The Representation of Nature in Physics: A Reflection On Adolf Grünbaum's Early Writings

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The Representation of Nature in Physics: A Reflection On Adolf Grünbaum's Early Writings On The Quantum Theory

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Before I turn to my main topic, which I shall explore here in the light of Adolf Grünbaum's early work in the philosophy of quantum mechanics, I want to say something to express my own debt to Professor Grünbaum, both for his guidance and for his work.

Our symposium included the opportunity to hear his autobiographical remarks, both touching and disturbing to those of us who have shared some of the last century's painful history. The remarkable outcome, a true sign of hope in my view, is that Adolf Grünbaum himself could have emerged from such a childhood and youth, all but lost to the oppression and alienation of that era, as the example of social conscience and personal charity for which I thank and admire him. For I learned as much from his personal engagement—with us students on a personal level, with social and moral issues, and with philosophy itself, where he never aimed to turn a student into a disciple—as from his scholarly achievements which provided the initial basis for my own reflections on the character of physical theory.

After graduation my first position was at Yale University, where I was fortunate to know and learn from one of Grünbaum's own teachers, Henry Margenau. It was with some curiosity, of course, that at this point I read two of Grünbaum's earliest publications, both critical responses to Margenau's philosophy of quantum mechanics. The first, "Realism and Neo-Kantianism in Professor Margenau's Philosophy of Quantum Mechanics," includes a strong defense of a scientific realist position with respect to quantum mechanics, but mainly as against neo-Kantian and Idealist themes then current in attempts to interpret the theory.[1] I will concentrate here on the second, "Complementarity in Quantum Physics and its Philosophical Generalization," together with some of Grünbaum's early articles on the Special Theory of Relativity (henceforth

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[1] A. Grünbaum, "Realism and Neo-Kantianism in Professor Margenau's Philosophy of Quantum Mechanics," *Philosophy of Science* 17 (1950): 26–34.

"STR").[2]

Although Margenau's interpretation of quantum mechanics and the Copenhagen interpretation were not at all the same, they shared an anti-realist orientation. The idea of complementarity was generalized quite far beyond the use it had seen in illuminating the appearance of incompatible observables, but those generalizations were then drawn on to suggest support for that orientation in ways that cried out for the philosophical critique that Grünbaum supplied. But the paper also engages actively with the question of how we should or can understand the world described by quantum theory, acknowledging that theory's radical departures from classical physics. This will also be my focus here. While I will not disagree nearly as much with Grünbaum's views as Grünbaum disagreed with Margenau's, I will defend one aspect of the Copenhagen interpretation of quantum theory that I see as radicalizing our understanding of physical theory.

1. Completeness Criteria For Science

Before we turn specifically to quantum mechanics and the Copenhagen interpretation I need to draw on another philosopher whose writings were a paradigm and a guide for Adolf Grünbaum as well as for myself: Hans Reichenbach. One lesson that I took away from those writings was that science is to be understood as an enterprise with a distinctive cognitive aim and with loyalty to a distinctive empirical methodology. Reichenbach himself was seriously concerned with the requirement such an understanding places on us to display the criteria of success that an enterprise thus understood must aim to satisfy — if only as an ideal, even if the perfect success, that would consist in completely meeting those criteria, is beyond reach of such finite beings

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[2] A. Grünbaum, "Complementarity in Quantum Physics and its Philosophical Generalization," *Journal of Philosophy* 54 (1957): 713–27; A. Grünbaum, "The Clock Paradox in the Special Theory of Relativity," *Philosophy of Science* 21 (1954): 249–53; A. Grünbaum, "Reply to Dr. Tornebohm's Comments on My Article," *Philosophy of Science* 22 (1955): 233; A. Grünbaum, "Reply to Dr. Leaf," *Philosophy of Science* 22 (1955): 53; A. Grünbaum, "Logical and Philosophical Foundations of the Special Theory of Relativity," in A. Danto and S. Morgenbesser, eds., *Philosophy of Science*, 399–434 (New York: Meridian Books, 1960); and A. Grünbaum, "The Relevance of Philosophy to the History of the Special Theory of Relativity," *Journal of Philosophy* 59 (1962): 561–74.

with finite resources as ourselves. His early writings on quantum mechanics included a strong defense of relinquishing certain earlier criteria, which had been held sacrosanct in modern science, but which rested, as he argued, on empirically vulnerable presuppositions.

As I learned from Reichenbach and Grünbaum, the second great scientific revolution in modern times took place around the previous turn of the century, with the coming first of all of relativity, and second, of the quantum. Inherited from modern science were the claim that all phenomena in nature derive from an underlying deterministic mechanics, and the philosophical conviction that a scientific account is complete only if it is deterministic. Supporting that conviction was the philosophical creed, current among neo-Kantians, that the very intelligibility of nature and the very coherence of experience require their possibility of being conceivable as set in a rigidly deterministic causal order. That is precisely the completeness criterion challenged most saliently in Reichenbach's early writings. The probabilistic resources of classical statistical mechanics were newly adapted in such a way that, as it seemed then, no grounding in an underlying deterministic mechanics was possible. Reichenbach sided with a vocal part of the physics community that explicitly rejectedthe task of finding or postulating hidden mechanisms behind such apparently stochastic processes as radioactive decay. Nature is indeterministic, or at least it can be or may be—and if that is so, determinism is a *mistaken* completeness criterion for theory.

Now Reichenbach, who did much to provide a rationale for this rejection of determinism, introduced an apparently weaker but still substantive new completeness criterion: the *common cause principle*.[3] This principle is satisfied by the causal models of general use in social sciences and for many purposes in the natural sciences as well. They are models in which all pervasive correlations derive from common causes (in a technical, probabilistically definable sense). But the demonstration in the 60s and later that quantum mechanics violates Bell's inequalities shows that even this third criterion

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[3] See for comparison my "Rational Belief and the Common Cause Principle," in R. McLaughlin, ed., *What? Where? When? Why? Essays in honor of Wesley Salmon*, 193–209 (Dordrecht: Reidel, 1982), and references therein. Under certain conditions this criterion actually demands determinism, as I show there.

was rejected, in effect, by the new physics.[4]

Determinism without causality? Grünbaum on Bohm's mechanics

As Grünbaum discusses (1957, note on pp. 715–16) both the denial of determinism and the analysis of causality connected with the Copenhagen interpretation of quantum mechanics was challenged by Bohmian mechanics—proposed alternatively as an interpretation of quantum mechanics and as a rival theory. Bohm describes a world of particles which have position as sole physically significant attribute, and whose motion is strictly deterministic. But that motion derives from the total quantum state, which implies that there are nonlocal correlations among these particle motions that cannot be traced back to any "synchronizing" process in their common past. So there are clear violations there too of the common cause principle, the Bell inequalities are of course violated. This example shows both that a deterministic interpretation is possible and that satisfaction of the common cause criterion is not logically implied by determinism. Bohm’s mechanics surprisingly presents us with a picture of *determinism without causality* so to speak. Citing Heisenberg and Reichenbach, Grünbaum emphasizes that on Bohm's reformulation of quantum mechanics "the behavior exhibited by the waves [the governing wave function for the multiparticle system] would be, classically speaking, every bit as strange as that of a "particle" whose motion depends on the presence of a slit through which it could not have passed." Since Bohm's mechanics has been given sophisticated new formulations in recent decades, we know now that it can accommodate the phenomena. But, as Grünbaum in effect pointed out at the time, Bohm's purport to give us a world picture close to the classical one is certainly not borne out.[5] In any case, both the lesson that a science can be indeterministic, and that the common cause criterion may

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[4] See my "The Charybdis of Realism: Epistemological Implications of Bell's Inequality," *Synthese* 5 (1982): 25–38, reprinted in J. Cushing and E. McMullen, eds., *The Philosophical Consequences of Quantum Mechanics* (Notre Dame, IN: University of Notre Dame Press, 1989).

[5] See K. Bedard, "Material Objects in Bohm's Interpretation," *Philosophy of Science* 66 (1999): 221–42; B. van Fraassen, "Interpretation of QM: Parallels and Choices," in L. Accardi, ed., *The Interpretation of Quantum Theory: Where Do We Stand?*, 7-14 (Rome: Istituto della Enciclopedia Italiana; New York: Fordham University Press, 1994).

be violated by physical theory, so that these cannot be defining criteria of success in science, remain.

However that may be, I'll now turn to a further completeness criterion that seems compatible with these rejections, and appears to be quite generally accepted at least among philosophers and by the general public.

2. Appearance versus Reality as a Scientific Problem.

The completeness criteria of determinism and causality involve demands for explanation. The sort of explanation demanded there from science is not just a supply of missing information needed for a simple, systematic account of the phenomena, but requires connections deeper than brute or factual regularity. Thus as an aspirant empiricist I tend to see those demands as placing a burden of unwanted metaphysics on the sciences. But now I want to suggest that there has in fact been a still deeper-going demand (criterion of success) upon modern science, which also came to be challenged precisely in the development of the new quantum theory. That is the demand that, however different the appearances (to us) may be from the reality depicted in theory, theory must *derive* the appearances from that reality. The sense of "derive" is strong, and once more connected with substantive notions of explanation. This demand can also be read as again a criterion of completeness: science is asserted to be incomplete until and unless it meets that demand. I need to explain this further, but let us at once give it a name: the A*ppearance from Reality Criterion*.[6]

Before asking for the precise sense of "derive" involved here, let us take some familiar examples in which science does offer us such a derivation. We credit science with adequate and satisfactory explanations of how many familiar phenomena are produced: how ash is produced when we burn a cigarette or some logs, how methane is naturally produced in a swamp, and how a flame is turned yellow when a sodium sample is inserted. Copernicus also explained the planets' retrograde motion, and the theory of sound as waves in air explains the Doppler shift. In all these cases the familiar witnessed

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[6] See my "Science as Representational and Non-representational," forthcoming in *Philosophy of Science* 2004 (Supplement) for a related exploration of this theme. [AU: this will have to be updated]

events are not just located in the theoretical world picture, but shown to derive from the theoretically described reality, although such terms as "ash", "cigarette," "swamp," "yellow," and "retrograde" have at best a derivative status there and at worst need to be treated rather cavalierly in the theoretical context.

A distinction: Phenomena and appearances

Let us introduce a distinction here, that may at first blush seem to be a distinction without a difference for such examples. By the *phenomena* I mean the observable parts of the world, whether objects, events, or processes. These the sciences must save (in the ancient phrase)—but these admit of objective and indeed purely theoretical description, which does not link their reality to contexts of observation or to acts of measurement. By the *appearances* I mean the contents of observation and of measurement outcomes. The phrase "to save the phenomena" is often rendered more colloquially as "to save the appearances" and "appearances" is generally taken as synonymous with "phenomena," but of course both are terms with a past. On philosophical lips they are often loaded with connotations that link them to mind and thought. So I am introducing a new technical distinction and use here, specially adapting these terms to our present discussion, eschewing such connotations. In this new sense the planetary motions—whatever they are or are like—are phenomena, but planetary "retrograde" motions are, *pace* Copernicus, (mere) appearances.

Galileo famously promised in *The Assayer* that the colors, smells, and sounds in the experienced world would be fully explained by a physics among whose descriptive parameters those qualities were not allowed. Descartes' posthumous work *The World, or Treatise on Light* purported to lay the foundation of a world picture entirely transparent to the human understanding—although the theory that was to provide us with that world picture was but a barely enriched kinematics. The colorful, tasty, smelly, and noisy *appearances* will be shown to be produced as (yes!) *interactional* events, in which the relata are in principle completely characterized in terms of primary qualities, respectively, quantities of spatial and temporal extension alone. These promises were not empty: there were solid achievements behind them. Those achievements accumulated into awesome riches by the late nineteenth century. Describing the success that Galileo had promised, and using our new terminological distinction, we can say: combustion of sodium samples is an observable process (phenomenon) that can be exhaustively described in physical terms, but this description can also be utilized to explain how that process produces a yellow appearance to the human eye, and of course, to a camera.

The Appearance from Reality Criterion

Given all that success, it is not surprising if the appearance from reality criterion should begin to pervade the ideals set for science. Theory must *derive* the appearances from that reality. By "derive" I do not mean a bare logical deduction. I mean a connection of the order of explanation through necessity and/or causal mechanisms to be displayed. The derivation is required to show and make intelligible the structure of the appearances as being *produced* by the reality behind them to their (possible) observers. The demand for such a derivation is not met if science should simply issue successful predictions of measurement outcomes, by means of systematic rules of calculation, from the state of nature theoretically described. That sort of success does not ipso facto amount to an explanation of why and how the appearances must be the way they are. The stronger demand that we should be able to see science as providing that sort of derivation/explanation is a continuing theme in much scientific realist writing on the sciences. I'll quote from Jarrett Leplin's *A Novel Defense of Scientific Realism*:

> A theory is not simply an empirical law or generalization to the effect that certain observable phenomena occur, but an explanation of their occurrence that provides some mechanism to produce them, or some deeper principles to which their production is reducible.[7]

On the other hand, I am not contrasting successful explanation with indeterministic or stochastic accounts.[8] An adequate explanation of how an event is produced need not be

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[7] J. Leplin, *A Novel Defense of Scientific Realism* (New York: Oxford University Press, 1997), p. 15.

[8] Attempts to provide such accounts which could perhaps provide such explanations even today include work by Stephen L. Adler and his colleagues on generalized quantum dynamics, as well

deterministic. For example, if we were to say that statistical thermodynamics explains how burning a cigarette produces ash, and add that there are random small fluctuations that modify the underlying mechanics, that would still leave us with a derivation (in the appropriate sense) of the phenomenon. Note well, though, that we can't turn this around and conclude that just any indeterministic account of how things happen then counts as such an explanatory derivation!

I am also not contrasting the Appearance from Reality Criterion with instrumentalism. For the instrumentalist denies that a theory is in any sense a story about what the world is like. That is implausible, for a story is usually precisely what a theory seems to be, though what it describes the world to be like is very unlike how it appears to us. At precisely that point the criterion applies: there is then a felt gap in the story that must be filled so that the appearances clearly derive from what is really going on. But on the other hand, again, we cannot turn this around. The assertion that the appearances are produced in some specific way, without displaying that way, does not by itself provide a satisfactory explanation. Indeed, the idealist and (quasi-) instrumentalist accounts, which Grünbaum depicted as prevalent forms of easy antirealism among scientists, seem to me to fall under this heading.[9] For it is easy enough, but entirely uninformative, to wave a hand at some relation of the theorizing and measuring agent to the aspects of nature that are measured and represented, and claim that this accounts for how the appearances differ from what science ostensibly describes. If left as a mere claim that does not suffice.

Suppose then, for a moment, that we have a science that does not manage to derive the appearance from the reality it describes. What are the philosophical alternatives? Those who accept the theory may well still believe that it correctly describes what things are really like. On the other hand, they have the alternative of *rejecting* the criterion. Then after this rejection they have still two further alternatives. For they can either deny that there is a gap "in nature," so to speak (that turns out to be the

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as earlier work by e.g., E. Nelson, *Dynamical Theories of Brownian Motion* (Princeton, NJ: Princeton University Press, 1967). Such accounts, if successful, can satisfy the Appearance from Reality Criterion no less than deterministic theories.

[9] A. Grünbaum (1957), pp. 717–19.

Copenhagen alternative[1010]), or they can adhere to a certain metaphysical doctrine. That doctrine would have the form: there is a sense of "derive" (presumably related to notions of causality or necessity in nature) in which the appearances do derive from the theoretically described reality, but that connection in nature is beyond the resources of theory to make explicit. To avoid the emptiness of such antirealist reactions as those critically discussed by Grünbaum, that metaphysical doctrine then needs to be given some content. This game is not over; there are examples still today in the literature on the interpretation of quantum mechanics, which attempt to do so. But we will concentrate here on what may be of value in the Copenhagen approach, however much it enmeshed itself in some of those philosophical tangles.

Apparent rejection of the Criterion

The new quantum mechanics developed in the 1920s was perceived even by some of the physicists most closely involved as not bridging the explanatory gap between reality and appearance. Some, as I will discuss, disagree that there is a gap there for science to fill. Some—at times the same as those who deny that there is a gap—strained to bridge it with philosophical as well as putatively physical explanations. Let us first note the bare facts of the matter. The vehicle for prediction in quantum mechanics is, at heart, the Born rule:

> If observable A is measured on a system in quantum state ψ, the
> expectation value of the outcome is $< \psi, A\, \psi >$

I take it that measurement outcomes are prime examples of what we should classify as appearances. The quantum states are then the theoretically described reality. At this point in my story it is of course not excluded that those appearances are completely describable in terms of quantum states. But is that so in fact?

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[10] In view of Don Howard's illuminating historical studies we must be very careful not to read too much into the term "Copenhagen"; I intend to keep its connotations minimal, and even so realize that my reading of Bohr may be contentious. See D. Howard, "Bohr's Philosophy of Quantum Theory: A New Look—'Who Invented the Copenhagen Interpretation?' A Study in Mythology," *Philosophy of Science* 71, no. 5 (2004): 669–82 (Supplement).

3. Grünbaum's Critique of Nonrealist Interpretations of Quantum Mechanics

Reportedly the Copenhagen physicists were surprised by Einstein's resistance to their approach to atomic physics because they felt they had followed the example he set in constructing the theory of relativity. Hadn't Einstein in effect subjected classical concepts of spatial and temporal relations to an "operationalist" critique, and thereby shown that they needed to be replaced by a radically different representation of nature? Einstein's critique had still left intact the possibility of ascribing simultaneous positions and velocities to given bodies within any given frame of reference. Now a similar operationalist critique had removed the warrant for such simultaneous ascription, and accordingly shown that the classical representation in phase space must be replaced by a radically different representation of a material body's physical state.

Grünbaum (1957) begins by pointing out very clearly that both in Heisenberg's and Margenau's accounts we can find consistent operational prescriptions for the simultaneous ascription of position and velocity. There is no logical contradiction, for example, in taking the data of a sequence of position and time measurements on particles emitted from a given source and ascribing a velocity during the relevant interval by means of the classical formula, dividing distance covered by time elapsed. But such ascriptions do not have the value that assertions about physical magnitudes are meant to have. The prediction of a future position on the basis of such an ascription of a current position and velocity will, *according to the quantum theory itself*, not be verified. In fact, neither operational incompatibility nor operational compatibility offers us any logically sufficient or necessary clue to theoretical significance.

What is a theoretically significant quantity?

What relations do such data then really have to future events? From the data we can, via the theory, infer *backward* to something about the quantum mechanical state of the emitted particles, and then on that basis infer *forward* to probabilities of various outcomes in further measurements to be made. What shall we conclude about the notion of a physical magnitude under these conditions? The notion of a simultaneous positioncum-velocity, while "operationally definable" has something wrong with it from a theoretical point of view. Just what is that?

Within elementary quantum mechanics we can offer the following criterion.[1111] (I will restrict this discussion to discrete observables, thus shying away from position and velocity which are continuous. Continuous quantities can be treated in terms of families of discrete observables, but this is not the moment to go into technical details.)

> **Criterion:** There is a theoretically significant physical quantity A with possible values a(1), a(2), . . . , a(k), . . . if and only if there is for each index k a possible state Ψ(k) such that if A is measured on a body in state Ψ(k) then the value found will be a(k), with probability 1.

To fix terminology: in that case Ψ(k) is called an *eigenstate* of A corresponding to *eigenvalue* k. In general, let us write P(Ψ, A, a) = r to say that the probability equals r that an A-measurement on a system in state Ψ will have value a as outcome.

Complementarity now appears as follows: by this criterion it may well be that both A and B are theoretically significant physical quantities, but there is no such quantity that would correspond to their simultaneous ascription. That is:

> Quantities A and B are complementary if and only if they have no eigenstates in common.

This is the extreme case: A and B might share some eigenstates, while not having all of them in common. In neither case is there a theoretically significant "conjunctive" quantity (by the above criterion), though in the less extreme case some relevant conjunctions do make sense.

Technical sense(s) of complementarity

Thinking of it this way we have of course no operational criterion, but rather (as Grünbaum points out) a theoretical one, since the availability of eigenstates is a matter on

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[11] I am staying here in the historical context in which observables are represented by Hermitean operators; the discussion would have to take a different form in more recent contexts in which the concept of observable is generalized to representation by positive operator valued measures.

which the theory pronounces. But note also that this criterion takes for granted that we have an independent specification of what it is to measure (putative) quantity A. We can illustrate this perhaps most clearly with an example of a well-known measurement of a discrete observable, which allows for the description of another putative observable, one that has an operational recipe for its (equally putative) measurement, but one that fails the criterion.

Imagine then a Stern-Gerlach apparatus with two exits, intuitively separating particles with spin Up and spin Down along its vertical axis. Let the first exit be the entry to a second such apparatus, rotated 45 degrees with respect to the former. The first we can certainly regard as measuring spin along the vertical axis, and it is possible to prepare particles in a state so that they are guaranteed to emerge from the first exit, or respectively from the second exit. But thinking of the two apparatuses as constituting a single compound measurement of a new observable A does not work. There is no state such that, if the particle is in that state and subjected to this compound measurement it is guaranteed to emerge from the top exit of the second apparatus. So this composite set up, while it has the looks of a measurement set up for a physical quantity characterizing the particle state, does not satisfy our criterion. In fact, there is no observable—theoretically significant physical quantity—that is being measured by this contraption.

There are clearly further questions we could investigate about the relationships between operational procedures and theoretically represented physical quantities.[1212] But this so far underlines Grünbaum's main conclusion concerning the actual status of complementarity in physics: "operational incompatibility of jointly significant sharp simultaneous values is [neither a necessary nor] *a sufficient condition* for their lack of joint theoretical meaning."[13]

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[12] In fact, the compound measurement set-up just described can be used to motivate a generalized concept of observable, not restricted to representation by Hermitean operators.

[13] A. Grünbaum (1957), p. 716.

What does a measurement reveal?

Given this negative conclusion, how shall we think of those physical quantities? If we could take it that the value found in a measurement were precisely the value that the quantity had when the object entered the measurement set up—that is, if the measurement *reveals* a possessed value—then it would seem that those complementary physical quantities would have simultaneous values after all. For it would seem then that if A is measured and value a(k) is found, we could add that if B had been measured, then one of its possible values b(j) would have been found—and since measurements reveal possessed values, then A had value a(k) while B had some value or other, simultaneously.

Logically speaking, there would be no contradiction between this conclusion and anything we have said above. But of course that conclusion would run counter to the Copenhagen view of the matter. At least as I read Bohr, to the above explication of what counts as a theoretically significant physical quantity, his view appears to add the tacit principle:

> no circumstance can be the case in nature unless it possible for nature to be such that a suitable measurement would be certain to reveal that circumstance.[14]

"Nothing can be real unless it can really so appear"—that might be the slogan to convey this. And of course that principle implies that quantities that are complementary in the above strong sense cannot, according to the theory, have simultaneous values ever.

If measurement outcomes do not reveal possessed values, what do they do? As I indicated before, they allow "backward" inference to features of the physical state. For example if particles emitted by a certain source are all submitted to an A-measurement and values a(j) are found in proportion q(j) of the outcomes, that may be taken as evidence that the source prepares particles in a quantum state Ψ such that (in the notation introduced above) P(Ψ, A, a(1)) = q. (Equivalently, in the notation I used to express the

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[14] Notice that I have made this weak enough to serve the present purpose without implying the so-called "eigenstate-eigenvalue link," that is, the stronger principle that an observable actually has a certain value if and only if the system is in a corresponding eigenstate of that observable. I have not ruled out that A has value a(k) in a given state, provided only there is some state (perhaps another one) that is an eigenstate of A corresponding to that value.

Born rule, such that $< \psi, A\psi> = \Sigma a(j)q(j)$.) But then of course A itself is not being mentioned as a feature of the physical state! How should we think of that state then? In what terms shall we describe it, once terms pertaining to familiar quantities such as position, momentum, spin, and so forth do not have the role of characterizing that state directly?

Relational properties and invariants

There are, as we now know, various possible replies to this, which provide the seed-kernels for various basically tenable interpretations of the quantum theory (even if none of them shall ever be beyond dispute). Grünbaum aligns himself with a two-pronged reply, in which he draws an explicit parallel to discussions of the theory of relativity, thus vindicating to some extent the Copenhagen contention to have followed Einstein's example. The first prong is to assign to the measured quantities a relational status: what is revealed by measurement is not a feature of the system that it had when entering the measurement set-up, but a relationship between the system and the set up with which it is made to interact:

> Instead of being simultaneous "autonomous" attributes of the microphysical object, belonging to it *independently* of the *particular experimental arrangement* into which it enters, exact theoretical values of conjugate parameters are each only *interactional* properties of an atomic object that is coupled *indivisibly* to a particular kind of observational macro-set-up. For the incompatibility of the circumstances allowing the theoretical ascription of a sharp value of one conjugate parameter with those allowing the corresponding assignment for the other renders these attributes *theoretically disjunctive* and interactional.[15]

(For the distinction between *relational* and *interactional*, see below.) The second prong follows Born in looking to the invariants in the situation for the basic features that characterize the system and its physical state independently of any measurement set-up.

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[15] A. Grünbaum (1957), p. 717.

Indeed, Grünbaum sees this as a necessary addition given the above, if realism with respect to the theory is to be tenable:

> To assert that the particular pairs of attributes which furnished the mechanical state descriptions in classical physics are neither autonomous nor theoretically conjunctive but rather interactional and theoretically disjunctive does *not* itself entail that there are also no *other* attributes of, say, an electron whose existence is *independent* of whether the electron is observed. If one denies the existence of any such other attributes as well, then indeed there is no articulate sense in which the electron can be supposed to exist independently of being observed.[16]

These other attributes Born and Rosenfeld identified as the invariant quantities such as, in the case of elementary particles, the rest-mass, charge, and [total] spin. They are invariant in two senses: they do not vary as the state evolves in time, and if measured, they do not allow of alternative possible values as outcomes.

The precise connection with realism about the individual particles is subject to further questioning. All particles of a given type (e.g., all electrons) are exactly alike with respect to those features. So it would seem that terms are also needed to describe differences—e.g., to say that in a given atom there are electrons at several different energy levels, or to say that one emitted photon was absorbed and another reflected. At first blush, at least, these are not descriptions of relationships to measurement set-ups. But at least we have here a first step in a description of the quantum state in terms that do not simply relate it to measurement contexts. In that sense the basic requirements of realism with respect to the theory are served.

Relational properties: perspectival or interactional?

As Grünbaum points out, there is an interesting and instructive parallel here to the reconception of the attributes that "furnished the mechanical state descriptions in classical

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[16] A. Grünbaum (1957), p. 717.

physics" in the transition from classical to relativity physics, but one that can all too easily be exaggerated. It is of course correct to say that the spatial distance between two events is a magnitude that relates those events to a given frame of reference, while the space-time interval between them, an invariant, is not a relational quantity in that sense. But spatial distance, though relational in that way, is not what Grünbaum calls *interactional*: it is not as if those two events are spatially a certain distance apart only if they are involved in some interaction—let alone, involved in a measurement. We might say that, in the theory of relativity, spatial distance is "perspectival" (or perhaps more literally "frame-dependent") while position and velocity in quantum mechanics (on the interpretation we are presently discussing) are "interactional," thus dividing "relational" into several subcategories. Of course this very remark also leads us to the question whether that interactional interpretation of the classically familiar mechanical attributes in the context of quantum mechanics was really forced upon us, or a matter of one interpretation among others. Indeed, it raises the question whether there might not be another interpretation according to which those classically familiar attributes are perspectival in a similar sense or similar way.

To explore this question I will proceed in several stages, beginning with some points about perspective, frames of reference, and measurement. I am very conscious of the tempting fallacies that one certainly sees beckoning in even famous physicists' writings when the scientific description of nature is linked to measurement as opposed to measurement-independent fact. These fallacies belong precisely to the family of fallacies that Grünbaum exposes in his discussions both of Margenau's interpretation of quantum theory and of Copenhagen-related writings about complementarity. But it may be possible to avoid those fallacies while still arriving at an understanding of the physical sciences that gives pride of place to the relationship between theory and what appears in perception and measurement.

4. Perspectives and Measurement Outcomes

I mentioned above that the Copenhagen physicists elaborating their interpretation of quantum mechanics tried at various times, admittedly with not such great success, to import insights from relativity theory into the putative observer-relativity of measurement results. Putative philosophical insights that exploited relations between frames of reference and visual perspectives were the subject of Grünbaum's still earlier "The Clock Paradox in the Special Theory of Relativity" and his related writings on the perspectival character of time dilation and length contraction (see the list in footnote 2 above). These early articles were a mainstay of my own first few steps in the philosophy of physics; I'll draw here especially on "Logical and Philosophical Foundations of the Special Theory of Relativity."[18]

As in the critique of Margenau we see Grünbaum here insistent in his rejection of idealist, subjectivist, or homocentric interpretations. Length contraction is a good example to illustrate the fallacies and confusions that led various authors into such interpretations. The correct understanding of the STR identifies the limiting character, constancy, and source-independence of the speed of light (all features having nothing to do with limitations of measurement) as accounting for the relativity of simultaneity and for the frame-dependence of length in the STR.[19] Just to see how this point played out in the literature it suffices to cite a small passage from Herbert Dingle and Grünbaum's commentary. Dingle had written:

> Every relativist will admit that if two rods, A and B, of equal length when relatively at rest, are in relative motion along their common direction, then A is longer or shorter than B, or equal to it, exactly as you please. It is therefore impossible to evade the conclusion that its length is not a property of either rod; and what is true of length is true of every other so-called physical property. Physics is therefore not the investigation of the nature of the external world.[20]

In response to this Grünbaum rightly remarks: "Far from having demonstrated that relativity physics is subjective, Professor Dingle has merely succeeded in exhibiting his

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[18] That was the first paper by Grünbaum's that I read, when still an undergraduate, and which made me want to study with him—lo these many years ago . . .

[19] A. Grünbaum, "Logical and Philosophical Foundations of the Special Theory of Relativity," in *Philosophy of Science*, A. Danto and S. Morgenbesser, eds., 399–434 (New York: Meridian Books, 1960),, pp. 411–12.

[20] Cited in A. Grünbaum 1960, p. 433n29.

unawareness of the fact that *relational* properties do not cease to be *bona fide* objective properties just because they involve relations between individuals rather than belong to individuals themselves."[21]

Yet Grünbaum finds a legitimate place for the introduction of measurement and perspective into a foundational discussion of the STR. When he explains the difference between the physical length contraction postulated (and explained) in Lorentz's theory on the one hand and the length contraction implied by the STR, he exhibits the latter as a perspectival effect that appears in measurements made under different conditions. This is perfectly consistent with the foregoing, but the nuances of the discussion will allow me to display the (for our discussion crucial) distinction between the ("objective") observable *phenomena* (which admit of frame independent description without loss) and the *appearances* in the outcomes of measurement operations:

> the Lorentz -Fitzgerald contraction is measured in the very system in which the contracted arm is *at rest*, whereas the contraction that Einstein derived from the Lorentz transformations pertains to the length measured in a system relative to which the arm is *in motion.*
> [. . .]
> Unlike the Lorentz-Fitzgerald contraction this "Einstein contraction" is a *symmetrical* relation between the measurements made in any two inertial systems and is a consequence of the intersystemic relativity of simultaneity, because it relates lengths determined from *different* inertial perspectives of measurement .... What Einstein did explain, therefore, is this "metrogenic" contraction, ... which poses no more logical difficulties than the differences in the angular sizes of bodies that are observed from different distances.[22]

We have therefore to look more carefully into this, and give explicit status to the distinctions on which the correct discussion of the relativity of certain physical quantities relies.

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[21] *Ibid.*, p. 433n29.

[22] A. Grünbaum 1960, pp. 419–20

Differences between perspective and frame of reference

The length of a body is a frame-dependent quantity: its value is not invariant under a shift in its description from one frame of reference to another. If we think of frames of reference as belonging to specific inertial systems—bodies experiencing no acceleration—then length is a relational property: A has length b in relation to body B but length b' in relation to body B'. That, I take it, is Grünbaum's reply to Dingle. We can of course add to this that there is an invariant quantity in the immediate neighborhood, which Dingle appears to ignore, and which can be illustrated Einstein-style by mentioning two lightning strikes at the two ends of body A. The space-time interval between those two events has a value that is the same in every inertial frame of reference, an "absolute" that, so to speak, takes over the role of the classically invariant length.

But there is something more to be said about this, which pertains to the relationship between measurements and frames of reference. Grünbaum is quite right to describe the content of the measurement outcome as perspectival, when he speaks here of "lengths determined from *different* inertial perspectives of measurement" and when he likens this to "differences in the angular sizes of bodies that are observed from different distances."

This is very important point about all measurement in general: measurement is perspectival. Let us think ourselves briefly back into pre-STR days when the illustrative example of angular separation in visual perspective could be conceived of in a space independent of time. The most advanced scientific measurements of Galileo's day, for example, were those of astronomy applied in navigation. For a simple example, think of two navigators on different ships. They are, let us say, simultaneously sighting the same mountain peak as well as one of the circumpolar stars and they record respectively:

I. Peak: direction NNW, elevation α
Star: direction NNE, elevation β

II. Peak: direction N, elevation α'
Star: direction E, elevation β'

From these together with time measurements and earlier log entries they calculate their "objective" position on the ocean (latitude and longitude). But the initial measurement outcome reports are perspectival: *the "from here" accompanies every observation judgment*!

Thus the quite common use of the analogy to visual perspectives when we discuss frames of reference and measurement outcomes hides an important difference as well. Measurement outcomes are perspectival in one way; descriptions or representations within a frame of reference (coordinate dependent representations) are perspectival in a different way.

For let us for a moment take the content of a visual perspective as itself a paradigmatic example of the content of a measurement outcome. The visual perspective contains (in some sense) the spatial relations between bodies as they appear at a certain time from a certain point of view. This content can be "intercepted" on a plane surface, by means of a painting, drawing, or photo. The character of that interception is described in projective geometry rather than Euclidean geometry. In contrast, the spatial relations between bodies in a frame of reference are described in a coordinatized Euclidean space. In the visual perspective content we see systematic marginal distortion as we inspect the projection farther away from the center, and we find many parts of the seen (measured) bodies entirely unrepresented (due to occlusion or to their location relative to the "eye").

Can we perhaps think of the frame of reference as an idealizing abstraction from the contents of such measurements? It is true that we arrive at a Euclidean space if we think of the "eye" as moving farther and farther away from the objects: when it becomes a point at infinity, the projective space has become a Euclidean space.[23] But that hardly counts as assimilating frames of reference to visual perspectives. Think of Galileo's two observers, one stationary on the shore and one on board ship. If we try to think of the latter's frame of reference as the content of a visual perspective with "eye" at infinity, we must still have that "eye" move with the ship. In what sense is that "eye" connected with the point where the mast meets the deck, which is the spatial origin of that frame of reference? The visual perspective metaphor has been strained to breaking at this point: it is as if we are invited to think of the "eye" simultaneously at infinity and at a specific

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[23] I am oversimplifying of course, but not so much as to obscure the main point. For a more detailed story of projective, affine, and Euclidean spaces along these lines, see e.g., B. E. Meserve, *Fundamental Concepts of Geometry* (New York: Dover, 1983), chs. 4–6.

location on the ship, from where it can look into all directions at once. . . .

Phenomena and appearances: the distinction continued

To undo our confusion here I suggest that we should mobilize the above introduced terminological distinction between *phenomena* and *appearances*. The observable processes, which can be described both in a coordinate-independent way and also relative to any frame of reference (i.e., within any suitable coordinate system) are the phenomena. The content of a measurement outcome of which the content of a visual perspective (whether personal or in the more hygienic form of such observations by the navigators I described above) can also show us those observable processes, but what it delivers are the appearances.[24]

Now we face a question with respect to the traditional demand that science has "to save the phenomena" until now expressed synonymously as "to save the appearances." In our terms, which is it? I want to insist firmly that it is the former. The observable processes must have a proper home in the models a science makes available for the representation of nature—that is the empirical criterion of adequacy. From the beginning of modern science there was also the claim that science was saving, or would save, the appearances: the entire smelly, colorful, noisy mess of them. And I do not think we do the traditional writers an injustice if we take them to have subscribed to the appearance from reality criterion of adequacy for the sciences in the sense that I have now given that criterion. But I submit that this is an additional criterion, going beyond the demand to save the phenomena.

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[24] I argue elsewhere that the content of a measurement outcome is to be conceived of as an indexical proposition. The description of a process in the language of physics itself, whether coordinate free or coordinate dependent, however, expresses a proposition that is not indexical. We need of course to distinguish between the attribution of a relational property on the one hand and the indexical attribution of some such property on the other. To say of a body that it has length b in the frame of the fixed stars is an example of the former—to say that its length is b, full stop, is to be understood as the indexical assertion that it has length b in the speaker's frame of reference.

Einstein and Minkowski

There was in the modern science initiated by Galileo's ship or shore observers and Descartes coordinate systems, for the formal representation of what they saw, one central idealization that was removed in the transition to the STR. In a visual perspective the lines of projection are light rays. When representing the content of a perspective at a given moment, such as in a painting, we can think of the light ray connection as instantaneous. In fact Descartes suggested that it was instantaneous. By the end of the seventeenth century already it was known to be a connection that takes time. The classical kinematics frame of reference, conceived of as a projective space with the “eyes” at infinity, seems to be oblivious of this point. The observer on Galileo’s ship, describing a motion on the shore in his own frame, does not take this into account. Enter Einstein: in relativistic kinematics this was corrected and as a consequence not only speeds but lengths and time intervals are affected—they are not the same in moving frames of reference. By taking the speed of light into account we arrive at descriptions of the phenomena much closer to actual deliverances of visual observation. Einstein’s thought experiments with moving trains, clocks, and lightning strikes shift us from painting or still-photo representation to motion pictures.

So far then the physics and geometry of light and moving bodies allow a perfect derivation of the structure of the kinematical phenomena—and indeed the appearances—from the underlying physical reality.

Such successes in the history of modern physics must surely be in large part responsible for the Appearance from Reality Criterion's grip on our imagination. It would have been very hard for anyone in the modern period, even extended to take in the Special and General Theories of Relativity, to resist the conviction that in this derivation of the appearances science is doing precisely what all science is in principle required to do. Which is to say: to satisfy the Appearance from Reality completeness criterion.[25] For after all, nothing succeeds like success, and philosophers have never been very resistant

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[25] That the structure of the phenomena as observed within a given frame of reference can be derived from the invariant features of the situation in both classical and relativistic physics "serve[s] to explain, though *not* to justify," I agree with Adolf Grünbaum, Einstein's rejection of the Copenhagen line, despite, as Grünbaum says, charges that his reasoning was here akin to that of early opponents of relativity. A. Grünbaum (1957), p. 720.

to what we might call the Inference from Success to Design![26]

5. Does Complementarity Really Have to Do with Frames of Reference?

It has often been noticed that observables in quantum theory are associated with something like frames of reference or coordinate systems, and there is therefore a tempting parallel or analogy to exploit in connection with complementarity. In fact it has been suggested that the same physical situation could e.g., be looked at in complementary ways in a ‘position frame of reference’ and a ‘momentum frame of reference’: in the one, positions are attributed to the bodies involved and in the other, momenta. Then one could think that these are two mutually incompatible representations of the same part of nature with equal rights as to truth and reality. But that really does not make sense at all.

The point behind the analogy is of course that a pure state space in this theory is a separable Hilbert space, and the eigenvectors of a discrete observable furnish a base for that space. If A and B are two such observables, complementary in the strong sense I mentioned above, then a base of eigenvectors of A will have members inclined at some angle to every element of a base consisting of eigenvectors of B. Considered as geometry that is precisely also how we can think of two Cartesian coordinate systems in a Euclidean space or two Galilean frames in its kinematic generalization. Hence the pair of bases for the Hilbert space consisting of eigenvectors of two complementary observables is the formal counterpart of a pair of spatial or kinematic frames of reference with different orientations.

But purely geometric point obscures the relevant difference between the two. In the case of physical space we can think of this pair of frames as containing all the bodies in that space described from two different points of view, associated with—as it were—two persons looking in different directions. In the kinematic case these might be Galileo's shorebound observer and mariner on a moving ship. So the descriptions of situations in those two frames of reference are *of the same situations in the same actual world*. The pure states represented by points in a Hilbert space, on the other hand, are alternative

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[26] Nor are ordinary people of course: if someone succeeds in the stock market s/he is automatically thought of as very clever, for example.

states that the represented system can have—alternative possible states. They are not the states of different systems in one world but *the states of one system in different possible worlds*, so to speak.

The analogy can be attempted in a more sophisticated way by looking then at a model of a system consisting of different parts. The Hilbert space whose vectors represent the pure states of the whole system is a tensor product of several Hilbert spaces. Both Hugh Everett and Simon Kochen introduced the idea of the state of one part relative to or witnessed by another part. That is much closer to the idea of a spatial or kinematic frame of reference. However, there is also a big gap in that analogy. Suppose the total system is X+Y. Then the notion really defined as a relative state is the state ψ ' of Y relative to state ψ of X, where ψ is a pure state that X can have. But there is nothing in the representation of X+Y that warrants associating ψ with X. If X+Y is, for example, in pure state Φ then X is typically in a mixed state (a reduction of Φ), with various of its possible pure states as components. So the nearest we have here to a perspective would be something like "what Y would look like to X if, per impossibile, X were in possible pure state ψ."

Of course, Everett's idea was then transformed into "many-worlds" interpretations on the one hand, and "modal" interpretations on the other.[27] Below we will take a look at the latter, and we will see that there is indeed a way to think of measurement-outcome contents as analogous to the contents of visual perspectives, though not in the naive way which I sketched above.

6. Is the Appearance from Reality Criterion Abandoned in Quantum Mechanics?

This criterion appeared to be blatantly violated by the Born rule when that was offered as the sole and sufficient bridge from quantum reality to observable phenomenon. The theoretically described reality presents us with a fully deterministic evolution of the unvisualizable quantum state, while the observable phenomena display an irreducibly

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[27] Because of their current interest in the field it would certainly be appropriate to go into the question whether the appearances are saved on a many-world interpretation. But that will have to be a later project.

stochastic process. Born gives us *precisely*, but *nothing more than*, the rule to calculate the probabilities in the latter from the former.

Heisenberg was the most straightforward advocate for the view that this is enough and completes the task of physics. If we look at the story since then it seems to me that the currently more or less acceptable interpretations offered fall into three classes: (i) the sort that purport to derive the appearance from the reality but fail, and (ii)those that do not purport to do this, but either (ii-1) merely pay lip service to the old ideal, or (ii-2) more honestly content themselves to flesh out the Born interpretation in a way that precludes this third sort of completeness altogether.[28] If that is correct, of course, then it was right to reject (in effect) the Appearance from Reality Criterion as imperative for the sciences.

Is there a 'collapse'?

When we look at the philosophy of quantum mechanics we must clearly distinguish between *changes* to the theory and *interpretations*. The former, even if proposed as interpretations, differ in that they change the empirical predictions. Von Neumann's version of the 'collapse of the wave function' introduced a change, although that was not at once apparent. He proposed that in a measurement, the quantum state of the object is projected or 'collapsed' into one of the eigenstates of the measured quantity. The immediate questions are: *What constitutes a measurement*? and *What explains this collapse*? An answer to the first question that remains within quantum theory itself offers no room for that collapse, let alone an explanation.

The two sorts of responses which attempt to maintain von Neumann's proposal were initially typified by Wigner on the one hand, and by Groenewold and Margenau on the other.

Wigner answered that a measurement is not an event completely describable in physics, it must include consciousness, a mind-body interaction. That was certainly a

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[28] I will actually only look at some sorts of interpretations, and realize that both the range I inspect and my assessment of what are currently more or less acceptable interpretations, are controvertible. With respect to the Bohmian option I'll again avoid a direct confrontation, but I place it in the first class.

radical suggestion. Imagine Schroedinger's dismay—he wrote later: "it must have given to de Broglie the same shock and disappointment as it gave to me, when we learnt that a sort of transcendental, almost psychical interpretation of the wave phenomenon had been put forward, which was very soon hailed by the majority of leading theorists as the only one reconcilable with experiments, and which has now become the orthodox creed, accepted by almost everybody, with a few notable exceptions."[29]

Unfortunately Wigner's reply only looks like it answers the second question. We must insist here on the difference between providing an explanation and merely postulating that there is something that explains! To add the postulate that there is a mechanism of a certain sort, even if intelligible, that changes a certain pure state into a mixture—thus 'collapsing the state'—is a far cry from having a science which derives the measurement outcomes from the quantum states in the relevant sense. In fact Wigner provides no clue at all to *how* the appearances thus derive from the aeality.

Groenewold and Margenau argued instead that von Neumann's added postulate was purely interpretative and did not really augment the Born rule. We can illustrate their argument with Schroedinger's famous cat:

> The Cat itself is a measuring instrument, with "dead" and "alive" as pointer states. So the collapse into one of these states may happen inside its closed box, consistently with Von Neumann's postulate. When the box is opened, a second measurement occurs, but no further collapse is needed. Alternatively we can suggests that the Cat lacks something unspecified so that it does not function as a measurement apparatus, and there is no collapse till the box is opened. Now the point is that the probability of finding a dead cat at the end is the same regardless of which scenario we assume.[30]

The ostensibly correct conclusion is that von Neumann's postulate does not affect the empirical content of the theory. Of course, if that is so, its 'derivation' of the appearances is still not by an empirically accessible mechanism. But actually, as David Albert has

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[29] E. Schroedinger, "The Meaning of Wave Mechanics," in Louis de Broglie Physicien et Penseur, A. George, ed., 16–30 (Paris: Editions Albin Michel, 1953), p. 16.

[30] [AU: Need full citation information for Schroedinger's Cat block quote REPLY: NO. THIS IS NOT A CITATION. IT IS PART OF THE MAIN TEXT, BUT NEEDS TO BE SET OFF IN THIS WAY FOR EMPHASIS]

forcefully pointed out, that conclusion is not correct anyway. For there is a definable quantity pertaining to the system *as a whole* (box with cat etc. inside) for which measurement outcome probabilities are certainly different on the two scenarios.[31]

Let's admit that von Neumann' s alteration of the quantum theory, together with Wigner's addition of a consciousness-matter interaction, implies that the phenomena do derive from the quantum-mechanically described reality. But recall the distinctions I made early on: this is a case where the appearance from reality criterion is nevertheless not satisfied because physics cannot *provide* the derivation.

What if we ignore Wigner as well as Margenau and Groenewold, and just propose that von Neumann's Projection Postulate explains what happens in measurement? The story of the world is that it is after all a stochastic process on the level of the quantum states themselves: these states develop deterministically except for abrupt 'swerves' during a class of special interactions, the measurements. Very well; but then we run up against the question that Wigner wanted to answer along the way, so to say: "*When* is a measurement made?" If we try to describe it quantum mechanically we can't easily distinguish the cat's interaction with the device, in the middle, from our interaction with the cat at the end.

It is probably for that reason that some physicists have insisted strongly that quantum mechanics is only a theory of *measured* systems. Wigner would of course hold that, but I think here of views that would allow also any macroscopic apparatus as truly measuring, without regard to consciousness, while ascribing quantum states only to the measured objects and not to the measuring set ups.[32] Quite obviously this sort of view

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31 "Recombination" experiments furnish today the most psychologically compelling support for rejecting collapse, but in my view David Albert's point is the most solid reason. Note of course that Albert's point does not give a reason to reject collapse theories—there is no a priori reason to expect the predictions of a no-collapse theory to be vindicated, as opposed to those of a collapse theory. His point serves only to reject the Groenewold-Margenau contention that the collapse adds no empirical import.

[32] This sort of view is to be contrasted with one congenial especially to cosmologists, and I think most discussants from the side of philosophy, to the effect we are to think of quantum mechanics as potentially applying as well to the universe as a whole. The choice between these two views was clearly and explicitly laid out by J. Wheeler's commentary on Everett's original paper, "Assessment of Everett's 'Relative State' Formulation of Quantum Theory," *Reviews of Modern Physics* 29 (1957): 463–65.

implies that there will be no explanation in physics of how measurements can have determinate outcomes, for the latter belong then to the part specifically not modeled in terms of quantum states.

These early discussions are illuminating not only because they begin to chart our range of options, but also because they were closely related to practice. Whatever the theoretical status of ‘collapse’ the way the working physicist calculates does always assume that the appearances will be at least *as if* states thus collapse in measurement. The Born rule is not genuinely explained, but certainly most easily conveyed in practice, by the assertion that upon measurement the object will be in one of the eigenstates of the measured observable, with given probability. *The appearances are as if von Neumann’s Projection Postulate is true.*

Mismatches in space

I can’t go far into the idea of complementarity for now, but want to draw your attention to one of its most provocative claims: space-time description and quantum state description are complementary. That means at least that both are indispensable to our full appreciation of nature and that they cannot be meaningfully combined in any straightforward way.

How could the Copenhagen school say that? First of all, Schroedinger’s quantum state is a function ψ (x , t) defined on (classical) space and time, with "x" the position parameter. Second, Heinsenberg’s famous uncertainty principle is an inequality relating the position and momenta parameters to the quantum state. So what is going on? Does this not mean that the quantum state description is fully integrated, or even based on, a spatio-temporal description of nature?

It does not. We can’t think of ψ, despite its appearance, as a quantity pertaining to space points like a classical field.[33] And Heisenberg’s principle is statistical, deduced

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[33] This becomes very clear as soon as we look at a many-particle state when, as Schroedinger rapidly appreciated, we cannot regard ψ as denoting a wave in physical space but rather in a many-dimensional configuration space. It is possible of course to regard what ψ denotes as physically real, and what happens in physical space as an aspect thereof, manifested on that level, or instead guiding and constraining what happens on that level, that is not being denied here. See

from the Born rule, which relates the quantum state to probabilities of measurement outcomes of those parameters. The spatio-temporal description pertains to the phenomena and to the appearances, and is maintained in the way Bohr explained: the concepts of pre-quantum (classical and relativistic) physics are the ones we must keep using, suitably restricted, to describe nature as it appears to us.

This is a point that is generally obscured even in quite theoretical, philosophical discussions. As illustration I'll take the Aspect experiment, which is now the standard "Einstein-Podolsky-Rosen paradox" example.[34] Here is how it is typically described. A pair of photons is emitted with opposite momenta toward two polarization filters. With the filters properly oriented with respect to each other, one photon passes its filter if and only if the other does not. Notice that in this description, two distinct directions of motion are attributed to the two photons. While we can't also specify positions in the same way, the time of emission is pretty definite, and the passing of a filter recorded with a click—so in that time interval the two photons are in clearly separate halves of the laboratory. Right?

Not right. For such a photon pair must have, taken as a whole, a symmetric state. If we derive from this total state, by reduction, the states for the individual photons, each receives the *same* mixture of the two pure states. Based on the quantum state *alone*, we cannot ascribe neither different directions of motion, nor different spatial regions, nor any other differentiating features to these photons. Yet everything appears to happen *as if*!

Now photons may be special, but we could repeat this entire discussion, *mutatis mutandis* for heavy particle pairs. The same point applies. One reaction is to interpret the mixed states of the photons as 'ignorance mixtures' The ignorance interpretation of mixtures says that to be in a mixture of *this* and *that* is to be really in one or the other, with no further information. That is, like 'collapse' a staple of working physics problems, but it is untenable theoretically precisely in cases like this. However, practice is not wrong as practice. *The appearances are as if the ignorance interpretation is correct.*

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further Bradley Monton, "Wave Function Ontology," *Synthese* 130, no. 2 (February 2002): 265–77.

[34] With thanks to Soazig LeBihan for a discussion of the experiment with respect to this point.

In the case of photons we are not so emotionally involved. We can give up on the idea that these are individual photons, and regard that way of speaking as but an asses' bridge toward a quantum field description. But if we think of that as a general solution we had better take the consequences for all physical objects. In that case there aren't any, at least not in the sense of objects that are really in one half of the room and not in the other half—as you and I and these chairs and tables appear to be.

Eddington gave a famous example contrasting the manifest image with the scientific image: the table as science describes it is utterly unlike the way we describe the observed table. But his tables are not all that unlike: they are both precisely located in space, and the contrast is not so different from that between a cloud of locusts seen from afar and from close by. In quantum mechanics his example has returned with a vengeance: everything we observe, even in Aspect's laboratory, appears to have a determinate place and if it moves it does not shock us with discontinuities. But the theoretical description of that laboratory assigns no determinate locations or movements to its parts—it is not too far fetched to say that that laboratory is only partly manifest in the spatio-temporal realm at all!

I think it is time to look at more recent interpretations, and for me to make the case that these vindicate what I take to be the Copenhagen insight that rejected the Appearance from Reality Criterion.

7. The Appearances Yoked Unto a Forbearing Reality

So I turn finally to the class of interpretations that seem to me endorse—implicitly, explicitly, or cryptically—the rejection of the appearance from reality criterion. In his recent book *Interpreting the Quantum World*, Jeffrey Bub displays a very large class of interpretations under the same heading: *modal interpretations* in a general sense.[35] On all of them an observable (that is, a physical quantity) can have a determinate value even if the quantum state does not make it so.[36] Thus no collapse is needed for measurement

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[35] J. Bub, *Interpreting the Quantum World* (Cambridge: Cambridge University Press, 1997).

[36] Ibid., p. 178. This class of interpretations include Bohm's interpretation, Bub's own, versions of Bohr, Kochen, and many others, though it does not in fact include all modal interpretations—see

outcomes—or indeed any other sort of event—to be characterized by a definite position, or definite velocity, or definite charge, or definite death-or-life. While in a quantum state which does not imply that at all, the object is *as if* it is in an eigenstate of the pertinent observable. So we have here a clear reality (the quantum state) contrasted with appearance (the ‘value state’; or ‘property state’).

Note well: in aligning these two aspects of a system (under such an interpretation) with the reality/appearance dichotomy I am departing from how modal interpretations have been presented so far (including by myself). The ‘value state’ or ‘property state’ is introduced to validate the assertion that physical measurement processes do have ‘definite’ outcomes. The pointer is really at the “17,” the cat is really dead inside the box—although the quantum state does not make it so. But now I want to say: that is not a separate aspect of the real situation; it is not the case that a system has two states. Rather what is called the value state or property state is the content of a perspective on the system—of a perspective of a (possible) measurer or viewer or measurement set up.

I am not suggesting either that there is a measurement apparatus located at every point, nor that the description of the world is restricted to what happens in actual measurements. In the case of visual perspectives as treated in projective geometry, and equally in classical kinematics, we think of every point and orientation determining a perspective, regardless of whether there is a thus oriented measurement apparatus or viewer present at that point. The mechanics plus optics does allow us to derive the contents of all those visual perspectives. While omitting this conviction that the appearances can be thus derived, adding only that they can be predicted probabilistically, think of it here in the same way. The appearances are the contents of possible as well as actual measurement outcomes.[37]

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my review of his book. The Copenhagen variant of the modal interpretation, which I shall discuss below, is not included, but shares the features I am outlining here.

[37] This must be read very carefully. All those measurement outcome contents must cohere together in a certain way, so that they can be thought of as all perspectives on a single world in some specific quantum state. In just the same way, the entire set of contents of visual perspectives, with origins in both possible and actual viewers, in a given room for example, must cohere so that they can be regarded as being "of" the same room. In the case of the modal interpretations I am discussing, the delineation of what the joint value states can be of the parts of a compound system, given a quantum state for the whole, is directed to this point.

The measurement outcomes, these are the appearances to be saved! They are saved in that the interpretation makes room for them in the theoretical world picture. But they are saved in a way that explicitly rejects their derivability from the quantum state. (In fact, they preclude *even supervenience on* the quantum state: for two systems in the same quantum state may have different value states.) As I use the terms now, on the other hand, the phenomena are those observable processes, objects, and events that can be described without loss entirely in terms of the quantum states and their evolution in time. On the view we are presently exploring, all real processes can be thus represented in quantum mechanics, though this representation does not determine what appears in the possible measurement set-ups in our actual world—let alone show how those specific appearances are produced.

What are the appearances like, on such an interpretation? We do see quite some variation there.[38] Bub's interpretation implies that the actual state of the world is characterized by the definiteness of a single "privileged" observable. It need not be position. We can think of his world as follows: it has a quantum state and in addition there is an observable which has a definite value, *just as if that observable was just measured on the world, with a collapse precipitated by that measurement*. Note well that this is a matter of appearance only: the quantum state is *not* collapsed.

In my own favored interpretation, the Copenhagen Variant of the Modal

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[38] Although Bub lists it as one of the interpretations covered in his framework, I am not going to take up Bohmian mechanics here. Bohm allows only one parameter to have a definite value—always the same one, always definite—namely position. This world is one of particles that are always somewhere—and larger objects "made up" of those particles, always in a precise spatial region. Their motions are continuous in time. This view may have been inspired by the extreme operationalist idea, going back to Mach, that in the last analysis every measurement is a length measurement. (Not very plausible: could you describe even a length measurement operation using only predicates denoting lengths?) Or perhaps it derives even further back from Descartes's dream of a world whose only objective properties are attributes of extension. That the phenomena are saved in a weak sense only and that there is still an appearance/reality gap here is argued in my "Interpretation of QM: Parallels and Choices," as well as in papers by K. Bedard (see references in note 5), and A. D. Stone, "Does the Bohm Theory Solve the Measurement Problem?" *Philosophy of Science* 61 (1994): 250–66.

Interpretation (CVMI), there is no simple privileged observable.[3839] But it is *as if the ignorance interpretation of mixtures is correct*, for every object in the world has a ‘value state’ that is pure. These value states are related to the quantum states and to measurement processes (quantum mechanically defined) so that in consequence it is also *as if the Projection Postulate (postulate of collapse of the wave function) is true*. Again the ‘as if’ describes the appearances, that is, the value states (which include the measurement outcomes) but not the quantum state.

On this interpretation we cannot say: it is just as if the ‘collapse’ idea is right and the world looks as if it has just been subjected to great single comprehensive measurement. Rather every object, including every part of an object, ‘looks’ as if it has just been subjected to a collapsing measurement of some observable (though not necessarily an observable with a familiar classical counterpart). That is not compatible with the idea that the appearances of the individual objects are all precipitated by an (imagined) single measurement carried out on the whole. The reason for this incompatibility lies in the holism of the quantum theory. If the state of a whole, compound system is projected into a given pure state, the result will in general not have pure states as its reductions to specific parts. Yet it is possible for both the whole and the parts to be definite in their apparent characteristics. So it is as if each part is seen individually from some measuring vantage point.

8. The Structure of Appearance

On this view, what is the world like? We restrict ourselves here to elementary quantum theory. The world consists of things that however, as Bohr said, resist description consonant with the older ideas of causality and locality:

> the renunciation of the ideal of causality in atomic physics which has been forced on us is founded logically only on our not being any longer in a

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[39] See my review of Bub, *Interpreting the Quantum World.*, *Foundations of Physics* 28 (1998): 683–89, for an explanation of how the CVMI is related to, but does not fall into, the class described in his book.

> position to speak of the autonomous behavior of a physical object.[40]

But these objects each have a quantum state (dynamical state); they are often compound, and then their parts all have quantum states too (derivable by "reduction of the density matrix"). The quantum state of an isolated system develops in time in accordance with the Schroedinger equation, that is, deterministically. All of this applies equally well to those cases in which one part of a system is a measuring apparatus in appropriate interaction with another part.

But besides these physical states that are the subject of dynamics, there are the appearances of these very things in possible determinate measurement set ups. These appearances are described in the same language as the dynamical states. They can be described as value states or property states, represented by vectors in the same Hilbert space, which represent the pure quantum states. In actual measurement, these value states are what appear in the measurement outcomes.

Appearances systematically unlike the postulated reality

I can't emphasize strongly enough that *what is 'seen' in a measurement outcome is never what the objects are really like*. What is 'seen' is what the object 'looks like' to the apparatus, viewer, or set up. One should say "That is what it is like *from here*." So in ordinary life, a still photo displays the shape of the object projected on a plane, in one-point linear perspective.[41] The content of the photo is the content of a measurement outcome. Similarly a video or motion picture displays the objects moving at determinate speeds—these are the speeds in its frame of reference. Those speeds are not part of the "objective," frame-independent quantities to be found in a more advanced classical mechanics model, whose basic quantities are the invariants of the motion.

Perhaps these analogies are going against one aspect of the perspectival version of the

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[40] N. Bohr, "Causality and Complementarity," *Philosophy of Science* 4 (1937): 293; cited in A. Grünbaum (1957), page 722.

[41] This is actually only correct for the pinhole camera. Its photos don't look nearly as lifelike as the ones made with cameras that have lenses, another demonstration that to create "realistic" appearances, distortion is precisely what is in order.

modal interpretation that I am presently offering. For I say that the appearances are described in the same language as the physical states—by attributions of value states represented in precisely the same way as pure quantum states. But in saying that I am taking a short cut. The outcome of a measurement, e.g., a record of a track in a cloud chamber, would be recorded in frame-dependent language too: e.g., the speed and direction relative to a frame connected with the apparatus. That is, the value state would be described both partially and relatively in the particular case. It would still be *as if* the alpha particle had a determinate momentum. Moreover, the relevant measurement outcomes here are typically not of individual events but of mean values, to be compared with the predicted expectation values. The insistence on representing the value states in the way I do implies that the appearances are never *as if* the objects are simultaneously characterized by determinate values of incompatible observables.

There is an ambiguity here too, as is well brought out by Grünbaum's and Margenau's discussions of the possibility of attributing both precise locations and precise momenta to individual particles for a certain time in a measurement. This can be done by e.g., two position measurements and a time of flight calculation. But, as mentioned above, the data thus gathered cannot be used to infer to a real quantum state in which those quantities are determinate, they have absolutely no empirical predictive value, and they have no analogue on a statistical (as opposed to individual) level. For these reasons, the addition of a time of flight calculation to position measurement outcomes could be greeted with "so the appearances are as if the particle had simultaneous determinate location and momentum," but that would have to be countered by "the appearances displayed in the aggregate destroy that initial impression."[42]

When I say that the appearances are describable in the same language as the quantum states, I am honoring one of the principles that became entrenched as the working Copenhagen ("orthodox") interpretation: *no two things can be true together unless they can have probability 1 together.* I add to this that the world of appearances is at all times

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[42] See by comparison A. Grünbaum, 1957, pp. 713–15; H. Margenau, *The Nature of Physical Reality* (New York: McGraw-Hill, 1950), pp. 376–77; and H. Reichenbach, *Philosophic Foundations of Quantum Mechanics* (Los Angeles: University of California Press, 1944; New York: Dover, 1998), p. 119.

as fully determined as it can be, compatible with this constraint. From this it follows that it is the language of pure quantum states that has the right structure to describe the appearances. And thus it is, as far as what appears in actual or possible measurement, *just as if* both the ignorance interpretation of mixtures and the Projection Postulate are true.

Relative states and the invariants

The value states are what appear in [actual and possible] measurement outcomes, in perfect analogy with how certain spatial aspects of bodies appear in the contents of visual perspectives on those bodies. (That is, their projections on certain planes from certain vantage points, whether on photo or motion picture.) But the appearances in different such measurement set ups are systematically related to each other. In the classical case in which spatial shapes are registered, that is fully explained by means of the three-dimensional shape of the object, and the straight line propagation of light, as described in geometric optics. The appearances are *relative* quantities, such as ‘shape as seen from’ and in mechanics, speed relative to a frame of reference, and they derive from *invariant* quantities that are the same from all visual vantage points (the cross-ratio in projective geometry), respectively in all frames of reference (such as acceleration). What about the quantum case, as we now wish to interpret it?

There are many different possible measurements to make on systems in a given quantum state. Because of the statistical character of Born's rule, individual outcomes have little or no significance (I'll say more about that below), but averages do. The recorded averages in different sorts of measurements all follow from the quantum state via the Born rule—"follow" of course in the minimal calculational, and not the explanatory, sense. The quantum state is characterized in terms of invariants; it is only very partially revealed in any measurement set up, but how it is there revealed follows (in that sense) from that invariant character of the system. This was strongly urged as crucial to any interpretation by Born in his Nobel Prize lecture.[43] But we must be careful not to

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[43] M. Born, "Statistical Interpretation of Quantum Mechanics," *Science* 122 (1955); see also his "Physical Reality," *Philosophical Quarterly* 3 (1953), reprinted in his *Physics in My Generation* (New York: Pergamon Press, 1956), pp. 151–63. See the discussion by A. Grünbaum (1957), pp.

assimilate this too closely to the relation between spatio-temporal invariants in mechanics to the spatial and temporal frame-relative quantities there. As Adolf Grünbaum comments:

> Now that we know the independently existing attributes of atomic entities defined in Born's sense by the quantum mechanical invariants, it is perfectly clear that they do *not* constitute attributes of *individual* events *in space and time* which are the values of a set of state variables linked by deterministic laws. This result was to be expected from any philosophical interpretation compatible with complementarity, since, as Bohr has explained, "the renunciation of the ideal of causality in atomic physics which has been forced on us is founded logically only on our not being any longer in a position to speak of the autonomous behavior of a physical object."[44]

In the interpretation I am now proposing, the quantum state contributes the invariants displayed in the relationships between the statistics of outcomes in different measurement set ups. To take the simplest sort of example, presented naively: if many particles are prepared in the same quantum state, and position measurements are made on one subaggregate while momentum measurements are made on another subaggregate, then the statistics will bear out Heisenberg's uncertainty relations.

Appearance 'kinematics'

How do those appearances change over time? That process is indeterministic, but it is strongly constrained by the quantum states of the objects involved. The value state must always be *possible with respect to* the quantum state.[45] And at those moments which mark the end of a measurement process (as identified by purely quantum mechanical criteria on the quantum states of object and apparatus), the Born rule gives the

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720–22, who points out that L. Rosenfeld made the same point in "Strife about Complementarity," *Science Progress* 41 (1953): 405–406.

[44] A. Grünbaum (1957), p. 722; italics and quotation marks in original.

[45] That is, one represented by a vector which is not orthogonal to the vector or statistical operator which represents the quantum state.

probabilities of the various possible value states.[46]

The Copenhagen school consisted of physicists, and we must all agree that their expositions often muddled themselves with half-baked bits of philosophy. But it would be silly of us to extrapolate from those, and not from the cases in which their dicta and practice agreed with each other. Thus Heisenberg's idealist and quasi-Kantian sentiments can be ignored, it seems to me, while such passages as the following are consonant with his actual work:

> the introduction of the observer must not be misunderstood to imply that some kind of subjective features are to be brought into the description of Nature. The observer has only the function of registering decisions, i.e., processes in space and time, and it does not matter whether the observer is an apparatus or a human being. . . . the Copenhagen interpretation regards things and processes which are describable in terms of classical concepts, i.e., the actual, as the foundation of any physical interpretation.[47]

So what happens now to our naive idea of objects that have specific and quite definite locations in space, remain there or move continuously from one place to another, with definite velocities?

This classical conception was always a vast idealization, and what appears to us in experience was compatible with it only under restricted conditions. But while a dynamic state governed by Schroedinger's equation cannot have its spatial support restricted to a finite region for more than a moment, the value state can remain localized in that way for some time. The ‘rigid’ connections between bodies which are reflected in the quantum state through correlations ("entanglements") of the states of the parts will keep the value states of the parts connected as well. The spatio-temporal description of the process, as it appears, corresponds approximately but not mistakenly to the value state description.

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[46] In the case of modal interpretations it has been strongly suggested that they must be supplemented by a ‘value state dynamics’ This may derive from not wanting to give up on the Appearance from Reality Criterion. However, as Bradley Monton pointed out to me, just adding a value state dynamics would in any case not suffice to satisfy that criterion.

[47] W. Heisenberg, "The Development of the Interpretation of Quantum Theory", in W. Pauli, ed., *Niels Bohr and the Development of Physics* (London: Pergamon Press, 1955), p. 22; cited in A. Grünbaum (1957), p. 719.

The appearances do not supervene

On this view the appearances do not even supervene on the quantum states, let alone be explicable from them by mechanisms of perception. That is not due simply to the indeterminism in this theory. It is easy enough to imagine classical stochastic processes, observed or measured at different times, but with the measurement outcomes perfectly derivable from the instantaneous state of the process, the state of the measuring apparatus, and the character of their interaction. That is the picture of the Lucretian universe, and there is no reason at all to see it as violating either the common cause or Appearance from Reality criteria. The nonclassical indeterminism of quantum theory breaks the mold.

Note here well, however, the difference between the perspectival version of the modal interpretation that I am now presenting, and the original ‘empirically superfluous hidden variable’ version. For if we classify the value state and the quantum state as together representing the complete physical state of the object, then how the object appears in the measurement outcome *does* supervene on its (combined) physical state. But supervenience fails too if the value state is simply classified as the content displayed (partially and relatively) in the given measurement outcome, and the physical state consists of the quantum state alone. Without stretching our reading of Bohr too far, I would say that is also precisely how it was when Born had introduced his rule and the Copenhagen physicists refused to add hidden variables, whether empirically contentful or superfluous.

So there is one striking difference between the original "empirically superfluous hidden variable" version of the modal interpretation and the present "perspectival" version. For a given quantum state there may be many value states possible relative to it. In the original version, one of these will be the real one, the actual one, presenting the definite properties the system actually has, in addition to its quantum state. But in the perspectival version, all those relatively possible value states are on a par: they are simply how the system ‘looks’ from one possible vantage point or another. If I (or a robot voice mechanism on a measurement apparatus) enunciate the content of an observation (of a measurement outcome) that may take the form, "The iron bar has negative charge," but it is tacitly indexical, accompanied by the tacit "from here"—so it does not contradict the statement that the quantum state of the bar is a superposition or mixture of positive and negative charge.

The final challenge

The details of quantum theory interpretation are fascinating, challenging, and frustrating, and its problems are by no means all settled. But my main aim in this paper is not to defend a specific interpretation—let alone its details in one form or another! Rather, what I mean to do is to argue that this actual part of recent history of science should convince us that it is perfectly scientific, and scientifically acceptable, to reject the completeness criteria for science that I outlined. That is a thesis concerning the aim and methodology of science, directed against at least certain traditional themes in 'realist' philosophies of science.

If my view of it is right, and if in addition the Copenhagen physicists were acting in a way that counts as real physics when they introduced and developed quite explicitly a theory and an interpretation incompatible with the Appearance from Reality completeness criterion, then that criterion is ***not*** a constraint on the sciences. It is, in that case, just another of those philosophically or metaphysically motivated imperatives that could hamper science if they were obeyed, and receive much lip service, but are anyway quickly flouted when that hampering is felt.