

describe them. Truth is more fundamental than representation. It is only because we are in the first place able to make true judgements about hot and cold bodies, the motions of planets and the geometrical forms of objects, as well as about the behaviour of measuring devices, that we can (truly) assert that the temperature of a body is 37.3°C , that Mars revolves around the sun in 687 days and that the rectangular table-top of my desk is $113\text{ cm} \times 187\text{ cm}$. The indexicality of our scientific representations is not a threat to the truth of statements that describe the facts on which their success relies. In a predicative statement, we may (indeed, we must) abstract some characteristics of the described phenomenon, but this does not prevent it from really possessing some properties, a fact which can also be ascertained by other observers. At the end of the day, true statements grounded on facts attested by observation provide the inescapable basis for the success of our scientific representations.²

*Université Catholique de Louvain
Louvain-la-Neuve
Belgique
michel.ghins@uclouvain.be*

- 2 I am grateful to Gabriele Contessa for very useful comments on a first draft of this article, as well as to the participants of the seminars in philosophy of science held at the Institut Supérieur de Philosophie during the academic year 2009–10: Bao Van Lan, Patrick Assir Toty, Isabelle Drouet, Leonardo Rolla, Olivier Sartenaer and Arne Vangheluwe.

Science without Representation

RICHARD HEALEY

Galileo set the agenda for modern physical science by requiring it to explain how such apparent features of our world as colours, sounds, tastes and smells are produced by a colourless, silent, tasteless and odour-free reality. Van Fraassen calls this the *Appearance from Reality Criterion*. He acknowledges our enormous advances in physics since Galileo's day, but argues that these have in the end come about by abandoning this along with other completeness criteria associated with necessity, determinism and causal explanation. The appearances physics (as practised and preached by the Copenhagen developers of quantum mechanics) has declined to explain are 'the contents of measurement outcomes'.

Even if that theory is superseded (or if fundamental physics develops in accordance with a new interpretation under which the Criterion can be satisfied) our view of science must be forever modified in the light of this historical episode. (291)¹

I think van Fraassen is right to see the development of quantum mechanics as a turning point for physical science with a profound moral for philosophy, and not just for the philosophy of science. But the moral is not that even a completely successful physical theory may fail to account for the appearances by showing how they arise within the reality it represents. The moral is more radical: it is that a physical theory – even a fundamental theory – may be completely successful in all its applications without offering a representation of reality at all.

The quantum challenge to the Appearance from Reality Criterion is presented in the final pages of the last chapter of *Scientific Representation*, a mature and densely structured work that sets out to chart the analytic topography of a significant part of contemporary philosophy of physical science. Since I endorse much of van Fraassen's new cartography, I begin by reviewing what I take to be common ground before addressing his challenge.

That measurement is a form of representation is a central theme of *Scientific Representation* to which van Fraassen devotes two chapters. In Chapter 6 he addresses the physical correlate of measurement – the physical interaction between the object of the measurement and some measuring device whose final reading yields the outcome of the measurement. As he says

If that interaction is in the theory's domain, the theoretical description will be of this interaction in the same terms as any other physical interaction, and involve no terms that signify anything intensional or intentional. (143)

It is just here that the quantum measurement problem arises, since quantum theory is hard put to it to provide any satisfactory description of a measurement interaction, as we shall see. But there is more to measurement than its physical correlate. We perform a measurement to acquire information about its object. Then measurement becomes an intentional act, and our theories colour the interpretation of information provided by its outcome, making this intensional. Chapter 7 analyzes the information provided by the measurement outcome. According to van Fraassen

What the outcome reveals is not directly what the measured object is like, but what it 'looks like' in that measurement set-up. (183)

1 All page references in the text are to van Fraassen's *Scientific Representation*.

He says similar things elsewhere (92, 149, 167, 179–80, 290). This deceptively simple formulation admits of several interpretations of varying credibility. In my attempt to cover common ground, I first interpret it in two ways that convey something correct about measurement, one more significant than the other.

Not all measurements are equally good. Some are carried out incompetently, others rely on flawed techniques. It is at best a coincidence when the outcome of a bad measurement reveals what the measured object is like. Van Fraassen is not making this obvious point. At times he seems to be making the correct, but less obvious, point that our taking a measurement outcome to reveal what the measured object is like is hostage to the fortunes of the theory in whose light we interpret its significance.

The outcome of a measurement provides a representation of the entity (object, event, process) measured, by displaying values of some physical parameters that – according to the theory governing this context – characterize that object. (179–80)

One may accept this, while continuing to maintain that a well-conducted measurement, soundly based on reliable techniques within the domain of application of well-tested theories, does indeed reveal what the measured object is like. That is consistent with acknowledging that any particular measurement's claim to reveal what the measured object is like is of course fallible, and may come to be rejected if, for example, any of these theories fails further tests.

In the course of his insightful discussion of measurement, Van Fraassen makes several important points we should take to heart. Measurement is not just the assignment of numbers according to rules. Rather,

locating something in logical space is the over-arching concept under which all actions of measurement can be arrayed. This is the only stopping point we have found in the successive generalization of the notion of number-assigning. (172–73)

The rules governing this locating may be viewed *from within*, as theory and measurement develop in tandem, or *from above* when this development has reached at least a temporarily stable stopping point. This dual perspective is required to solve the persistent problem of how theoretical concepts come to be coordinated to the world through measurement procedures. The content of a measurement outcome is essentially *indexical* since an act of measurement locates *this object of measurement* in the logical space of some system of representation. But even though he calls their contents appearances, measurement outcomes are public and intersubjectively accessible, as scientific methodology requires them to be.

On all these points I expect, or at least hope for, wide agreement with van Fraassen. But his attachment to constructive empiricism continues, and here I

part company with him, leaving our common ground. These days a great deal of activity undertaken in scientific research laboratories is directed towards measuring magnitudes pertaining to objects or events that van Fraassen would count as unobservable since they elude our unaided sense organs: consider measurements of the mass of a neutrino or of the black hole at the centre of our galaxy, the temperature near the centre of the sun, the anomalous magnetic moment of the muon, the value of the Weinberg angle in the unified electro-weak theory or even the width and helical angle of the DNA molecule. I venture that most scientists engaged in such activity believe that they are aiming to find out the value of the magnitude in question on the measured object. Not so, according to van Fraassen. He would maintain that (at least in some of these examples) their true purpose is to locate the *supposed* object in the logical space of theory so as to preserve empirical adequacy – science’s real goal. Meeting that goal is what science is about, for the constructive empiricist. That leaves it up to the individual scientist whether to believe there *are* any neutrinos, black holes, muons, electro-weak interactions or DNA molecules: commitment to the sun is not optional, but the status of its *centre* seems less clear! Here, we see a less innocent interpretation of the phrase ‘what it ‘looks like’ in that measurement set-up’, according to which ‘looking like’ something need not imply that thing exists. This may not be an interpretation van Fraassen means to allow. But to exclude it by requiring that the only measurements are on *observables*, yielding appearances as their outcomes, would be to ride roughshod over scientific usage of the term ‘measurement’. I take his discussion of the measurement of spin-component of (unobservable!) silver atoms by a Stern–Gerlach device to provide evidence of his conformity to that usage.

To begin to explain my disagreement with van Fraassen about the correct moral to draw from the development of quantum theory, I return to his discussion of the physical correlate of measurement in Chapter 6. As he notes, this was tailored to fit the peculiar features of quantum mechanics. The result shows enough evidence of strain in the fabric to prompt the concern that quantum measurement is a topic unto itself. In a justly influential paper, the physicist John Bell concluded that no fit should be attempted. In his view

the word has had such a damaging effect on the discussion [of the foundations of quantum mechanics] that I think it should now be banned altogether in quantum mechanics.²

One of Bell’s charges against the word ‘measurement’ was that

the word comes loaded with meaning from everyday life, meaning which is entirely inappropriate in the quantum context. When it is

2 Bell 1990: 34.

said that something is ‘measured’ it is difficult not to think of the result as referring to some pre-existing property of the object in question.³

Van Fraassen uses a toy example to illustrate why it would be a mistake to think that is how the word is used in quantum mechanics.⁴ But if the veracity of measurement fails in quantum mechanics because it does not faithfully reveal the value of the measured magnitude, what useful information could a quantum ‘measurement’ convey? He gives an answer in terms of the probabilities and frequencies involved in a classic example of (what is called) a quantum measurement: the Stern–Gerlach apparatus. This is said to measure the spin component of a system like a silver atom by passing it through a suitable magnetic field and then ‘seeing’ where it goes. As is well known, there are powerful reasons to deny that the position at which a silver atom is subsequently detected faithfully reveals its spin component along the axis of the magnetic field. But if many silver atoms are similarly prepared by some source, the relative frequencies with which they are detected at various locations do provide information about the source, and thereby permit reliable statistical inferences about the measured behaviour of such silver atoms in *other* kinds of experiments.

The outcome does not reveal a prior state for an individual silver atom, but the frequencies in the outcome do give information about the prior state in which the source prepares what it sends out. (155–56)

His example illustrates van Fraassen’s general theory of the physical correlate of measurement. This is intended to apply to physical theories in which the relation between physical state and measurement outcome is only characterizable in terms of probabilities. What is required of a measurement interaction is just that the final state of the apparatus be appropriately correlated to that of the measured object, for each of a wide class of initial object states. The key Criterion for the Physical Correlate of Measurement therefore requires only that these states agree in the *probabilities* they assign – on the one hand to the measured parameter of the object, and on the other hand to the ‘pointer position’ parameter of the apparatus.

This is problematic, since the probabilities in each case are for *measurement outcomes*. If we were looking for a way to restore some kind of veracity to measurement by moving to probabilities, then we have made no progress. Satisfaction of the probabilistic Criterion for the Physical Correlate of Measurement would have given us what we wanted only if each individual

3 Ibid.

4 Bell’s main charge was that no such word has a place in a formulation of quantum mechanics with any pretension to physical precision. Van Fraassen does not claim to offer such a formulation in his book. Certainly this is not to his purpose in Chapter 6, though in its footnotes and later in Chapter 13 he seems quite content to adopt a standard formulation that disregards Bell’s injunction.

outcome whose probability is specified were *itself* veracious. Van Fraassen disagrees

we can see now that *Veracity* is honored at some appropriate level. ... In practical terms it is precisely the source on which the measurement, taken as a whole, is performed. (155–56)

In assessing this response to the problem we need to distinguish two claims:

- (1) The relative frequencies with which silver atoms are detected in various locations beyond the magnet constitute the outcome of a measurement on the source that prepared them.
- (2) Each detection of an individual silver atom at a specific location beyond the magnet constitutes the outcome of a measurement on that atom.

When a Stern–Gerlach magnet is considered part of an apparatus for measuring the spin component of a silver atom, it is the second claim that is relevant. A Stern–Gerlach apparatus is not a device for performing a quantum measurement on the atom’s source: its function is to perform (typically) *non-veracious* quantum measurements on individual silver atoms.

Quantum measurements of spin-component (or the analogous magnitude polarization) are now routinely carried out on individual spin 1/2 atoms including silver (respectively, photons) without regard to their source, and sometimes when this source is unknown. The quantum-mechanical representation of such a system’s state is by a qubit: quantum measurements on individual qubits are fundamental to the flourishing new field of quantum computation. A qubit represents the simplest kind of quantum state, and the only universally acknowledged role of *any* quantum state in the theory is to assign a probability for each outcome of any possible measurement on the system whose state it is.⁵ The way these probabilities are assigned guarantees that no quantum measurement on an individual system can reliably reveal its previously unknown quantum state. But as van Fraassen correctly notes, the frequencies of outcomes of one kind of measurement on similar systems do give information about their common quantum state, and by combining the frequencies of outcomes of enough different kinds of measurements on similar systems one can reliably estimate that state.

Van Fraassen returns to quantum mechanics in Chapter 13 to argue that its development shows science is not bound by the demand to explain how the

5 In a case where the probability equals 1 that a measurement of Q on system s at time t would yield outcome q , some assign the quantum state of s a further descriptive role in which it implies that Q has value q on s at t even if no apparatus is actually set up to measure Q at t . But Bohr does not do so, even though Einstein assumed that on the Copenhagen interpretation the quantum state plays this descriptive role while arguing against that interpretation.

appearances are produced by the underlying reality it represents. The appearances in question are the outcomes of quantum measurements, and the failure of quantum mechanics to use its representations to explain their production is intimately connected to the notorious quantum measurement problem. In the course of his argument van Fraassen offers an empiricist dissolution, or rather dismissal, of *that* problem. In response, I shall argue that the quantum measurement problem could be remedied only by stronger pragmatist medicine. The pragmatist moral of the development of quantum mechanics is then that the development of a scientific theory may constitute great progress even though that theory offers no novel representation of a reality capable of producing measurement outcomes.

Quantum measurements have outcomes whose probabilities the theory correctly predicts through its Born rule as applied to the quantum state of the measured system(s). If it is to explain how these outcomes are produced, it must represent them within its models. The only available candidate is the mathematical object (vector or density operator) the theory uses to represent the quantum state of a system. So any description the theory offers of the physical correlate of the measurement outcome must be provided by such a representation of the quantum state of the apparatus at the conclusion of its interaction with the measured system. The theory does have the resources to model a suitable interaction satisfying the Criterion for the Physical Correlate of Measurement. But this is not enough to show how any individual measurement outcome is produced. To do that one would have to use the theory to show, for each of a wide range of initial quantum states of a single quantum system, that this interaction would put the apparatus into a correlated quantum state representing the outcome of the measurement. The problem is that can't be done: for most initial quantum states of the measured object, the final quantum state of the apparatus after an otherwise suitable interaction fails to represent the measurement as having *any* determinate outcome.

Van Fraassen argues that this is *not* a problem when the theory is seen through empiricist eyes:

... [N]one of this entails that what happens in the actual situation must be displayed as entirely identifiable in the theoretical model. The most stringent demand that can be made here is that the relative frequencies of certain events in this sort of situation must have a good fit to probability functions, extrapolated from them in surface models, which are identifiable as parts of corresponding probability functions in the theoretical models. (305)

This demand is met by observed frequencies of measurement outcomes, as classified in accordance with standard laboratory practice, and that is enough – for Copenhagen physicists, and for van Fraassen's philosophy of science. A further demand, to explain how each individual measurement outcome is

produced by representing its production within the theory, is *not* met in quantum mechanics. So the Appearance from Reality Criterion has been rightly rejected in the development of our most successful scientific theory.

But Van Fraassen's dismissal of the measurement problem is premature. To see why, focus on the event spaces of the relevant probabilities, in quantum mechanics on the one hand and in the surface model of the experimental frequencies on the other.

The surface models will provide probability functions for events that are classified as outcomes in situations classified as measurements of given observables. Those probability functions need to be parts of the theoretically specified Born probabilities for the same situation as theoretically represented in terms of possible states and evolutions. (305)

The probability function event space for the surface model of a particular measurement is relatively unproblematic: it is constituted by the various outcomes of that measurement, as classified by standard laboratory practice. If these probability functions are to be parts of the theoretically specified Born probabilities for the same situation, both must share the same event space. But the only available theoretical representation of a measurement outcome is by a quantum state, and the evolution of the quantum state during a measurement interaction as modelled within the theory implies that the final apparatus quantum state almost never represents *any* determinate outcome of the measurement.⁶ It is true that one could continue to represent each of the various outcomes of a laboratory measurement by a corresponding quantum state, simply ignoring the problem of how this state could have evolved in any quantum-mechanically describable measurement interaction.⁷ But once the link to quantum dynamics has been cut, no significance attaches to the fact that the theoretical probabilities of these quantum states match those of the surface model: the representation of a measurement outcome by a quantum state of the apparatus has been rendered idle.

It is precisely because he assumes quantum states (are used to) represent reality in quantum mechanics that van Fraassen has not yet succeeded in dismissing the measurement problem. By dropping this assumption, we can put the problem behind us and come to a better appreciation of how the development of the theory should change our view of science.

The developers of quantum mechanics did not agree on the nature of the quantum state, and the topic remains controversial to this day.⁸ To deny that assigning a quantum state to a system is a way of describing or representing

6 Just as the quantum state of Schrödinger's cat does not represent it as alive or as dead.

7 Perhaps this is why van Fraassen believes his dismissal of the measurement problem evades the dilemma he set up himself in the dialectic that creates the problem on pages 298–99.

8 As was manifested by the striking lack of consensus among the participants at a conference 'New Perspectives on the Quantum State' held recently at the Perimeter Institute for Theoretical Physics: see <http://pirsa.org/C09022>

(some of) that system's properties is to take a position in this controversy held by some, but not all, of the theory's Copenhagen founders. But the lack of consensus on this issue contrasts strikingly with the overwhelming consensus on how to apply the theory, and the wholly successful results of all such applications. This is strong evidence that one can consistently accept quantum mechanics while denying a descriptive or representative role to the quantum state. One distinct advantage of doing so is that this permits a simple response to the quantum measurement problem.

If quantum states neither describe nor represent any reality according to the theory, then *a fortiori* the theory cannot represent the outcome of a measurement interaction by any quantum state of the apparatus. (So the denial commits one to supposition 1 as stated by van Fraassen on page 298.) This makes the theory *descriptively* incomplete (as Einstein famously argued it was). But, as Bohr insisted, no *predictive* incompleteness follows. Given a full specification of any situation in which one wishes to apply quantum mechanics, including a description of the various measurement outcomes in terms available independently of quantum mechanics, an assignment of a quantum state to the target system always generates a well-defined probability function over these outcomes. There is no tension between the dynamics of the quantum state and the Born rule, since that dynamics represents no physical process while the latter concerns events not represented by any quantum state.

If the role of the quantum state is to generate probabilities for various measurement outcomes, doesn't playing this role entail describing or representing something after all, namely these probabilities? That depends on the status of quantum probabilities. According to one popular view, quantum indeterminism is a locus for objective chance: at least some quantum state assignments can then be understood to describe such objective chances. David Lewis developed an influential account of objective chance and connected it to subjective credence through his Principal Principle. This account does not mesh well with the way quantum states generate probabilities.⁹ According to self-styled quantum Bayesians, there is no such thing as objective chance: the quantum state generates subjective/personal probabilities. They readily infer that quantum state assignments are equally subjective. Interestingly, I think van Fraassen's own view of a theory's use of probability is to be preferred to either of these alternatives. He reviews this in an Appendix to Chapter 13.

9 In an experimental test of violations of Bell inequalities at spacelike separation, how and when does the chance of Bob's outcome change as Alice makes her measurement? In a delayed-choice entanglement-swapping experiment involving four particles, how can the chances displayed by correlated measurement outcomes on one pair change when the second pair is measured *after* those outcomes have occurred?

The background to this view is van Fraassen's abandonment of any *objective* notion of probability and move towards something like Richard Jeffrey's radical probabilism in epistemology. The move did not make him a quantum Bayesian, however, in part because he does not regard acceptance of a theory as just a matter of Bayesian updating of prior degrees of belief. What is involved in acceptance of a probabilistic theory like quantum mechanics is rather adoption of that theory's probabilities as one's own degrees of belief. So if application of the Born rule in a situation that is described in terms available independently of quantum mechanics generates a probability function for outcomes of a quantum measurement, then one who totally believes quantum mechanics will take these probabilities as his guide by adopting them as his own personal degrees of belief for these outcomes. (For a constructive empiricist, accepting quantum mechanics will mean doing this only when the outcomes are themselves observable.) In Gaifman's terms, this means taking Born rule probabilities as one's expert functions for the relevant set of propositions.

I find Van Fraassen's view of quantum probabilities attractive (in its non-constructive-empiricist version!), because it explains their peculiar status as neither wholly subjective nor wholly objective. I prefer to call ascriptions of quantum probabilities *authoritative*, since their role is not to state facts but rather to offer prescriptive advice. On this view, quantum states do not generate probabilities that describe or represent anything: rather, they generate *instructions* as to how one should form one's beliefs. These beliefs are not about probabilities, and nor are they about any property of the quantum system whose state generates them. They are beliefs about outcomes of measurements on that system, described in terms available independently of quantum mechanics.¹⁰ So, perhaps, I temporarily rejoin common ground with van Fraassen in denying that probabilities in quantum mechanics are used to represent anything in that theory. It follows that the quantum state does not inherit any descriptive or representative role by generating them. The quantum state is first and foremost a recipe for generating instructions to a physically realized agent in a specific physical situation on how to form beliefs about results of (actual or hypothetical) measurements of whose outcome he is ignorant.

If one accepts this, then neither quantum probabilities nor the quantum state that generates them serve to represent anything, according to the theory that introduced them. Outcomes of quantum measurements are represented, but not by anything newly introduced by quantum mechanics: rather, they are represented by linguistic expressions or mathematical objects that come from

10 Notice how nicely this handles cases that present problems for objective chance. Beliefs about outcomes of measurements on *S* that are appropriate for an agent (Bob) physically related to *S* in one way may be inappropriate for an agent (Alice) in a different physical situation *vis-a-vis S*.

elsewhere. Bohr's (rather misleading) way of putting it was to speak of ordinary language suitably enriched by terminology of classical physics. Quantum mechanics does introduce new classificatory terminology such as spin and the distinction between bosons and fermions. But even here one can understand such terms as functioning non-descriptively in the theory – as constraining the kinds of quantum state ascription that it makes available rather than describing or representing newly introduced attributes. Spin, for example, is a form of angular momentum – a magnitude previously introduced by classical physics. Quantum mechanics simply treats it differently, by (for example) admitting outcomes of spin measurements on systems like silver atoms that cannot be understood as revealing classically permissible values of that magnitude.

So van Fraassen is right that the development of quantum mechanics shows that science is not bound by the Appearance from Reality Criterion, but not for the reason he gives. The enormous scientific progress brought about by the development of quantum mechanics shows that even our most fundamental scientific theory need not achieve its success by representing anything that science could not represent without it, however inadequately. Quantum mechanics cannot explain how measurement outcomes are produced since to apply the theory one must simply assume that they are. It is a great theory because it provides such a reliable guide in forming beliefs over an enormous range of such applications where classical physics fails.

Pragmatism provides a better analysis of this episode than constructive empiricism. Unlike constructive empiricism, pragmatism directs our attention to what the quantum state and the probabilities it generates are used to do rather than to what they represent. Quantum mechanics is simply a more refined tool than classical physics that may be successfully used in situations where the latter fails. In such situations, this tool may be used for both predictive and explanatory purposes, even though it adds no new descriptive or representational resources of its own.¹¹ For the constructive empiricist, measurement outcomes are unproblematic: the development of quantum mechanics does not modify the function of the language already used to describe or represent them. This is something the pragmatist will question. Precisely because of the success of quantum mechanics in situations where previous theories failed, he will be alert to the consequent changes in how the language of those theories functions, even as it continues to be used in describing or representing quantum measurement outcomes in order to apply quantum mechanics.

But this minor disagreement between constructive empiricist and pragmatist is a mere family squabble compared to the gulf that separates van Fraassen and me from those philosophers who hold science responsible for supplying an accurate description of the fundamental structure of the

11 This is not the place to elaborate and defend the claim of explanatory superiority, a task that must be discharged to distinguish pragmatism from instrumentalism.

physical world as a solid base for their own metaphysical endeavours. *Scientific Representation* should be required reading for contemporary physicalists and analytic metaphysicians. It is an important contribution to a grand tradition of work in philosophy of science by physicists like Boltzmann, Hertz, Mach and Poincaré as well as philosophers including Russell, Reichenbach, Carnap and Putnam willing to engage with science as it is rather than how they imagine it to be.¹²

University of Arizona
P.O. Box 210027
Tucson, AZ 85721-0027, USA
rhealey@email.arizona.edu

Reference

Bell, J.S. 1990. Against measurement. *Physics World* 3: 33–40.

- 12 This material is based upon work supported by the National Science Foundation under Grant No.SES-0848022. I also wish to acknowledge support of the Perimeter Institute for Theoretical Physics: research at the Perimeter Institute is supported by the Government of Canada through Industry Canada and by the Province of Ontario through the Ministry of Research and Innovation.

Reply to Contessa, Ghins, and Healey

By BAS C. VAN FRAASSEN

Gabriele Contessa (2010), Michel Ghins (2010) and Richard Healey (2010) each broach issues concerning realism, and their constructive critique presents a strong challenge, requiring me to specify precisely where I take it that *Scientific Representation* (henceforth SR) lands us. Contessa argues that there I have left not only metaphysical realism but also common sense realism behind. I'll argue that it isn't so, though I reject the metaphysical realism that might be taken to underpin our common sense. But then Ghins and Healey challenge just what it is that is represented, if at all, by scientific models and theories, and I will maintain that in a truly robust sense models do represent the observable phenomena.

1. What is Realism?

Contessa begins, following Stathis Psillos, by depicting scientific realism as consisting of a metaphysical, semantic and epistemic thesis. That goes against my contention that instead, scientific realism is in the first place a view that