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The thinker we honor in these meetings, Henri Poincaré, was favorable to the value of simplicity ; but he was even more favorable to the value of good sense in matters of theory choice. This aspect of his philosophy is illustrated by the way in which, late in life, Poincaré came to accept the existence of atoms, an idea he had opposed for years. Since atoms could not be established to exist in any direct experimental way, he regarded them merely as useful calculational devices. Shortly before his death, however, Poincaré changed his mind, overwhelmed by the indirect evidences that Perrin and others had put together in favor of the atomic hypothesis — a dozen experimental methods, all distinct yet convergent, of calculating Avogadro's number. He was a man of « good sense ». In this paper I want to explore this virtue : what is good sense in matters of theory choice?[*] The subject is famously intricate, but there is agreement about some basics. Consider, for example, the following methodological claims[1] .

(i) « Theories should be fruitful — like Newton's gravitational theory, Maxwell's electrodynamics, and evolutionary biology ; they should reveal, or make explicit, significant connections between previously separate domains, and they should direct our attention to new phenomena and novel predictions ».

(ii) More comprehensively, « A decision between competing theories should focus on such traits as coherence, explanatory power, modesty, independent testability and predictive power, fruitfulness, and simplicity ».

But, what is the epistemological status of methodological claims like these? What can be their warrant? Can they be construed as foundational elements beyond the reach of science ? It has long been argued that our standards for warranting theoretical proposals require scientific justification and are, in principle, as open to the possibility of revision as everything else in science[2] . My intention in this paper is to explore in detail the continuity between methodological good sense and science. I will try to make my case

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1 [Quine & Ullian 1978], [Kitcher 1982].

2 See, in particular, [Shapere 1895], and [Leplin 1992].

through a discussion of some recent developments in the foundations of quantum theory, which, I will argue, show the existence of strong links between scientific methodology and current information about the world.

But first, some points about prevailing methodological norms.

Methodology, Wisdom and Experience

Let us agree, for the sake of argument, that scientific hypotheses are currently accepted or rejected depending on how well or how poorly they optimize such epistemic traits as coherence, explanatory power, modesty, predictive power and testability, fruitfulness, and overall simplicity. It will suffice for my purpose to concentrate on just two traits : simplicity and predictive power.

Simplicity and predictive power are interpreted differently by instrumentalists and realists. Instrumentalists value simplicity largely as a calculational virtue ; by contrast, realists value it in objectivist terms, often linking simplicity to « beauty » in nature and, the like. Similarly, the value granted to predictive power varies depending upon which philosophy one adopts. For realists, the insistence that theories have testable consequences functions as a protection against both our natural gullibility and the fertility of our imagination.

Now, here is my question : could we find ourselves in a situation in which either simplicity or predictive power would no longer be required of our best scientific theories? If the answer is no, if we can rule out such a methodological shift *a priori*, then we need to specify what grounds we have for the *a priori* objection involved. No convincing metascientific specification seems available, unless of course one waters down the objection and speaks of necessity relativized to present knowledge. But that would simply concede the point about the contingency of methodology.

Unless one adopts an instrumentalist perspective on theories, simplicity and predictive power look very problematic as necessary traits. Consider simplicity. In many contexts simplicity is the mark of falsity rather than truth[3]. Often, as with so many premature

[3] [Bunge 1963].

reductionist programs, it is not reasonable to expect simple accounts to be any good. This is not to deny that keeping a theoretical construct simple makes pragmatic sense in healthy utilitarian contexts. For example, it makes good sense to prefer spherical coordinates to rectangular ones for representing a spherical wave. But, « simple » does not make « true » ; truth and simplicity do not stand for the same thing.

The case for predictive power is more subtle. We have evidence that its value has been learned from experience, especially from numerous disappointments with theories that had once seemed absolutely true. Recall, for example, the old explanation of heavenly motions in terms of rotating spheres. Trying to improve on the system proposed by Eudoxus, Aristotle added twenty-two spheres to ensure that the planets receive motion in a way harmonious with prevailing mechanical intuitions. This modification was not intended to add new predictions ; its sole purpose was to make the heavens *intelligible* in terms of Aristotle's conceptions of motion and local action.[4] When, after the time of Alexander the Great, better astronomical data became available, the Aristotelian spheres were found at odds with many phenomena. Adherence to the theory continued, however, because it was thought to be the properly explanatory. By the time of Ptolemy, lip-service was still paid to the Aristotelian system, but astronomy had effectively divorced itself from physics. The proliferation of anomalies had encouraged a skeptical attitude toward physics that lasted until the Renaissance. Heavenly motions could be accounted for in various imprecise ways ; but then many radically different theories were able to do that. When, centuries later, Newtonian scientists insisted that we should be wary of claims that cannot be tested observationally in their own right, they were reacting against the embarrassing fertility of the human imagination when it comes to merely « explaining » phenomena. It was against this fertility that the efforts in favor of mathematizing scientific descriptions of nature, and of putting such descriptions to stringent experimental testing, grew. Predictive power was a discovered value.

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[4] See E. McMullin's contribution in [Cushing & McMullin 1989], « The Explanation of Distant Action », pages 272-302.

The points raised invite some questions: Do good theories have to be simple or have predictive power? Given a set of competing theories, and other things being equal, would simplicity by itself necessarily make a difference? Could new knowledge rationally lead us to endorse nonpredictive theories? And, could such theories subsequently serve as a rational basis for a methodology more liberal than ours about the values of predictive power? The preceding discussion suggests that simplicity and predictive power are empirically learned virtues. Far from being supported by valid metascientific reasoning, our methodological rules look contingent on current scientific information, which rules to endorse being a matter of contemporary good sense. To obtain a more precise idea of how available knowledge connects with the latter, however, we need to focus on a concrete case. The case I want to discuss concerns some recent efforts to free quantum theory, our most fundamental theory of matter, of its notorious conceptual problems.

A Theory in Need of Change

It will be good to recall a few basic points about quantum theory [QT]. QT covers a large domain of phenomena, from the sub-atomic level to, at least, medium-size molecules, and also condensed matter; quantum mechanical descriptions are of a very high level of precision. A quantum system is dynamically described by a *wave function*, which is calculated by the theory. Applying QT to ordinary macroscopic objects (chairs, cats, mountains, etc.) is, however, extremely problematic. The standard version of the theory (standard quantum theory [SQT]) simply assumes that there are two different kinds of systems: quantum systems, which follow the dynamics represented by Schrödinger's equation (or its field-theoretic generalizations); and ordinary macroscopic objects, which obey the laws of classical physics rather than those of QT. Though the two dynamics are deterministic, they are otherwise very different — which is odd, given that macroscopic objects are made out of quantum systems.

Even more puzzling is the existence of yet a third dynamics, which is nonlinear and indeterministic, and becomes operative whenever a quantum system and a standard macroscopic object meet.

This third dynamics, which is represented by the so-called « Projection Postulate » [PP], *collapses the total wave function to one of several possible final states*, with probabilities given by a simple rule (Born's rule[5]). Isolated quantum systems are not affected by PP, evolving by the linear deterministic Schrödinger's equation — I will use the term « QT_0 » to refer to this linear part of SQT. We are given no clue, however, about how or when PP becomes operative. Quantum systems are simply said to be governed by two independent dynamics. First, there is the linear and deterministic dynamics embodied by QT_0, represented by an operator, U_t, which is generally defined in terms of the total Hamiltonian. Second, there is the nonlinear and indeterministic dynamics embodied by PP, represented by an operator **C** associated with the phenomenon of wave function collapse. **C** has the effect of aborting « unwanted » quantum superpositions (those that involve classically incompatible states of macroscopic objects).

A prime example of an unwanted superposition is found in the so-called « Schrödinger's cat paradox », one version of which goes as follows. An electron e is initially in a superposition of two states, one corresponding to motion toward a detector-detonator D (state « up »), and the other corresponding to motion away from it (state « down »). Upon the arrival of the electron, the detector, which is initially in a « ready » state, activates the detonator. When the trial starts (time t=0), the cat C is alive and an observer O is ready to register the results of the experiment. The initial state Ψ_0 of the total system is thus given by :

$$|\Psi_0> = 1/\sqrt{2}\ \{\ |up>_e + \ |down>_e\}\ |ready>_D\ |alive>_C\ |\ alive\text{-}cat\text{-}observed>_O\}$$

This initial state evolves through U_t to :

5 For a system in a state $\Psi(r) = \Sigma c_n \varnothing_n(r)$, where the functions ϕn are the proper functions of the quantum operator associated with a magnitude A(r,p), so that ϕn corresponds to the value an of this magnitude, then the probability of obtaining the value an in a measurement of A is $\|c_n\|^2$.

$$U_t \,|\Psi_0\rangle = 1/\sqrt{2}\,\{\,|\text{up}'\rangle_e\,|\text{explosion}\rangle_D\,|\text{dead}\rangle_C\,|\text{dead-cat-observed}\rangle_O + {} + |\text{down}\rangle_e\,|\text{ready}\rangle_D\,|\text{alive}\rangle_C\,|\text{alive-cat-observed}\rangle_O\}$$

In the above expression $|\text{up}'\rangle_e$ represents the electron's state after interacting with D. SQT explains the fact that we never encounter this kind of state in our experience by saying that the third dynamics reduces the above superposition, almost as soon as it arises, to just one of the two incompatible states involved.

Clearly, PP looks like a self-serving element in a fundamental theory of matter. Not surprisingly, therefore, many attempts have been proposed for eliminating PP, including the denial that QT has anything to do with individual systems (ensemble interpretation of the quantum algorithm), and various forms of instrumentalist interpretations of the theory.[6]

In recent years the foundations of quantum theory has become an active field, especially after some experiments which strengthen the claim that QT provides a complete description of physical reality (in particular, confirmations of quantum entanglement in so-called « Bell experiments »[7] and experiments with single systems[8]. The result is a revival of interest in objectivism and realism about the wave function. Three programs for advancing QT are now particularly vibrant ; all take an objectivist stance toward the wave function. Each advances an earlier, cruder approach to deal with the conceptual problems of QT. The programs in question are (1) the « Quantum Theory of Motion » [QTM] based on David Bohm's work, (2) the « Many Decohering Worlds » interpretation of QT [MDW], and (3) the Spontaneous Collapse of the Wave Function Approach [SCA]. Let us briefly examine these projects.

1. The Quantum Theory of Motion. Since the days of Einstein, Podolsky and Rosen, some critics of QT have insisted that the wave function provides an incomplete dynamical description of physical

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6 [Squires 1994].

7 For an excellent discussion of this topic, see [Cushing & McMullin 1989].

8 See, for example, [Wineland & Itano 1987].

systems. The latter, these critics claim, cannot be fully described without adding variables to the quantum state. These extra variables, generally called « hidden variables », are meant to play a role similar to that of the extra spheres Aristotle added to the Eudoxan system : they are introduced to make QT *intelligible* in terms of received categories, in this case those of classical particles and fields, determinism and particle trajectories. Doubts about the simplest and most seemingly plausible hidden variable proposals (the so-called « local theories ») abounded from the start, first from some formal theorems, and then in the 1980's from experiments which have finally discredited the program.[9] In the 1950's, however, Bohm had advanced a nonlocal hidden variables proposal that dodged those theorems and, as it turned out, also the said experiments. In Bohm's proposal the wave function is taken as a nonlocal (and very peculiar) field. Initially, the theory incorporated all sorts of *ad hoc* assumptions and seemed very artificial, but recent work has managed to derive some of those assumptions from natural (seemingly highly probable) initial conditions.[10]

The ontology of QTM includes material particles, local fields, and the quantum wave function. Particles are always well localized ; they move guided by the *total wave function*, their instantaneous velocity being a function of that field. Unlike local hidden variables theories, in QTM ontic quantum entanglements are developed at the level of the total wave function. This renders the theory nonlocal, because, through the wave function, actions in one spatial region can cause instantaneous changes that affect particles placed very far away. Sharp properties may be attributed to individual systems, but with two provisos. First, specific values generally depend on the total physical context at the time of attribution ; properties are, in this sense, « contextual ». Only position and trajectory are intrinsic properties of particles. Second, knowledge of the complete property state of a system is limited by the so-called « Heisenberg relations ». According to QTM, however, this limitation is not ontic (as in SQT) but epistemic, springing from the way the world was originally put together.

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9 For a good presentation of the formal theorems, see [Hughes 1989], Ch 5. The relevant experiments are discussed at length in [Cushing & McMullin 1989].

On this theory the universe follows one well-defined, many-particle trajectory. No collapse of the wave function ever occurs — the wave function of a total system remains widespread and nonlocal forever. Sectors away from the universe's position in configuration space carry on as unoccupied wave fronts ; though empty, however, these parts remain ready to act on their associated particle and to interfere with other parts of the wave function if the opportunity arises. The appearance of wave function collapse is explained as a decoherence effect, by showing that normal interaction with local environments blurs phase relations between spatially separate parts of any wave function, an effect which becomes particularly strong when complex environments or systems like ordinary apparatus are involved. Under the appropriate conditions, therefore, a particle behaves « as if » its wave function had been reduced to the field immediately around it.

2. Many-Worlds. The second approach I want to discuss is an improved version of the Many-Worlds interpretation of QT_0. Encouraged by the vast success quantum mechanics, MDW presents QT_0 as a complete dynamical theory, with U_t acting as the sole evolution operator. There is no collapse of the wave function, and so systems go on entangling themselves indefinitely, which means that the only well-defined wave function is that of the entire universe.[11]

How does MDW account for situations of the Schrödinger's cat variety? As we have seen, in such situations, the total state decomposes into several superposition terms, each associated with a different state for the macroscopic and mental substates involved. MDW theorists talk of « branches » or « relative states » when a superposition involves terms that correspond to markedly different (classically incompatible) substates of ordinary macroscopic objects. In the 1980's, studies of the effects of complex environments on the wave function gave special physical significance to the position basis. It was found that superposition terms involving complex systems (like, for example, a small solid object) rapidly decohere in the position basis, making subsequent detection of wave function interference virtually impossible. Calculations showed that

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[10] [Bohm, D. & B. Hiley 1993].

[11] [Gell-Mann & Hartle 1990].

interactions with such environmental factors as background radiation, surrounding molecules, etc., quickly blur the relative phases between branches. Applied to the Schrödinger's cat case, this means that the main superposition terms rapidly decohere ; and it has been claimed that this explains the classicality of the world we ordinarily experience.[12]

Decoherence studies have encouraged valuable work on states involving macroscopic systems, but their contribution to resolving the cat paradox seems limited to showing that, in practice, it is not possible to observe interference effects among the « incompatible » branches. Decoherence by itself cannot reduce the wave function to anything like the expected post-measurement mixed states. Conceptually, decoherence provides a solution to the measurement problem which is good only *for all practical purposes* — « FAPP » using the happy term introduced by J. S. Bell's critique of the approach.[13]

On the favorable side, decoherence studies have identified a natural way of introducing probability in the deterministic world of QT_0. This is important, as the phenomenon of interference makes it generally difficult to link superposition terms to probabilities. In particular, probabilities cannot be assigned to superposition branches unless all the values add up to 1. Building on this result, and on the quick pace at which decoherence proceeds in situations involving complex systems, MDW identifies superposition branches in Schrödinger's cat situations with quasi-classical « worlds »[14]. This is based on the fact that decoherence, by making the terms of a Schrödinger's cat superposition orthogonal in practice, allows one to attach well-defined probabilities to them in the position basis, both synchronically and over sequences of events. The sets of events thus delineated in configuration space-time are called « consistent histories ».

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12 [Zurek 1982], [Zurek 1993].

13 [Bell 1990].

14 Such branches present a natural degree of spatial coarseness, inherited from the constitutive systems themselves. Arguably, the size of large organic molecules provides a natural scale.

Nevertheless, decoherence cannot reduce the wave function ; it can only induce a type of behavior which mimics that of a mixed state. An account is needed of (a) how we come to experience a classical-like world, and (b) how quantum mechanical probabilities enter the picture.

The obvious first task ahead is to try to supplement the decoherence approach with a convincing physicalist model of mental states. No more needs to be assumed than that the latter supervene on the physical states of the brain. Working out the required model is ridden with difficulties, but the first step seems clear. Whenever we end up entangled in a state of the Schrödinger's cat variety, our experience corresponds to one and only one of the terms in the superposition : we find ourselves either with the cat dead or with the cat alive, but never in an « intermediate » case. Common experience seems at odds with the QT_0 description here, but this, followers of MDW say, happens only because we do not let physics tell us what is *really* going on.[15] Once we let QT_0 speak, partisans of MDW insist, we discover that behind the illusory experience of wave function collapses lies a quantum mechanical universe in which a growing collection of many decohering « worlds » expands and multiplies indefinitely.

3. Spontaneous Collapse. Lastly I want to discuss theories that incorporate spontaneous collapse [SC] of the wave function into the fundamental dynamics. According to this approach, the linear dynamics of QT_0 is correct but incomplete, because it cannot describe the evolution of ordinary macroscopic objects. Entanglements of the Schrödinger's cat variety are simply eschewed by such objects. In order to guarantee that cats and mountains do not spread out too far away quantum mechanically from their habitual sharp states, SCA supplements the dynamics of QT_0 with a nonlinear stochastic. The corresponding operator, which will be represented by the symbol « π », is introduced as a generalization of C, the operator associated with the PP. Unlike C, π operates universally and contains no intrinsic reference to « measurement » or « conscience ». The

[15] Recent descriptions of mental states inspired by the Many Worlds approach provide several possible schemata. See, in particular, [Lockwood 1989], and [Albert 1992], [Saunders 1993], and [Squires 1993].

total dynamics thus postulates two independent and universal modes of evolution : U_t and π. The ontology of the theory is that of the quantum wave function.

Among the salient features of π, the following are especially relevant. π acts very slowly when quantum systems with only few degrees of freedom are involved, and very quickly when systems of the complexity of ordinary macroscopic objects take part. Under standard measurement conditions, the dynamical term associated with π renders states of the Schrödinger's cat variety both unstable and short-lived. π operates on a preferred basis, proposals varying about the choice here.[16] The probability that the wave function will collapse around a particular value on the preferred basis is generally postulated to follow Born's rule (or something very close to it).

The most developed SC theory to date is a proposal articulated in the mid-1980's by Gian-Carlo Ghirardi and several other thinkers.[17] Ghirardi et al. postulate that all systems spontaneously undergo random reductions of the wave function on the position basis, and that these reductions concentrate the system's wave function within a radius of about 10^{-7} meters. The spatial center of concentration is selected at random, with prior probabilities given by a law similar to Born's rule. All measurements are taken to correspond to a determination of some macroscopic position. In an isolated particle lacking internal degrees of freedom, the average time between two spontaneous reductions is postulated to be very large (10^{16} seconds). This means that the action of π on a system made up of just a few quantum particles will be exceedingly weak. Accordingly, isolated pairs of elementary particles, small groups of atoms, and larger systems up to at least middle size molecules, are acted upon by π only once in a long while in human terms. By contrast, π prevents even small macroscopic objects from developing « embarrassing » entanglements of the Schrödinger's cat variety. This

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16 See, for example, [Ghirardi 1986], [Gisin 1989], [Cordero 1996].

17 The most relevant references include [Ghirardi, Rimini & Weber 1986] ; [Ghirardi, Pearle & Rimini 1990] ; [Ghirardi, Grassi, Butterfield & Fleming 1992] ; and [Ghirardi, Grassi & Benatti 1995]. Other possibilities concerning wave function collapse are discussed, for example, in [Gisin 1989], and in [Cordero 1996].

is so because even a barely visible speck of solid matter contains something like 10^{18} atoms ; it must thus be expected to undergo 10^4 atomic spontaneous localizations per second, on average, if kept in isolation — a good deal more otherwise. Since, in addition, interatomic bonding in solid materials is extremely strong, actions of π on individual atoms will generally amount to localizations of the total center-of-mass wave function. One important effect of π is, therefore, the continual resetting of every ordinary macroscopic object to a sharp position state. And so, whenever the wave function can be written as the sum of macroscopically different histories, SC process must be expected to occur with very considerable frequency.

SC theories explicitly modify the dynamics of QT_0, and this makes them differ in predictions from the other approaches reviewed. Linear proposals are, in principle, empirically at odds with SCA theories because the effects of lingering interference phenomena are drastically curtailed by SC processes. In the proposal by Ghirardi et al., for instance, SC processes are accompanied by minute violations of energy conservation. Clashes like this with mainstream quantum mechanics initially led to vibrant expectations of resolving the question about the existence of SC processes experimentally.[18] But, then, some surprising theoretical analyses from decoherence studies came to the fore. Detailed (and increasingly realistic) calculations revealed that regular interaction with an environment of medium complexity induces decoherence in the position basis in times much shorter than anyone had anticipated. Particularly important in this regard are scattering analyses which yield decoherence times much too short for the Ghirardi et al.'s mechanism to make *any measurable difference.*[19]

We are thus left in a strange position. The three most highly articulated objectivist proposals produced to deal with the measurement problem embody very different ontologies and predict different phenomena. Quite unintentionally, however, the approaches seem to allow for no actual experimental discrimination, not even

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18 See, for example, [Shimony 1989].

19 Put formally, whenever complex systems are involved, the decoherence effect diagonalizes the density matrix much faster and more powerfully than any of the SC mechanisms proposed so far. See [Tegmark 1993].

between collapse and no-collapse proposals. This is not a result imposed « from the theory down », but something imposed by the way the world is. We have landed in a situation of *contingent observational equivalence*.

This brings us back to the questions about methodology with which we started.

Assessing Theories

I have considered only some current foundational proposals concerning QT ; and, admittedly, the debates generated by the decoherence analyses outlined in the previous section are far from over. Nevertheless, the case of experimental underdetermination we have encountered, has, I think, important methodological implications.

As already admitted, in current scientific methodology differential prediction is only part of the story. Proposals are also expected to be internally consistent, coherent with the larger body of accepted information, modest and fruitful. As yet of the three reviewed programs satisfies all these requirements to perfection.

Bohm's approach, though much improved by recent work, continues to look artificial. This is so especially because the proposal incorporates a peculiar kind of force, called the « quantum force »,[20] introduced to mimic the effects of interference. As previously indicated, the field associated with this force is essentially the total wave function from QT_0. Unfortunately, however, this element is at odds with the rest of current scientific knowledge. For starters, unlike all other forces known, the quantum force does not decrease with distance. Second, the wave function is anomalous as a force-field in that it acts on the associated quantum system without any reciprocal effect from the latter. Third, to the extent that the quantum force acts instantaneously over arbitrarily large distances, there is a direct clash with special relativity. The theory also allows for a most uneconomic multiplication of empty wave function fronts.

[20] See, for example, [Holland 1993]. The field associated with this force is essentially the total wave function from QT_0 introduced to mimic the effects of interference.

The problems with the Many-Worlds approach are no less significant. At the forefront there is a serious issue about probabilities. According to most thinkers, probabilities must refer to things that actually happen. However, depending on how one sees the matter, in MWA, either every possible outcome is actualized in some branch, or (from the perspective of the total state) simply no event properly ever happens.[21] On the most coherent versions of MWA the probability space is correlated with the outcomes we experience. Though more work is needed here, within the framework of QT_0 it seems viable to define the required probabilities (that an observer in a particular Schrödinger's cat branch will or will not *experience* a definite outcome). This would make the probabilistic events associated with wave function reductions epiphenomenal, but they would be no less real than, say, events of color vision.[22] However, to the extent that MWA imposes an endless multiplication of effectively independent *worlds* on physical reality, the approach is deficient from the point of view of ontological economy. In addition, MDW faces significant metaphysical difficulties about identity over different branches, including personal identity.[23]

The difficulties confronted by the specific SC program advocated by Ghirardi et al. seem also serious. Since the wave function is interpreted realistically, its collapse generally involves superluminal changes of physical structure. This is not, however, the type of change that allows for signal transmission, and so only the spirit of special relativity is violated. So, Lorentz invariance must be interpreted as a stochastic symmetry[24] ; and, to avoid contradictions

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[21] See [Albert 1992], and [Squires 1993].

[22] Several approaches have been advanced. In Lockwood's physicalistic theory [Lockwood 1989], the state of the mind is correlated with a physical parameter ; when a mind makes an observation, it splits according to regions within the parameter's range. A more mentalistic approach is found in [Albert 1993], where there is one mind per branch of the Schrödinger's cat variety, with all the possibilities represented by these branches being experienced. A radical mentalistic proposal is advocated in [Squires 1993], in which consciousness is taken to be something from outside of physics and to select at random from the possibilities given by the wave function, the probabilities yielded by Born's rule giving weights for the random selections.

[23] See, however, [Saunders 1993].

[24] See, for example, [Ghirardi, Grassi, Butterfield & Fleming 1992].

in the assignment of probabilities, the wave function must be defined on preferred hyperplanes in space-time rather than in the usual way.[25] Perhaps more seriously, the wave functions yielded by Ghirardi et al. present tails which export the internal structure of every condensed physical system to all regions of space. Arguably, this makes their wave functions, and ultimately their ontology, too qualitatively similar to those of MWA.[26] In the world depicted by Ghirardi et al. there is a dominant branch (whose amplitude is very close to value 1) and myriads of branches of « negligible » amplitude. Ghirardi et al.'s mechanism all but guarantees that the dominant branch will remain dominant forever. The problem is that, what goes on in a branch — the history that it unfolds — has nothing to do with amplitude. The resulting ontology thus really seems of the Many-Worlds variety. This finding does not render the approach incoherent, but it does seem to upset its original purpose, which was to provide an ontological alternative to MWA. Arguably, however, the preferred basis advocated by Ghirardi et al. is not the only possible one within SCA. There are indications that other SC proposals, by focusing on the energy basis rather than the position basis, may solve the measurement problem without falling into a Many-Worlds theory.[27]

Whatever the fate of the above approaches, for present purposes, the important aspect of the case is its methodological potential. Therefore I want to turn now to an exploration of the conceivable (though not necessarily probable) situation in which the three reviewed approaches emerge as the only serious alternatives in QT, while remaining observationally equivalent as a matter of contingent fact. Three scenarios are of particular interest : (a) the case in which none of the proposals solves its standing problems ; (b) the case in which all of them do so ; and (c) the case in which only one proposal resolves its difficulties.

In case (a) the efforts to find the nature of the world underlying the standard quantum algorithm would have ended in stagnation. It is difficult to imagine how, under such circumstances, a skeptical response could be avoided.

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[25] [Fleming 1992].

[26] [Cordero 1996].

[27] [Gisin 1989], [Cordero 1996].

Scenario (b) confronts us with a case of genuine contingent empirical underdetermination. We would have three incompatible theories. QTM assumes a mixed ontology of particles and waves, incorporates nonlocal interaction, and requires a stochastic interpretation of Lorentz invariance. MWA is both strongly field-theoretic and consistent with strict locality, assumes just one basic quantum entity (the wave function), and postulates only one dynamical law. Finally, SCA is strongly field-theoretic, incorporates just one basic quantum entity (the wave function), postulates two dynamical laws, and requires a stochastic interpretation of Lorentz invariance.

Locality and simplicity considerations might, in this case, tempt some to favor MWA over the other competitors. But, as previously explained, the status of strict locality has been lowered by the Bell experiments. And, as for simplicity, its epistemic status depends on how nature is believed to operate. Unless one already knows that nature must be « simple » or « beautiful », simplicity considerations are out of place. The value of simplicity is unproblematic only in terms of merely instrumental expediency. This may become important when, for example, what is at stake is a fuzzy theoretical account, i.e., one given by laws and descriptions of the form :

$$f(q \pm \delta_q, p \pm \delta_p) \pm \Delta_f = 0$$

Here many choices are possible for f. The decision between candidates will involve an element of convention, and it will generally make sense to select the simplest function — let us identify it as $\mathfrak{I}$ — capable of representing the above set. Whatever the choice, however, the primary referent will be the total fuzzy set, and any two possible functions $\mathfrak{I}$ and $\mathfrak{I}'$ will have to be close to each other within the parameter Δ. But, none of this can be relevant to the competition among the three approaches we have examined. For whatever the proximity of theoretical substructures at the observational level, the competing theories diverge dramatically at deeper levels. Their proximity is thus not at all as with $\mathfrak{I}$ and $\mathfrak{I}'$.

If simplicity cannot be the basis for choice in this case, what about other considerations? SCA is more like a deduction from phenomena than MWA, providing detailed models of the measurement situation, including explanations of why and how measurement interactions take time. Arguably, QTM stands in an intermediate position between the other competitors ; it builds on the fact that nearly all the known elementary particles are detected *as particles* in the laboratory, and expresses an intense commitment to classical ontology.

So, what if no other ways were found for preferring one proposal to the others? Then, the appropriate response would seem to be a suspension of judgment about the deep structures differentially described by the approaches reviewed. Such a suspension would not transport us back to a superficial or pre-scientific sphere of belief, for the structures common to the three approaches already correspond to some depth, particularly if a reasonable criterion of approximate structural similarity is used to measure the latter.[28]

Scenario (c), where only one proposal resolves its problems, is, I think, the most interesting from the methodological point of view. Acceptance of the winning proposal might still depend on its fruitfulness, particularly in terms of explanation of previously disconnected events and regularities. But, should the surviving theory win acceptance, differential prediction would have played no role in the decision. The basis for confidence would not have been a basis for expectation of being proved right by experiment and observation. What would have been decisive is total coherence with the best information available, harmonious integration of the total picture of the world, and minimization of leaps of faith. For example, if the winner were a SC theory, its fruitfulness might make itself evident as new light on the second law of thermodynamics. But, whatever the theory chosen, it would imply its own lack of differential predictive value compared with the competitors. Here lies the methodological interest of the case. For, once such a theory is taken as true, the very fundamentality of the theory would seem to devalue the importance of predictive power for the assessment of ulterior hypotheses.

[28] [Cordero 1995].

Knowledge and Methodology

We seem to have, therefore, a prima facie case for claiming that scientific considerations could conceivably compel us to move away from current methodological values. At any rate, we can imagine a correct fundamental theory of the world that does not admit of the sort of empirical corroboration or simplicity required by current standards of scientific acceptance. The case reviewed allows us to see how scientific results might shift the prevailing methodology of theory choice from requiring predictive power to merely welcoming it as a feature. Subsequently, failure to detect experimental differences between a theory and other proposals would not have to be interpreted as a failure of theory. Methodological change thus appears to be both possible and continuous with scientific conceptual change.

The case discussed ties in with recent work in epistemology. In particular, it instantiates a rational modality of conceptual change advocated by Leplin, in which a new theory is accepted by previous methodological standards, and subsequently this theory has the effect of supplanting those standards. If, then, the new theory turns out to be sufficiently impressive to serve as a model of good theory, its features will be naturally adopted as criteria of adequacy.[29] Consistency requirements would, of course, have to be observed. In particular, elements of the new theory that were originally recommended by the initial methodology would have to continue to fare well by the successor methodology.

I have explored only a limited scenario, but I hope my main point is clear : *Good sense* in theory choice is a learned virtue. For it does seem possible for us to rationally come to accept a theory that effectively lowers the epistemic status of such methodological features as simplicity and/or experimental testability. If so, through the reflective practice of science we discover not only which features of our theories advance our current epistemic goals, but also which of our goals turn out to be in harmony with what have learned about the world and ourselves in it.

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[29] [Leplin 1993].

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