viz, change of position. ...
>
> (c) a single elementary causal law, according to which particles influence each other by pairs...
>
> (d) a single and simple principle of composition, according to which the behaviour of any aggregate of particles, or the influence of any one aggregate on any other, follows in a uniform way from the mutual influences of the constituent particles taken by pairs (Broad (1925), pp. 44-5).

Despite its evident simplicity, notice that Broad's characterization sneaks in some features that might be regarded as suspiciously extra-mechanical. As opposed to the general scheme of an elementary causal law, isn't the only allowable interaction elastic collision between the putatively ultimate and fundamental tiny atoms of matter? But it is extremely difficult to make such a super austere scheme work. Perhaps Descartes's vortex based physics comes close but it was demonstrated quite early on that systems of vortices could not generate the elliptical orbits of the planets[3]. Broad's principle of composition also suggests some constraints beyond that of the impenetrability of matter.

The additional element to the mechanical picture was that of *forces*: the general power to instill motion into matter. As is well known, even Newton regarded forces with misgivings, most especially ones that, like his own gravitational force, acted over a distance and instantaneously[4]. But Newton recognized the significance of adding forces to nature and hoped for a force based chemistry:

> For many things lead me to have a suspicion that all phenomena may depend on certain forces by which the particles of bodies, by causes not yet known, either are impelled toward one another and cohere in regular figures, or are repelled from one another and recede (Newton (1687/1999), pp. 382-3).

[2]By the term 'atomic' it might be understood either an absolutely smallest piece of matter or a merely contingently unbreakable and very tiny piece of matter. Most thinkers of the early modern period would have opted for the second conception if they wished to endorse atomism, since they regarded an extended piece of matter as in principle divisible, say, at least, by God.

[3]Both Leibniz and Jacob Bernoulli, among others, attempted a quantitative explanation of Kepler's laws in terms of vortex theories, but neither account was fully worked out or, as was eventually realized, could be worked out (see Aiton (1972) for details).

[4]Newton acidly observed that taking his own account of gravity as revealing a property 'innate, inherent and essential to Matter' which could generate instantaneous effects at a distance would be to embrace such an absurdity that 'I believe no Man who has in philosophical Matters a competent Faculty of thinking can ever fall into it' (see Newton (2004), p. 102).

Every new force represents a step away from pure mechanism. Imbuing matter with mysterious powers does not accord with the goal of showing how complex structures appear simply as the result of simple units interacting according to an intelligible scheme of interaction.

Modern science as gone very far down the road of adding forces whenever convenient for explanation and with the acceptance of field theory by the late 19th century abandoned even the pretense of requiring a mechanical explanation for all effects. The pioneers of the scientific revolution would likely have recoiled from the proliferation of 'immaterial' fields and forces found in modern physics and 'the forces... of contemporary microphysics would likely not have been regarded as matter by the architects of the mechanical philosophy' (Normore (2007), p. 117).

Taking a very broad and distant view of things, we can see the history of science as a grand project, which we might call the *Parts Project*. Newton famously expressed the project in terms of the correlative activities of analysis and synthesis:

> By this way of Analysis we may proceed from Compounds to Ingredients, and from Motions to the Forces producing them... And the Synthesis consists in assuming the Causes discover'd, and established as Principles, and by them explaining the Phænomena proceeding from them, and proving the Explanations (Newton (1730/1979), Query 31).

The goal of the project was to begin with the commonsense vision of the way complex objects are constructed out of simple parts, whose arrangement and interactions explain the resulting properties and dispositions of complex objects. Commonsense observes that the world manifestly has a part-whole structure to it. The Parts Project was to show that *everything* fits into this general schema. Pure mechanism was the first serious effort of the project. Its purity was exemplary. Its adherence to the commonsense view admirable. But its ability to actually explain the complex structures and processes of the world was woefully inadequate.

Newton conjectured a minimal retreat. Take the world as composed of material parts, atoms or atom-like units of matter, and add to them primitive powers or forces in order to explain mechanistically inexplicable interactions. Gravity is only one example and one that Newton himself was suspicious of insofar as it strayed from pure mechanism.

2 The Great Irony

The Parts Project inaugurated the most successful intellectual project every undertaken by the human race: empirical science in general and in particular mathematical physics. Once freed of the constraints of pure mechanism, the project raced ahead. In the mid-19th century, James Clerk Maxwell added fields to our physical ontology. Fields as such do not operate by mechanical contact, though Maxwell initially made considerable efforts to devise mechanical models of the electromagnetic field[5]. There was much worry that without such models a

[5] For discussion of various aspects of Maxwell molecular vortex model see Siegel (2003), Chalmers (2001), Dyson (2007). It seems that Maxwell at first regarded these with, as Siegel puts it, 'ontological intent' (Siegel (2003), p. 56) but came to see them later as heuristic aids to understanding. Maxwell's own presentation of his model can be found in Maxell (1890/1965), pp. 451 ff.

vicious gap in intelligibility would ensue but over time such scruples faded away. At least one could content oneself that the electromagnetic field was generated by material sources of charge even if it it did then embody its own causal powers. The Parts Project remained viable as the 19th century drew to a close. A number of prominent physicists went so far as to declare that the scientific metaphysics of the (albeit extended) mechanical world view was virtually complete (see e.g. Badash (1972), Schaffer (2000)).

But the Parts Project soon thereafter collapsed. It was exploded by the development of quantum mechanics. The world does not resolve itself into elementary, independent objects which fit together under simple laws of interaction. The most successful intellectual project ever undertaken by the human race actually ends with the collapse of the project's initial motivating idea. This great irony was emphasized throughout his philosophical writings by Hans Primas, from a number of different viewpoints. For example:

> Modern quantum mechanics put an end to atomism and hence to reductionism: The so-called 'elementary particles' (such as electrons, quarks, or gluons) are patterns of reality, not building blocks of reality. They are not primary, but arise as secondary manifestations, for example as field excitations, in the same sense as solitons are localized excitations of water, and not building blocks of water (Primas (2007), p. 8).

Much earlier Primas wrote:

> The historical idea that the material world is already structured by some kind of interacting 'atoms' is in sharp contradiction to basic insights suggested by quantum mechanics. According to quantum theory the material world is a whole, a whole which is not made out of independently existing parts. As a rule, separated subsystems of a quantum system do not exist (Primas (1998), p. 88).

It remains very difficult to grasp fully the implications of these ideas which replace rather than modify the mechanistic account of the world, even in its extended form. Most philosophers, scientists and even physicists struggle to come to grips with the idea that the world in not constructed from fundamental micro-objects. The flood of popular modern physics books does little to dispel the idea that the world is made of small, discrete and independent objects, and Primas conceded that 'in spite of the fact that quantum mechanics put an end to atomism, modern science is still to a large extent based on an atomistic ontology (Primas (2007), p. 8). Even though most physicists would probably agree with David Wallace's acidic assessment that 'the popular impression of particle physics as about the behavior of lots of little point particles whizzing about bears about as much relation to real particle physics as the earth/air/fire/water theory of matter bears to the Periodic Table' (Wallace (2013), p. 222) there remains a widespread impression that the world is made out of tiny objects which physics tells us about.

3 Emergence

There is, of course, a large assumption that underwrites the fatal diagnosis of the Parts Project which is that quantum mechanics (QM) is true or at least 'true enough' that its non-mechanistic and holistic picture of the world will be sustained in successor theories. It is impossible for anyone to say with absolute certainty that QM will form the core of all future science or that it will not be entirely eclipsed in some huge scientific revolution. But it would take someone very brave to bet against QM.

QM is the most thoroughly scientific theory of all time, by a wide margin. Recently, some of these tests have taken a remarkable form. It is a curious fact that the features of QM that are most deeply antithetical to the mechanistic view of the world are accessible to experimental investigation. This is sometimes called experimental metaphysics, and it got itself onto a firm footing after the work of John Bell (see e.g. chs. 1 and 2 in Bell (1987)). Through a somewhat intricate but conceptually straightforward proof, Bell showed that no mechanistic account of nature could duplicate the predictions of QM. The crucial aspect of mechanism here is that of local interaction between independent units or 'hidden variables' which are supposed to underly the empirical regularities explained and predicted by QM[6]. This discrepancy in the predictions of local realistic theories and QM can be and by now has been extensively tested, with results uniformly and completely in favour of QM (some recent results can be found in Hensen *et al.* (2015), Poh *et al.* (2015); Wikipedia has a nice history of the relevant experiments[7]).

But another peculiarity of QM is that even if we grant, on the grounds of its vast empirical success, that it presents a reasonably accurate account of reality, it remains unclear exactly what kind of reality it is portraying. This is the problem of *interpreting* QM, a problem with little or no counterpart in any other part of science. How could a mature theory used by thousands of scientists every day be so interpretively opaque?

The best guess is that QM strains our ability to conceptualize an ontological scheme which incorporates all of QM's bizarre theoretical features. This has led to a host of interpretations which run the gamut from micro anti-realism to many worlds ultra-realism.

Micro-antirealism is the view that QM does not describe and is not intended to describe an existing microscale world at all. Rather, what exists is the macroscopic domain of manifest experience which is amenable to description in classical terms. QM then provides us with rules for predicting the evolution of features in the manifest realm, or perhaps can be regarded as encoding the intrinsically probabilistic epistemic limitations observers confront when attempting to make such predictions (roughly speaking, the former view is more like Bohr's so-called Copenhagen interpretation while the latter, very closely related, has been labeled quantum Bayesianism[8]).

Bohr's perceived micro anti-realism was once a kind of orthodoxy but has fallen into disfavour more recently amongst philosophers of science and physicists interested in quantum

[6]The idea that the world is made of particulate units is not refuted by Bell's result, if the units lose their independence and are, so to speak, in a kind of universal communication with one another. Theories such as this go back to the early days of quantum mechanics with the 'pilot wave' of Louis de Broglie in the 1920s. Since David Bohm's rediscovery of the de Broglie approach (1952) it has seen extensive development (see Holland (1993) for technical details, Bohm and Hiley (1993) for a more general overview and some philosophical extrapolations). The point is that the de Broglie-Bohm approach does not reinstate the mechanistic dream.

[7]The URL is https://en.wikipedia.org/wiki/Bell_test_experiments

[8]Bohr's philosophy of science is difficult to spell out precisely but see Murdoch (1989); quantum Bayesianism was developed over a number of publications by Carlton Caves, Christopher Fuchs and Rüdiger Schack; for an overview see Timpson (2008).

foundations. A particularly stark description has been given by Tim Maudlin:

> Bohr sometimes sounds like this: there is a classical world, a world of laboratory equipment and middle-sized dry goods, but it is not composed of atoms or electrons or anything at all. All the mathematical machinery that seems to be about atoms and electrons is just part of an... apparatus designed to predict correlations among the behaviors of the classical objects (Maudlin (2010), p. 127).

While it is far from clear that this is a completely fair characterization of Bohr it can stand as a characterization of micro anti-realism, and it is anathema to most current philosophers of science. Maudlin's own blunt assessment is simply that 'I take it that no one pretends anymore to understand this sort of gobbledegook ... ' (Maudlin (2010), pp. 127-8). It is interesting that at least to a certain extent, and long before Maudlin wrote, Primas took a similarly stark view of Bohr's view of the micro-world, by contrasting it the viewpoint of practicing chemists: 'Chemists never have adopted Bohr's view that microphysical objects do not exist' (Primas (1983/2013), p. 158).

I am not, myself, so sure that Bohr should be relegated to the dustbin. After all, the route to the micro-world begins with our everyday observation that common physical objects are made of parts, which have further parts, etc. A brick wall is made of bricks, and the bricks themselves are made of grains of sand, and the grains of sand are made of ... But we have already seen that this is the pathway that leads to the Parts Project, and we know how that turned out.

Whatever we think of the micro-world, one core lesson of QM is that it is not anything at all like a world of small objects zipping about and independently interacting to compose more complex entities in anything like the way grains of sand compose bricks. There must indeed be some link from the story which QM tells to our familiar world of manifest experience. But this link from whatever the quantum realm is to the classical or manifest world of experience cannot be the dreamt of system of whole to part decomposition because, in Primas's own words, 'according to quantum mechanics, the material world is a whole, *a whole which is not made out of parts.* ' (Primas (1995), p. 611, original emphasis).

The linkage from how QM describes its part of the world (micro-world or not) to the world of manifest experience is the general problem of *emergence*: how to construct or retrieve the world as we experience it from the peculiar world QM presents us with. The problem of emergence is ancient because of the common observations that lead to the Parts Project. It is evident, for example, both that birds are not made out of more birds and that birds are made out of parts. So the question naturally arises how the non-bird parts 'combine' or come together to produce a bird. The ancient pre-Socratic philosophers struggled with this and came up with the basic dichotomy: inherence versus origination (see Mourelatos (1986)). Advocates of inherence cleave to the dictum *ex nihilo nihil fit*; whatever emerges must in some substantial sense already be present in the submergent base. Defenders of origination hold that at least sometimes emergent features are genuine ontological novelties which are not determined by the state and laws governing just the submergent features.

Much, much later–in the late 19th and early 20th centuries–arose a sophisticated account of emergence which opted for origination. Since most of the thinkers associated with this view were British, it has come to be known as British Emergentism (for an overview see McLaughlin (1992)). The British Emergentists were realists about the physical world and held that everything was determined by the fundamental physical features of the world. But they also held that some features were merely the causal result of certain configurations of matter, where the causal laws which related the submergent to the emergent were themselves fundamental. The emergent features were not determined by the laws governing just the basic physical features. Instead, the laws of emergence were 'free additions' to the world, or what C. D. Broad called 'trans-ordinal laws' (see Broad (1925), pp. 77 ff.) and what John Stuart Mill had earlier labeled 'heteropathic' effects (see Mill (1843/1963), pp. 443 ff.)

Philosophers like to use a theological metaphor here. What did God have to create in order to create the world? If one follows inherence about emergence then the answer is that God simply needed to create the laws of fundamental physics and arrange the fundamental physical features in some suitable initial condition. Everything else (stars, planets, geology, life, mind) would follow, strictly determined by the ongoing purely physical development of the world after its creation. On the other hand, one who takes the origination line on emergence would hold that God was not finished His creative work simply in virtue of His initial laying down of the fundamental physical laws and features. In addition, God would have to institute certain 'laws of emergence' (Broad's inter-ordinal laws) which would come into effect whenever physical configurations arose of the proper complexity and which would originate some genuinely novel feature. One might also put the point in terms of whether all laws of nature stem from the laws of physics alone (plus, perhaps, the arrangement of physical features if, as it may, be some laws are contingent upon matter being arranged in the appropriate way).

The heyday of British emergentism was the early 20th century, up to about 1925. They regarded their origination based account of emergence as almost obviously true and their lynchpin, supposedly uncontroversial example was chemistry. Here is Broad:

> We will now pass to the case of chemical composition. Oxygen has certain properties and Hydrogen has certain other properties. They combine to form water, and the proportions in which they do this are fixed. Nothing that we know about Oxygen by itself or in its combinations with anything but Hydrogen would give us the least reason to suppose that it would combine with Hydrogen at all. Nothing that we know about Hydrogen by itself or in its combinations with anything but Oxygen would give us the least reason to expect that it would combine with Oxygen at all. And most of the chemical and physical properties of water have no known connexion, either quantitative or qualitative, with those of Oxygen and Hydrogen (Broad (1925), pp. 62-3).

Rather unfortunately for Broad and the rest of the British emergentists, 1925 was the year that QM was put on a secure theoretical footing and it began to be clear that the fundamental physical features that make up oxygen and hydrogen actually do determine that they will combine in a ratio of 1-to-2 and that the qualitative features we observe of water are similarly determined by the underlying physical constituents.

By 1929, Paul Dirac could seriously proclaim that:

> The underlying physical laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known, and the difficulty is only that the exact application of these laws leads to equations much too complicated to be soluble (Dirac (1929), p. 714).

Now, the correct characterization of the relation between physics and chemistry remains controversial. Primas had much to say about this, more than I have space or the ability to go into. Primas certainly denied that chemistry could be *reduced* to physics, in the distinctively philosophical sense of reduction as developed by Ernest Nagel (see e.g. Nagel (1961)) and others. This formal conception of reduction envisions a translation scheme according to which the reduced theory (here, chemistry) could be completely rewritten in terms of the reducing theory (here, physics) Primas regarded such philosophical accounts of reduction as insufficiently well defined to be of use in real scientific work (Primas (1998), p. 83).

However, it does seem clear that Primas did not endorse the kind of radical ontological origination espoused by the British emergentists. The physical world does have a fundamental structure which determines everything else, but the relations between theories is highly complex and dependent on creative abstractions, mathematical procedures, approximation techniques, experimental selection and other acts of mind: a host of factors which Primas included in the general notion of *contextuality*. Emergence can then be characterized thus:

> Emergent properties are not manifest on the level of the basic theory, but they can be derived rigorously by imposing new, contextually selected topologies upon context-independent first principles (Primas (1998), p. 83).

Two central concepts developed by Primas to explain the quantum to classical transition are those of 'endophysics' and 'exophysics'. The context independent domain is that of endophysics; the domain of contextuality is exophysics (see Primas (1994)[9]). Exophysics is derivable from endophysics, once the context has been fixed.

If all possible contexts of experimentation were mutually compatible then exophysics would be reducible to endophysics. Emergence would then simply be a reflection of complexity and our own epistemic limitations. One of the astonishing lessons of QM, however, is that it is impossible, even in principle, to perform measurements simultaneously on all observable or measurable properties of physical systems. In terms of the distinction between endophysics and exophysics, this means that there is no standpoint from which all exophysical features can be derived purely from the endophysics, even though it is true to say that the endophysical realm is what is ultimately real and fundamental. QM forces us to recognize that even though 'the first principles of physics are intended to give. . . a context-independent description of the material world' (Primas (1998), p. 85) this will not yield access to the world we directly experience. To move from the 'intrinsic description' of the world as described by the first principles, which 'makes no reference to other physical systems' (how could it?), we have to impose a context, for example, of measurement.

The world of exophysics is like a set of tiles that cannot be laid down together to cover the floor, even though each tile does cover some part of the floor and no part of the floor is not covered by some tile or other. We need contextualization to select, so to speak, one of the tiles to lay down. One of the most remarkable aspects of Primas's view was the way he linked contextualization to perspectives and pattern recognition. The exophysical world is a set of patterns which can only be discovered from particular perspectives. Going back to the 1983 first edition of Primas (1983/2013), the emphasis on patterns anticipates the work

[9]Primas's conceptions of endophysics and exophysics are developed from the initial formulation of David Finkelstein (1995). Interesting philosophical discussions of Primas's notion of endo- and exophysics can be found in Shimony (1999) and d'Espagnat (1999).

of Daniel Dennett and subsequent development in the philosophy of science of the so-called ontological structuralists (see Dennett (1991), Ladyman *et al.* (2007)). Dennett's conception of patterns is entirely classical and indeed mechanistic at heart (his main example is John Conway's[10] 'game of life' cellular automata). Primas's system of patterns inherits the non-classical nature of QM. Patterns are recognizable regularities that arise in experimental (or observational) contexts. While these contexts are themselves classical domains, there is no way to arrive at a description of the total system by 'summing' or 'combining' the set of contexts–they are incommensurable.

The core metaphysical vision of the world at work is that of an underlying monistic and holistic reality, perhaps reminiscent of what Spinoza called God. This endophysical fundamental reality is not manifest in experience. It is entirely independent of mind and is fully objective ('endophysics refers to a subject-independent reality'). Our most fundamental theories strive to describe the endophysical reality in terms of 'metaphysical universal laws', but the 'endoentities... are hidden from us and... not directly observable'. The realm of the observable is that of exophysics which 'aims to give us empirically adequate descriptions' (all the foregoing quotes from Primas (1994), p. 168).

The world of manifest reality is the exophysical world. It is, to a first approximation, a classical world that appears atomistic and mechanistic. Primas was able to express the essence of classicality by a distinction between systems describable in terms of Boolean logical structures (classical) versus those which could not be so described (quantum). The field of quantum logic has long recognized that there is no way to encode quantum theory in a Boolean logic but Primas emphasized the way that the manifest reality of experience, the realm in which experimentation takes place, must be describable in Boolean terms but that it is impossible to combine these Boolean descriptions into one overarching description of the entirety of reality (see e.g. Primas (2003, 2007); Atmanspacher and Primas (2003)).

The great irony discussed above is the dissolution of the project which attempted to take the exophysical for the endophysical. There is no way to render the endophysical totality in an exophysical picture. Classical (or semi-classical) domains are exophysical features emergent from the underlying holistic endophysical reality where this emergence is conditioned by the perspective of the experimenter via choice of apparatus and context, revealing a pattern. However, the system of all such patterns is not coherent; the world cannot be regarded as the sum of patterns into an overarching world in which they all appear.

In recent philosophy of QM, there is a view which one could be forgiven for identifying with Primas's account. It bears many affinities with our sketch of the relation between the endophysical and the exophysical. Yet, Primas did not accept this view even though he had been originally attracted by it.

4 Many Worlds

This view which superficially resembles Primas's goes by several names: the relative state interpretation or QM, the Everettian interpretation and the many-worlds interpretation. It was invented by Hugh Everett in 1957 (Everett (1957)). The core idea is that we ought simply to accept what the mathematics of QM seems to be telling us. This mathematics holds that

[10]First introduced widely to the world by Martin Gardner (1970).

there is never any sudden and discontinuous transition of the quantum mechanical wave function which makes one of its components 'become real'. As is very well known, quantum systems are generally in states which are described by superpositions of states which represent observable properties having definite values. For example, an electron might be in a state which is the superposition of two possible spin states. No electron has ever been directly observed to be in such a state. Whenever measured, an electron reveals itself to be in a quite definite spin state. The orthodox explanation for this peculiar state of affairs is that, upon measurement, the state of the system transitions, or *collapses*, into one of the components of the superposition. Orthodoxy is enshrined as an 'axiom' of QM called the projection postulate[11].

Everett's theory eliminates the projection postulate. The quantum wave function always and everywhere evolves according to the deterministic mathematics which is the core of QM, as in the Schrödinger equation. How then to explain the failure to ever observe a system actually in a superposition? Everett took the bold step of accepting that the observing equipment and the experimenter as well would evolve into a superposition no less than any other physical system.

If we take the somewhat audacious view that the entire universe is a physical system then, cosmologically speaking, there is a 'universal wave function' which, so to speak, evolves into an immense superposition which is a foliation of all possible state evolutions. The branches of the foliation include the system being measured, the measuring instrument, the human experimenter and indeed the entire environment which ever has interacted with any component of these components–in short, the entire universe we inhabit is but one component of a vast all encompassing superposition of all physically possible evolutions. Defenders of the many-worlds interpretation of QM like to say that it's not really an 'interpretation' since it is simply what the mathematics tells us. The metaphysical structure of many-worlds is just 'read off' the mathematics.

Although Everett's many-worlds interpretation was for a long time a decidedly minority position amongst both physicists and philosophers of physics, it has enjoyed a remarkable renaissance in the 21st century. Most especially, there has grown up the so-called Oxford program in which a number of philosophers of science, mostly indeed housed at Oxford University, have produced an impressive defense of the many-worlds interpretation (see e.g. Wallace (2012) and its references). The Oxford program has addressed directly what many regard as the most important objections to the many-worlds interpretation.

There are two fundamental challenges facing the many-worlds interpretation which were noted almost as soon as Everett announced it (in fact, Everett recognized them in his seminal work and attempted responses). The first is the Probability Problem. QM has an algorithm for determining the probability of any observation which is called the Born Rule (formulated by Max Born in (1926)). In the simplest and historically significant case, the rule states that the probability of finding a particle at a certain position is the square of the amplitude of the wave function at that point in space. For the case of a particle in a superposition of two spin states the probability of observing the particle in a particular spin state is the square of

[11] John von Neumann articulated and attempted to justify the postulate in his magisterial Neumann (1955). It has been the subject of a vast literature which has been largely negative because of the unattractive way that the postulate simply asserts that there will be a sudden break with the otherwise smoothly predictable evolution of a quantum system when a hard to define event of 'measurement' occurs.

the 'weight' of that component. For example, such a state might be is written as

$$\sqrt{\frac{3}{4}}A^+ + \sqrt{\frac{1}{4}}A^-$$

In this case the Born Rule tells us that there is a $^3/_4$ chance of finding the system in state A^+ and a $^1/_4$ chance of finding it in the A^- state. The Probability Problem is now evident. If the world 'splits' upon a measurement there are only two possible outcomes and the many-worlds interpretation holds that both actually occur (along with a similar dual splitting of everything connected to the system under observation, most notably the experimenters themselves). If both outcomes occur, how can there be any differentiation in the probability of the outcomes?

To put the point starkly, what, according to the many-worlds interpretation of QM, is the difference between the above state and

$$\frac{1}{\sqrt{2}}(A^+ + A^-)?$$

The amplitudes seem to be metaphysically otiose. They make no difference to the way the world actually evolves.

Before discussing the Probability Problem further, let us turn to the second problem afflicting the many-worlds interpretation. This is a problem of emergence. Although the range of quantum possibilities is truly vast, we only ever seem to observe a world that is to a good approximation classical. Objects have highly definite positions and never just disappear and reappear in another location, objects do not migrate through walls unscathed, etc. How is the deep strangeness of the quantum world suppressed or eliminated in the world(s) that we experience?

This is a problem that Everett himself tackled and pointed the way towards a solution. Since then huge amounts of work have been done addressing the question of how classical branches appear and dominate the foliating superposition of all possible states which the many-worlds interpretation asserts is the true reality of things. The key concept is that of decoherence: the general tendency for quantum superpositions to lose their internal correlations as they interact with the environment. This is most evident in the case where the 'environment' is a measuring device.

The famous two slit experiment is a perfect illustration. This experiment is so well known that it hardly needs describing but I will recall its structure here very briefly. Imagine a beam of particles directed at a screen on which there are two very small openings through which they can pass. Beyond this barrier screen lies a detector screen on which we can observe where the particles impact. QM predicts that the pattern of impacts will not be the simple addition of impacts from passage through each slit (a kind of 'two hump' distribution that would be the result of shooting classical particles, such as bullets from a machine gun) but will rather exhibit a system of bands of impacts. This is caused by the quantum interference effects of the two possible paths. However, if a detector is placed so that we can determine which slit a particle passes through, then the band pattern disappears to be replaced with the two hump distribution. Mathematically, the two detector states are orthogonal: any terms in an equation where they combine will go to zero. Once we put the detectors into our two-slit experiment, the interference terms will contain combinations of the two detector states and these terms will disappear. And so the interference has been eliminated, as we can observe … or has it?

A complete quantum description of the experimental setup with detectors would predict that the (experiment + detector) system would itself go into a superposition. If we could somehow, and it would already be very difficult, arrange the appropriate experiment on the combined (experiment + detector) system it too would exhibit interference effects. In order to actually do this, we would have to completely isolate the (experiment + detector) system to preserve its quantum coherence. This is very difficult to do and the more complex the system and the longer the time period of observation the greater the degree of interaction between the (experiment + detector) system and various parts of the general environment. In effect, under normal conditions the environment is acting something like a detector, watching over, so to speak, its own parts. It can be shown that most environmental states will be effectively orthogonal to each other and they will enforce the loss of quantum coherence. Distinct quantum effects will thus tend to be suppressed.

Of course, many of the very most complex and highly relevant parts of the environment are the brains of observing scientists. These 'physical devices' will themselves be in thorough interaction with huge number of environmental parameters, so we would expect that the observation of quantum effects by human observers will also be suppressed. Brains too will tend to act classically[12]. This is the general scheme of decoherence, the details of which are involved, intricate and have been developed with great precision and sophistication (a seminal sourcebook is Joos *et al.* (2003); see Wallace (2012) for philosophical discussion).

From the perspective of the many-worlds interpretation of QM, decoherence strongly suggests that almost all[13] the branches in the universal foliation, and certainly almost all of them with physically complicated conscious observers, will appear to be a classical world with definite objects having determinate positions and velocities.

It now seems that the decoherence approach will eventually provide a full understanding of how classicality emerges from the universal wave function postulated by the many-worlds interpretation of QM. What is interesting here is that there is an almost irresistible mapping from the decoherence approach to Primas's own account of the emergence of classical systems. The equation is simply this. Endophsyics = the universal wave function. Exophysics = the elements of the foliation, or the branches, or the 'worlds' of the many-worlds interpretation. The points of similarity between this interpretation and Primas's views are manifold. The branches are individually classical (or virtually classical), as are the exophysical systems. The branches cannot be combined or summed into one coherent world which is either available to or manifest in ordinary experience and yet the totality of them is the underlying and fundamental reality of things, in line with Primas's account of the endophysical. Following from the basic structure of QM, the branches are contextual and perspective based for the particular observables that will take a determinate value in each branch depend on the measurement setup plus environment, choice of experimenter, etc. In this way again they

[12]While the brain must, at bottom be a quantum system (since *everything* is), it remains very controversial whether distinctive quantum effects are a significant component of brain function. See Hameroff and Penrose (1996) for a positive view; Tegmark (2000) and Eliasmith (2000) for the negative side.

[13]I am using the phrase 'almost all' colloquially but it may also be true in the mathematical sense that the elements of the universal foliation, which are an uncountable infinity, are all save for a set of measure zero essentially classical. I don't know whether this is provable.

are very similar to Primas's exophysical systems.

If we step back and regard the universal wave function, the vast superposition of all possible states, we see more links to Primas's views. The totality of the universal wave function is decidedly non-classical exhibiting a holistic character with deep entanglement throughout (albeit the correlations between components are 'smeared out' into the wide environment of each branch). Metaphysical dependence runs from the whole to the parts rather than the reverse, in a way reminiscent of Primas's endophysical world (and Spinoza's holistic monism).

In light of the at least interesting correspondence between the many-worlds interpretation and Primas's endophysical-exophysical division, it would be worth exploring Primas's attitude towards the many-worlds interpretation. This project can begin on an optimistic note. In his early philosophical writings, Primas took a very positive view of Everett's theory. In 1983 he wrote that that Everett's account was 'superior in logical economy' and, more significantly, that it provides a 'a more intelligible pattern of the world' (Primas (1983/2013), p. 135).

I have been reliably led to believe that over time Primas's positive attitude towards the many-worlds interpretation soured, but I have not been able to find anywhere in Primas's writings where he engages in any sustained criticism of Everett's views (and I would appreciate any tips about where to look). Primas early on noted that 'the conclusions of the Everett interpretation may be considered as bizarre' (Primas (1983/2013), p. 135) but that would hardly, and especially for a thinker like Primas, count as a cogent argument against it (he immediately adds to the last quote: 'novelty and repugnance are not valid arguments').

We may find the beginning of a possible solution to this puzzle if we go back to the first of the two major challenges facing the many-worlds interpretation: the Probability Problem. Recall that this is the difficulty of justifying the Born Rule's method of assigning probabilities to outcomes of quantum measurements. One might have thought that one of, if not the, core idea in our conception of probability is the distinction between the possible and the actual. Because many things are possible but only one can be actual, it is natural to seek some way to gauge the chances of any specified possibility becoming actual. The 'gauge of chances' is just what we call probability. But in the many-worlds picture of reality there is no distinction between the possible and actual: if something is a possibility it will be an actuality. There are no merely possible, unactualized branches in the foliation of the universal wave function. This is a deeply counterintuitive conception of reality, very much at odds with how we organize our own experience.

So there has naturally been a great deal of effort expended on showing that the Born Rule can be vindicated. Early efforts go all the way back to Everett's own work. It can be shown with considerable rigour that branches that violate the Born Rule will be branches with low quantum amplitude. But, as noted above, without a connection already established to probability, amplitudes are just numbers assigned to, in this case, branches in the foliation of the universal wave function, by an arcane mathematical procedure. Why should we care about them?

The Oxford Program takes this critique to heart and jettisons discussion of objective probability. If the distinction between possibility and actuality is empty, we could recast probability in terms of subjective degrees of belief (a key concept in a venerable research program in any case). Beginning with work of David Deutsch (1999) and further developed by David Wallace (2007) a remarkable link between the Born Rule and decision theoretic considerations has been forged. Basically, Deutsch and Wallace aim to show that rational agents should assign their degrees of belief according to the Born Rule. This is not the place to delve into the burgeoning literature on this issue, but broadly speaking, the proofs offered by Deutsch and Wallace either ignore or deny the claim that adding the genuineness or reality of all the branches should affect our predictions and preferences[14]. But it seems to me that if we are to regard all the branches as equally real, we have to or should take them into account in our decision making.

If all this seems very abstract, let me give a simple, but fanciful, illustration of how quantum amplitudes could intelligibly operate in our decisions in such a way as to justify the Born Rule. Imagine, if you can, that human personal identity is an fundamental metaphysical feature of the world, no less than anything else you regard as fully objective[15]. So how should you then think of your own future in the branching structure postulated in the many-worlds interpretation? Each branching will lead to many copies of yourself but by hypothesis only one of these will truly be you. What if the quantum amplitudes were a measure of the likelihood of you ending up in a particular branch? Then it would be obvious that you should apportion your subjective beliefs according to amplitude. If you face a measurement process with unequal weights, it will really be more likely that you, yourself, will end up in the more heavily weighted branch observing the more heavily weighted outcome. Notice that this thought experiment reintroduces some genuine uncertainty about the future into the picture, which the standard many-worlds interpretation has eliminated. That explains why it immediately offers an intuitively attractive link between the quantum amplitudes and probability even if it is perhaps metaphysically extravagant (it also has a hidden bias of self concern built into it if you stop to think of it).

Needless to say, our scientifically minded philosophers are not attracted to the idea of an objective, presumably substantial, self. We will simply regard it as an illustrative exercise.

It is easy to think up examples where differences in the way branches are created in measurement seems to matter a great deal. A typical example is the biased quantum coin flip. Let us set up a quantum experiment with two possible outcomes (call them Heads and Tails) and set the amplitudes so that the quantum mechanically calculated probability of Heads is one in a trillion. Would you pay $10 to play this game: if Heads comes up you get $1 billion, Tails you get nothing? Orthodox reasoning and commonsense prudence are both strongly opposed to your participation in this game. But the many-worlds picture suggests otherwise. After the measurement one of you will be very rich and one of you will be out $10. Obviously you should play[16].

[14]This denial is enshrined in what Wallace calls the equivalence principle (Wallace (2007), p. 318) which asserts that all that matters to assigning subjective uncertainty about some proposition, P, is the quantum amplitude of P irrespective of, say, the way that P is observed or measured to be true. That means that the number of worlds 'generated' by the measurement of P is irrelevant to subjective uncertainty. This seems peculiar, since many lives, including those of our quantum descendants, will hang in the balance of how many branches are pumped out by a measurement. This approach has, of course, been criticized, notably in Albert (2015) and Kent (2010).

[15]This option is sometimes called that of 'primitive identity over time' (see Greaves (2004)).

[16]As many thinkers who have contemplated the many-worlds interpretation have pointed out, it is actually very difficult to count the number of branches that will be generated by a measurement, just because of the vast number of connections between the measuring device and the rest of the world. So it is somewhat naive

There is also the bizarre problem of quantum suicide (see Moravec (1988), p. 188 ff.). Would you play Russian roulette for a big prize? Imagine a version of Russian roulette in which death is instantaneous and painless. If you played with a quantum gun that had two outcomes (death or life, in short) then no matter what the amplitudes of the two outcomes were, you are guaranteed to survive and live on with the big prize. We can alter the game by adding, in principle, any number of outcomes leading to death and only one leading to life (that is, the death outcome can be linked to some quantum measurement process with a huge number of possible values). Now, say, millions of my descendants die off yet we are supposed to believe that this should make no difference to how I regard these situations.

An instructive illustration of the oddity of using the Born Rule to set subjective probabilities and inform decisions can be constructed from the bizarre conceit that informs the film *The Prestige*. In the movie, a magician discovers a teleportation machine. He uses it to develop an astonishing magic trick in which he miraculously transports himself across the stage. There is one horrible drawback: the machine creates a duplicate of the teleported object. So every time he performs the trick, there is the problem of what to do with the extra duplicate. The magician thus has his newly created and unwanted duplicate drowned in a locking tank of water under a hidden trap door. At one point, the magician muses to himself that he was always terrified that he would end up in the tank of water instead of appearing across the stage in the target cabinet. This seems like a very odd remark unless one believes in a metaphysically substantial self that has to go 'into' one or the other of the duplicates. More realistically, one supposes that *every time* the trick is performed the drowning duplicate should exclaim: 'oh no, I'm the drowning one this time'.

But now, suppose that the teleporter/duplicator is a quantum device. We can suppose it creates a not quite perfect duplicate to evade the no-cloning theorem and we can also suppose that neither created copy is a exactly like the original to evade an obvious way to track identity over time. Let's say that one duplicate, D1, has a new tiny mole on the left cheek and the other, D2, has one on the right cheek. With considerable abuse of notation we can write the desired quantum state as:

$$\alpha\left(D1_{tank}\otimes D2_{cabinet}\right)+\beta\left(D1_{cabinet}\otimes D2_{tank}\right).$$

If we make α large enough we can make it such that the magician should (according to the view of the many-worlds interpretation we are considering) expect that D2 will end up in the cabinet, safe and sound. But how can the magician guarantee the he will be D2? By adjusting the weights, the magician can project himself, so to speak, into the non-drowning successor with arbitrarily high probability. Modern many-worlders deny there is anything like primitive identity over time or a substantial self, but they do hold that one should use the Born Rule derived probabilities to set one's expectations and help one form decisions about actions. How, then, can the magician project himself into the cabinet? Simply by adding another quantum measurement. To make it vivid, suppose that the duplicates will be shown a coloured card as they are created in either the tank or the cabinet (say either a red card or a green one). Which colour they see is determined by a quantum process. The

to analyze this quantum game as leading to just one rich you and one very slightly poorer you. But there is no reason at all to think that the outcome won't have equal numbers of rich yous and slightly poorer yous so the point of the analysis stands.

magician arranges that the probability that D2 will see the green card is extremely high no matter whether D2 ends up in the tank or the cabinet. So the magician should expect to be D2 after duplication and since α is very high should expect himself to be in the cabinet.

This should drive home the oddity of the claim that worlds as such don't matter. In this case, there are just as many magicians drowning as surviving. It is entirely unclear why the amplitudes should make one feel even one bit safer about engaging in this magic trick[17].

5 Complementarity

I have no idea whether worries about the Probability Problem lay behind Primas's worries about the many-worlds interpretation. The philosophical core of the problem has to do with the distinction between actuality and possibility, or potentiality, and also with the question of whether the world is subject to genuine temporal becoming. And these issues did come to have importance for Primas in his later philosophical writing (e.g. Primas (2003, 2007)). There we see that Primas seems to have moved towards a yet more radical view of reality that has interesting affinities for a dual aspect picture inspired by Wolfgang Pauli and Carl Jung. Such a view avoids the claim that QM itself provides the correct metaphysical account of reality, thus relieving some of the pressure that leads to the many-worlds interpretation because there is no compelling need to regard QM as providing a complete picture of reality.

Pauli had striven towards such a dual aspect view of nature, for example in a letter to Jung writing that 'physis and psyche are probably two aspects of one and the same abstract fact' (Pauli and Jung (2001), p. 159). But the lesson which QM teaches is that dual aspects can stand in a very special relationship, that of complementarity: 'It would be most satisfactory if physis and psyche could be conceived as complementary aspects of the same reality' (Pauli (1952/1994), p. 260). This view is explicitly endorsed by Primas when he writes that 'all physical theories at our disposal are essentially incomplete theories: they are incapable to deal with the complementarity of matter and spirit' (Primas (1995), p. 611).

There are two key features of complementarity that matter here. The first is that complementary attributes are ontologically equal, neither reduces to the other. Second, complementary attributes do not reduce to underlying fundamental attributes; they are co-fundamental. Here is obviously a break with the views of most philosophers who accept the many-worlds interpretation of QM, for they regard it as a way to reduce the mental to the physical. The many-world interpretation is supposed to be part of the general advance towards a thorough physicalism, removing some of the mystical garbage (or, in Maudlin's term gobbledegook) that has accrued around QM. Applied to the mind-matter relation, complementarity suggests that the mental and the physical are co-fundamental features (attributes) of some single underlying substance which is itself un-representable (as Pauli sometimes called it: *unanschauliches*).

It is natural to ask which aspects of the mental require a complementarity based understanding. And the natural answer is that it is consciousness or the subjective elements of

[17] It should also add to worries about the intelligibility of the primitive identity over time approach. The link between the quantum amplitudes and personal identity seems entirely arbitrarily imposed, without even a hint of any coherent connection between quantum measurement and the location of the self in the quantum world.

experience (the 'what it is like' of experience famously described in Nagel (1974)). Typically, these are considered to be the qualitative features of experience, especially sensory experience but the subjective elements of consciousness are multiple and various. Primas was especially interested in temporal consciousness: the experience of time passing, or the flow of time or the sense that we exist in a fleeting 'now' or present. Hence Primas holds that 'tenseless physics... cannot give a complete description of the world' (Primas (2007), p. 30). Here again is a break with the orthodox many-world interpretation of QM, which is prima facie completely comfortable with the four dimensional block view of reality (the block is however infinitely foliated like a coral encased in a glass block) and regards the idea of flowing time with deep suspicion.

One puzzle that Primas's views raise is about the complementarity between mind and matter. As noted, complementarity would suggest that mind and matter are co-fundamental. Yet Primas's own pattern based metaphysics would tend to give a premier role to the mind of the experimenter. This subjective element or choice and perspective seems to be the, or at least a, ground for the emergence of the physical world. Primas wrote that 'for a conceptually clean specification of the initial conditions of physical experiments, the homogeneous parameter time of physics has to be complemented by a time with nowness' (Primas (2007), p. 29) and this too might suggest that the experiential side of reality has a metaphysical primacy.

The puzzle is deepened by the fact that at least once when discussing the relation between the physical and mental aspects of the world, Primas denies they are truly fundamental features. For he writes that:

> the tensed domain is supposed to contain the mental domain, while the tenseless domain refers to first principles describing matter and energy. However, the tenseless domain is not identical with physics, it more resembles Plato's non-temporal world of immutable ideas (Primas (2007), p. 30).

This is perplexing because the complementarity of mind and matter would suggest that they are ontologically on a par and co-fundamental. If there is a domain beyond or below that of the material world (Plato's non-temporal world, that is) then the mental too will fail to be fundamental. In philosophy, this worry marks the division between dual aspect theories and so-called neutral monism[18]. The latter posits a kind of reality which underpins both mind and matter, which can continue to stand in a complementary relation to each other though they lose their status as truly fundamental features of reality. It is pure speculation to attribute either of these views to Primas. It is a great shame that he did not have more time to develop his thoughts on this.

6 The Philosophical Legacy of Hans Primas

Primas was of course famous first and foremost as a chemist and quantum chemistry theorist. But it is important to note his philosophical contributions. He made a host of interesting contributions to the philosophy of science. In particular, he was an important force in

[18]Neutral Monism was famously espoused both by William James and Bertrand Russell as well as Ernst Mach. For an excellent historical overview and modern development of the view see Banks (2014).

the revival of the philosophy of chemistry resisting as he did the easy claims that physics had revealed how to reduce chemistry to basic quantum mechanics. But for me the more interesting aspect of Primas's work goes beyond the philosophy of science. He was not afraid to extend his thought into the metaphysical implications of his views and what he took to be the deep philosophical lessons we should draw from the mysteries of quantum mechanics. Also, although he spent his life as a working scientist, he always resisted an easy or complacent physicalist scientistic vision of the world and opted for an always provisional but audacious embrace of a much richer view of reality. The battle over how narrow a view of reality is acceptable is ancient and still raging. Scientific thinkers such as Primas who marry technical sophistication, deep scientific knowledge and openness to metaphysical speculation are vital warriors helping to keep alive rich and open avenues of thought.

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