

# Representation and the Quantum State

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## 1. Introduction

Alternative views of quantum states are often expressed using the language of representation. For example, after titling his 2014 review article “Is the quantum state real?”, Leifer went on to say “The question of just what type of thing the quantum state, or wavefunction, represents, has been with us since the beginnings of quantum theory.” It is important to distinguish three questions here: What is a quantum state? How may a quantum state be represented? What, if anything, does a quantum state represent? I shall defend answers to these questions against alternatives. In brief, a quantum state is an objective relational property of a physical system that describes neither its intrinsic physical properties nor anyone’s epistemic state. Since its primary role is to assign Born probabilities to certain physical events involving the system, a quantum state may be represented in quantum theory by any mathematical object that can play this role. If it represents anything, a quantum state represents the objective probabilities it yields in this way.

The paper continues like this. Section 2 surveys a variety of equivalent ways a quantum state may be represented in order to serve its function in quantum theory. Section 3 argues that a quantum state is not a physical entity, while section 4 argues that it is not a physical magnitude. In section 5 I argue that a system’s quantum state does not represent its intrinsic physical properties or those of three-dimensional space. While few, if any, of these arguments are original or decisive, I take them to motivate consideration of an alternative that can help improve our understanding of quantum theory. So in section 6 I develop a relational account of a quantum state as what I call an extrinsically physical property of a system,

contrasting this with Rovelli's relational quantum mechanics and QBism. In section 7 I ponder whether this makes a quantum state representational: in my sense it is representational and many quantum states are real. Section 8 says what quantum states may represent and why this makes them modal properties. In section 9 I show why quantum states give a naturalist a reason to reject Representationalism.

## 2. How quantum states may be represented

Schrödinger (1936) used the word 'representative' to refer to a wave function, but a quantum state may be represented by many different mathematical objects. A quantum state may be represented by a wave function in the Heisenberg, Schrödinger or interaction picture. This wave function may be in position, momentum or energy representation. In a Hilbert space of square-integrable functions it may be represented by an equivalence class of functions that differ only on a set of measure zero. It may be represented by a vector or a ray of vectors in an abstract Hilbert space: a more general class of quantum states then includes mixed states representable not by vectors but by density operators on the space. In algebraic quantum theory a quantum state is represented by a normed, positive, linear functional from a  $C^*$  algebra into the complex numbers. The von Neumann algebra of bounded linear operators on a Hilbert space admits representations of states that cannot even be represented by density operators. What all these different representations of a quantum state have in common is their role in yielding probabilities when (the appropriate form of) the Born rule is applied to them.

The negative conclusion of this section is that it is both a category mistake and an unwarranted restriction on the scope of inquiry to identify the question "What does the quantum state represent?" with the question "What does the wave function represent?" But implicit in the very diversity of mathematical representations of quantum states is a positive

suggestion about what a quantum state is and what, if anything, it represents.

Generating probabilities is a key role of a quantum state, no matter how that state is represented. This suggests a preliminary answer to the nature of quantum states: a quantum state is whatever it takes to generate the Born probabilities it represents. I think this is basically the right answer, though more needs to be said to clarify and justify it.

### 3. Quantum states are not physical entities

One objection arises immediately. If all a quantum state does is to yield a bunch of probabilities then that state is not real: but we should accept the reality of a central posit of a spectacularly successful theory like quantum theory.

What lies behind this objection is a conception of what it is for a central posit of a physical theory to be real. Oxygen is posited as a physical entity by a successful theory of combustion, and to say that it is real is to say that the physical world contains such an entity. On this conception, quantum states would be real if and only if the physical world contains such entities as quantum states. But (the objector continues) probabilities are not physical entities<sup>1</sup>, and if all a quantum state does is to generate probabilities then it is not real either.

I'll defend the reality of quantum states in section 7 and the objective probabilities they yield in section 8. But first, in deciding whether they are real, quantum states should not be thought of as (potential) physical entities.

A typical physical entity such as a speck of dust or a sample of oxygen bears physical properties and relations and has physical parts, all of which may change with time. It interacts

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<sup>1</sup>When the subjectivist statistician Bruno De Finetti (1974) famously wrote **PROBABILITY DOES NOT EXIST** he meant to deny that the physical world contains any such thing, just as it contains no phlogiston, fairies or witches.

causally with other physical entities. Typical physical events are also entities with physical properties, relations and parts: They have spatiotemporal locations and they interact causally with other physical entities. Atypical physical entities may lack some of these characteristics. Democritus's atoms had no parts and their intrinsic properties did not change, though their changing spatial relations were supposed to underlie all other physical change; classical physics contemplated point events with no spatiotemporal extent and fields located everywhere in spacetime.

By contrast, a quantum state has no physical properties, relations or parts: it has no spatiotemporal location and does not interact causally. These claims may be disputed. The ground state of a hydrogen atom is often depicted as an electron cloud of varying density surrounding a central proton. But this does not locate the state itself, but merely represents the position-probability distribution (or probability amplitude—a real number in this case) for the electron in accordance with the Born rule.

Some views privilege a particular representation of a quantum state. Ney (2020) advocates wave function realism, according to which the wave function of the universe represents a field in a high-dimensional configuration space. For a wave function realist, this field is a physical entity occupying the whole of this high-dimensional analogue of the ordinary three-dimensional space alleged to emerge from it dynamically. The universal wave function is supposed to act on matter (represented by a point in configuration space), confirming its physicality. But wave function realism does not square well with how physicists typically use quantum states in all forms of quantum theory, not to represent the entire universe all at once but to predict and explain the behavior of selected physical subsystems (such as the proton, helium atom, or ammonia molecule; superfluid helium-3, a Heisenberg ferromagnet, or an entangled photon pair) by assigning them quantum states and

using these to generate probabilities concerning them and their four-dimensional spacetime environment. There is nothing in these applications to warrant privileging a configuration-space wave function as representative of the quantum states assigned, or to show these states are physical entities.

#### 4. Quantum states are not physical magnitudes

Bell (2004) introduced the term ‘beable’ to refer to whatever a theory takes to be physically real—as what may be “described in ‘classical terms’, because they are there.” As examples he mentioned the settings of switches and knobs and currents needed to prepare an unstable nucleus. These are not physical entities; each is a physical magnitude. The famous EPR paper (1935) used the phrase ‘element of physical reality’ to refer to such quantities in arguing that there are some that quantum mechanics fails to describe. Perhaps quantum states are themselves such elements of reality—real physical magnitudes, not real physical entities?

Wallace and Timpson’s (2010) spacetime state realism suggests that a density operator is a magnitude representing a spacetime region’s physical properties the way a real number  $T$  represents a room’s temperature properties. Anticipating an incredulous stare, Wallace and Timpson say (*op. cit.*, p. 710):

There need be no reason to blanch at an ontology merely because the basic properties are represented by such objects: we know of no rule of segregation which states that only those mathematical items to which one is introduced sufficiently early on in the schoolroom get to count as possible representatives of physical quantities, for example!

If general relativity represents a quantity in a region of spacetime by an order-two tensor field, why should quantum theory not represent the physical properties of a region of

spacetime by a density operator on a Hilbert space?

There is a good answer. Each component of the stress-energy tensor field at a spacetime point gives the flux at that point of a 4-momentum component across a 3-hypersurface. Each of the 16 components of this tensor in a coordinate system has a real-numbered value on a common cardinal scale to satisfy the tensor's transformation properties. The components of any tensorial magnitude (scalar, vector, or higher order) have values on some cardinal scale. But a density operator on a Hilbert space is none of these, and its matrix elements in a basis for that space are not the values of any magnitude on any cardinal scale. A quantum state is not a physically real magnitude.

## 5. A quantum state does not represent any (intrinsic) physical properties

The instantaneous physical state of a system of  $n$  classical particles may be represented by a point in a  $6n$ -dimensional phase space that determines the value of every other dynamical variable of the system. Associated with each measurable region of phase space is a physical property that the system possesses just in case the phase space point representing its state lies in that region. Some have thought a system's quantum state plays an analogous role in quantum theory with phase space replaced by Hilbert space, each subspace  $N$  of which is associated with a physical property the system definitely has if the density operator  $W$  representing its state projects onto  $N$  but otherwise has only with probability given by  $TrWP_N$ , where  $P_N$  is the projection operator uniquely corresponding to  $N$ .

But the analogy between phase space and Hilbert space as bearers of a probability measure breaks down as a consequence of results due to Gleason (1957) and others. Gleason proved that the only measures on (closed) subspaces of a Hilbert space of dimension greater than 2 are those generated by some density operator. No such measure is dispersion-free, in

that it assigns either 0 or 1 to each subspace in a way that can be interpreted as saying which properties corresponding to subspaces are possessed and which are not. These negative results show that a quantum state does not represent a system's physical properties the way a phase space point represents the dynamical properties of a classical system. Attempts to evade this conclusion by adopting a kind of quantum logic governing reasoning about statements assigning physical properties to a quantum system have the character of a degenerating interpretative research program.

But the framework of ontological models (see Harrigan and Spekkens (2010), Leifer (2014)) explores the possibility that a quantum state yields a probability distribution over some space of random variables, perhaps of a wholly novel kind, the points of which may be parametrized by a variable  $\lambda$  whose value more completely describes the system assigned that quantum state. In that framework, Pusey, Barrett and Rudolph (PBR) (2012) proved a result they took to show both that suitably prepared quantum states are physically real and that they are properties of the systems so prepared.

The basic assumption of the ontological models framework is that after the quantum state of a system has been prepared, the value of the variable  $\lambda \in \Lambda$  provides a complete specification of the physical properties of that system. But a preparation procedure for a state represented by vector  $\psi$  may yield one of many distinct real states  $\lambda$ , with a probability distribution  $\mu_\psi(\lambda)$  on  $\Lambda$ . So distinct quantum states  $\psi_1, \psi_2$  result in different distributions  $\mu_1(\lambda), \mu_2(\lambda)$ . These might or might not overlap: if they did, then distinct quantum states would be compatible with the same underlying real state  $\lambda$ . The parameter  $\lambda$  is also supposed to specify a fine-grained probability measure over all possible outcomes of measurements of magnitudes ("observables") to which a quantum state assigns a probability via the Born rule. Indeed, that Born probability is assumed to arise by integrating this fine-grained measure

weighted by the distribution  $\mu_\psi(\lambda)$  over the space  $\Lambda$ .

For PBR, the variable  $\lambda$  represents the real state of a system assigned a quantum state represented by  $\psi$  following some preparation procedure. They consider a state represented by  $\lambda$  to be physically real because:

- (1) it determines all actual physical properties of the system, and
- (2) for each observable, it determines a probability distribution over the possible outcomes of a measurement of that observable.

Assuming that systems that are prepared independently have independent physical states, PBR proved that the quantum state assigned to each system is uniquely determined by the value of  $\lambda$  that provides a complete specification of the actual physical properties of that system. Because it is determined by the physically real state  $\lambda$ , they conclude that this quantum state is also a physically real property of the system.

But the proof establishes its conclusion only if a system has a state meeting both conditions (1) and (2). The ontological models framework simply assumes that it does. But a quantum state meeting condition (2) may be real even though it does not meet condition (1): and (*pace* PBS) a system may have a real physical state meeting condition (1) but not condition (2). The PBR theorem does not show that a quantum state is a physical property of the system to which it is assigned.

Some views of quantum theory assign a descriptive function to a privileged universal quantum state. For non-relativistic quantum mechanics this would be the state of all  $n$  particles in the universe (for some finite  $n$ ). Monton (2006) takes this universal quantum state to be pure, and to determine a holistic physical property of the universe through the eigenstate  $\rightarrow$  eigenvalue link: the universe's particles have property  $P$  at time  $t$  if its state vector  $|\psi(t)\rangle$  is an eigenstate of a projection operator uniquely corresponding to  $P$  with eigenvalue 1. If this

description were complete, then no particle would ever have a precise position, since a well-defined configuration-space wave-function has no corresponding projection operator. But some take Bohmian mechanics to offer a clear version of non-relativistic quantum mechanics that also includes a precise trajectory for every particle in the universe determined by a universal wave-function  $\psi(\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_n, t)$  in accordance with a law sometimes called the Bohmian guidance equation.

This universal wave-function can then be understood either to represent a holistic physical property of the  $n$  particles at  $t$ , or to represent an  $n$ -place physical relation among the points of space they then occupy. The latter option has been called the multi-field conception of the wave function (by Belot (2012)), as opposed to viewing it as a field on configuration space. The former option has been proposed as a way of fleshing out a so-called nomological conception of the wave function—as something required to state the law determining particle trajectories. The idea here is to regard this holistic property of the particles as a disposition grounding that law (see Esfeld *et al.* (2014)).<sup>2</sup>

The main problem I see with either of these options is that it applies only in the artificially restricted context of a particular take on non-relativistic quantum mechanics that assumes the existence of a universal wave function. But quantum theory is applied much more widely outside of that context, where the quantum state of a system is not represented by a wave function and it is not assumed that there is any universal wave function. Quantum states play their role in all applications without that assumption.

## 6. A quantum state is an extrinsically physical property of a system

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<sup>2</sup> Suarez (2015) has proposed an “intermediate” view with a dispositional velocity field defined at each point of space that also faces the following problem.

A property may be either intrinsic or extrinsic to its bearer. Mass is an intrinsic property of an electron (at least according to classical physics)—a property it has in and of itself, without regard to the existence or properties of anything else: Being lighter than a proton is an extrinsic property because it involves the electron's relation to the proton. Here this is a physical relation to something physical: I'll call such an extrinsic property *extrinsically physical*. Being married is an extrinsic property but it is not extrinsically physical since it also involves a person's social or legal relations to another. These change with the death of a distant spouse but this is no instantaneous action at a distance since it involves no immediate change in the person's intrinsic properties.

Having a particular position or velocity is not an intrinsic property of a classical particle insofar as it implicitly depends on its relation to a reference frame. To highlight the contrast with a system's quantum state I shall ignore this complication and treat these and all other classical dynamical properties determined by a system's phase space point as intrinsic properties. But a quantum state is an extrinsically physical, not an intrinsic, property of a physical system.

QBists and others regard a quantum state as a state of knowledge or opinion of an agent and take this to imply that it is not a property of the system to which the agent assigns it. The system does have the extrinsic property of being assigned that state by that agent. But this is not an extrinsically physical property because it depends on an intentional relation to an agent, not a physical relation to a physical object or situation.

A quantum state is ontic in Leifer's (2014) sense, and not a state of knowledge or opinion of some agent (though an agent may come to know this state).

...an ontic state refers to something that objectively exists in the world, independently of any observer or agent. In other words, ontic states are the things that would still

exist if all intelligent beings were suddenly wiped out from the universe. *op. cit.* p.69

Because a quantum state is an extrinsically physical property, a system in given circumstances may have more than one quantum state, each relative to a different physical relatum. But a system has a quantum state only relative to something physical.

Everything in the previous paragraph accords with Rovelli's (1996) relational quantum mechanics. For Rovelli, the physical item relative to which a system has a quantum state is a distinct physical system. He maintains that just as "the observer" to which velocities must be relativized in Galilean relativity may be any physical object (such as a table lamp), so also "the observer" to which the state of a physical system must be relativized in quantum mechanics may be any physical system (such as an electron). In his view

Quantum mechanics is a theory about the physical description of physical systems relative to other systems, and this is a complete description of the world. (1996, p. 1650)

But it is difficult if not impossible to reconcile this view with the objectivity of physical description in quantum theory.

By examining how quantum states are used in applications of quantum theory one can arrive at a better relational view. Quantum theory is applied not in order to describe a physical system but in order to assign probabilities to a range of statements about it. Such a probability assignment is useful for an agent in a particular physical situation whose physical conditions make it impossible to determine which statement in that range is true. What makes a quantum state an extrinsically physical property of a system is not its relation to another physical system but to such a physical situation. A system has a quantum state relative to a physical situation because of features of the physical environment that constrain the information accessible to any agent that may (or may not) happen to be in that situation. That

is why a system's quantum state is ontic and not epistemic: to say the system has that state is not to say what any observer knows, believes or suspects of it.

A localized agent has direct epistemic access only to the contents of their momentary past light-cone: but this may permit indirect epistemic access to events outside it. Quantum theory mediates this access because a quantum state relative to the agent's momentary spacetime location yields probabilities concerning such possible events. Bohm's version of the EPR *Gedankenexperiment* provides a memorable illustration of such relativity.

A pair of spin  $\frac{1}{2}$  particles has a physically extrinsic property represented by the spin-singlet state vector. The  $z$ -spin component of particle  $R$  is measured with spin-up outcome. Relative to points to the (absolute) future of that  $R$ -measurement event, the quantum spin state of the  $L$  particle is represented by the vector  $|\downarrow\rangle_z$ , a spin-down  $z$ -spin eigenstate: but relative to other points,  $L$ 's spin state is represented by a reduced density operator—the two dimensional identity operator  $\mathbf{I}$ .

$|\downarrow\rangle_z$  and  $\mathbf{I}$  each represent the state of particle  $L$  (relative to different spacetime locations), and the change from  $\mathbf{I}$  to  $|\downarrow\rangle_z$  is not a physical event, caused by the measurement on particle  $R$ . It is a change in relativization from one spacetime region to another to accommodate the change in physical situation of any agent Alice whose world-line entered the future of the  $z$ -spin measurement on particle  $R$ . As her physical situation changed, so would the quantum state that such a (merely hypothetical) Alice should assign to particle  $L$  to yield the relevant Born probabilities for her new situation. The spin-up outcome on  $R$  is the physical reason why any such Alice should update her quantum state for  $L$  after gaining access to new information about what happened to  $R$ .

The spacetime location of an actual or merely hypothetical agent may present a less fundamental physical barrier to informational access. In the *Gedankenexperiment* of

Wigner's friend, Wigner has no informational access to the contents of his isolated friend's laboratory and so cannot observe the outcome of her quantum measurement even when this does lie in his past light-cone. The Schrödinger picture state vector of his friend's laboratory evolves unitarily relative to Wigner's physical situation so after her measurement the system she measured has a mixed quantum state relative to this external physical situation. But this is consistent with that system's having a pure quantum state relative to the physical situation of his friend after she has measured it.

## 7. Is a quantum state representational?

The term 'representational' has been used in recent discussions to classify opposed views of the nature of quantum states.<sup>3</sup> The pragmatist view of quantum states I have taken elsewhere (2012a, 2017a, 2017b) and assumed here has sometimes been classified as non-representational. But usage has not been consistent. To clear the air I shall distinguish several possible senses of the term while explaining an important sense in which a quantum state is representational in this view.

A quantum state could count as representational simply by being represented by a wave function or other mathematical object. Since representation is an intentional concept, a quantum state would then count as representational whether or not it exists. A quantum state is representational in this minimal sense whether or not it is real, and so are the philosophers' stone, caloric and the properties of being dephlogisticated or at absolute rest.

One could choose to say that a quantum state is non-representational if a quantum state is neither a physical entity nor magnitude and does not represent a system's intrinsic

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<sup>3</sup> See, for example, Krissmer (2018), Bub (2019), Wallace (2019) and several papers in French and Saatsi (2020), Glick and Darby (2020), Hemmo and Shenker (2020).

physical properties. Since sections 3-5 ruled out these views of a quantum state one would then call a quantum state non-representational.

An alternative use of ‘representational’ ties it to truth-aptness. Emotivists claimed that an ethical statement such as “Stealing money is wrong” expresses an emotion rather than stating a fact and so cannot be evaluated for truth. They maintained that despite its subject-predicate form, this statement is not truth-apt and the term ‘wrong’ is non-representational. Similarly, someone could deny that a statement ascribing quantum state  $\psi$  to a system is truth-apt and so the predicate ‘being in quantum state  $\psi$ ’ counts as non-representational, on the grounds that this statement does not state a fact but expresses an epistemic attitude.

But while the primary function of a statement ascribing a quantum state to a system is not to describe or represent that system’s intrinsic physical properties, that statement *does* have a truth-value (relative to an appropriate physical situation), since a quantum state is an extrinsically physical property of a system. In this sense, a quantum state *is* representational. Indeed, a statement ascribing a quantum state to a system is useful only to the extent that statement is true (true enough, that is: see Elgin (2017)) and so the state is real. It is because there are many such statements ascribing a quantum state to a system that I consider those quantum states to be real.

Wallace (French and Saatsi, p.87) has offered yet another understanding of what it is for a quantum state to be representational. He considers

the classic Schrödinger-cat state  $\alpha |\text{live cat}\rangle + \beta |\text{dead cat}\rangle$  which unitary quantum theory can straightforwardly produce. If the quantum state can be understood representationally—that is, if distinct quantum states correspond to distinct objective ways a physical system can be—and if the theory is unsupplemented by hidden variables, then it looks as if such a state must somehow represent a cat that is

simultaneously alive and dead.

Since a quantum state is an extrinsically physical property of a system, that system may have distinct quantum states, each relative to a different physical situation. There is nothing subjective about its having these ontic states, and in that sense each represents a distinctive objective way for that system to be. But a cat's death certainly involves a change in its intrinsic physical properties. The passage suggests that two ways a physical system can be count as objectively distinct only if these involve incompatible intrinsic physical properties of that system.

Entanglement-swapping features quantum states that count as non-representational on this narrower understanding of objective distinctness (see Healey (2017b)). In entanglement swapping a particular pure entangled state is assigned to a system after a measurement is performed on a second, distant system: which state is assigned depends on the outcome of that measurement. Assuming it is a local event, in the absence of retro- or spacelike causation the distant measurement does not alter any intrinsic property of the first system. So it has the same intrinsic physical properties no matter which of two or more distinct pure quantum states it is assigned. In that sense, these distinct quantum states do not correspond to distinct objective ways that physical system can be. That is why these states count as non-representational in this narrow sense of objective distinctness.

But there are other cases in which a quantum state is assigned to a system following a procedure that is said to prepare or put the system into that state, suggesting that being in this quantum state involves having associated intrinsic physical properties. A Stern-Gerlach (SG) experiment is a paradigm of such a procedure. Spin  $\frac{1}{2}$  atoms in a beam may be detected by one of two detectors placed on the  $z$ -axis symmetrically above and below the incoming beam after passage through the magnet's inhomogeneous magnetic field. If the upper detector is

Replaced by some experimental equipment, any atom that is subsequently detected in this experiment is said to have been prepared in a quantum spin eigenstate  $|\uparrow\rangle_z$  through its local interaction with the magnetic field.

Naively, the incoming beam has been split by the magnet into an upper “wave-packet” of positive  $z$ -spin atoms and a lower “wave-packet” of negative  $z$ -spin atoms. But as Wigner (1963) pointed out, unitary evolution of the quantum state vector during passage through the magnet results in an entangled superposition of the translational and spin quantum states of the atoms. Wessels (1997) called passage through a  $z$ -oriented SG magnet a mere pseudo-preparation of  $z$ -spin eigenstates in upper and lower beams on the grounds that the (reduced) quantum spin state of emerging atoms was therefore a mixture rather than a pure state. She noted that something similar is true of most if not all actual laboratory preparation procedures.

But these are *real* state preparations, involving a local interaction warranting assignment of a superposed state followed by a conceptual selection of one component with a view to a possible later local measurement-type interaction involving the target system. The selected state does not represent an intrinsic property of this system (like positive  $z$ -spin). A different selection would not have represented a different intrinsic property: it would merely have selected the state relative to a different possible subsequent local measurement-type interaction. State preparation does not prepare a system’s intrinsic physical properties.<sup>4</sup>

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<sup>4</sup>The state of an individual system can sometimes be prepared with no selection step by controlling its interactions with its environment, as in laser cooling or just letting the system relax when coupled to a vacuum (Fröhlich and Schubnel, 2016). While it is tempting to conclude this works by modifying its intrinsic properties, certification of the procedure by quantum tomography on many similarly prepared systems does not establish this conclusion.

## 8. What quantum states may represent, and why this makes them modal

A quantum state is an extrinsically physical property of a physical system. It is representational in the sense that a statement ascribing this property to a system is truth-apt and may be true; when it is true, that state is objectively real, like a speck of dust. But a speck of dust does not represent anything: does a quantum state? In my (2017b) I said that if a quantum state represents anything, it is the objective probabilistic relations between its backing conditions and its advice conditions. Backing conditions describe physical situations and processes on which the state supervenes: advice conditions are magnitude claims of the form  $M \in \Delta$  to which the Born rule assigns probabilities when legitimately applied. This requires the system to be involved in an appropriate interaction—one modeled by rapid and robust decoherence of a quantum state.<sup>5</sup>

Once one understands the function of a quantum state it matters little whether one chooses to say that it represents the objective probabilistic relations between its backing conditions and its advice conditions. Many true statements supervene on these backing conditions. What distinguishes a statement assigning a system's quantum state is that it implies objective probabilistic relations between its backing conditions and its advice conditions *via* the Born rule. Since probability is a modal concept—a quantified possibility—if a system has a quantum state this means that this statement has modal content because it implies many modal statements.

What makes Born probabilities objective is not that they are determined by all local matters of particular fact but that they offer authoritative advice to any user of quantum theory on how to set their credences (coherent degrees of belief) in magnitude claims in a physical situation that blocks any more direct epistemic access to the truth of those claims.

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<sup>5</sup>For further details see my (2012b).

The advice carries this authority insofar as adjusting one's credences to accord with Born probabilities is on the whole the most reliable way of forming expectations in a situation of uncertainty.

Objective probabilities arise outside of quantum theory, in statistical physics and so-called games of chance. The function of probability is to guide belief (and hence action) in a situation of uncertainty: different situations require different objective probabilities, in applications of quantum theory and elsewhere. A probability could not adequately serve this function if its value were determined by any actual frequency because following its guidance may not yield the expected results, even in the long term. A quantum state has modal content because its function is to yield modal objective probabilities. This content is doubly modal because these probabilities concern sets of possibilities, where each set pertains to a different hypothetical decoherence context, at most one of which is actual.

## 9. Representationalism and the quantum state

Price (2011, 2013) has argued in favor of a distinctive view he calls subject naturalism by contrast with object naturalism. The object naturalist holds that ultimately all there *is* is the world of science and that all genuine knowledge is scientific knowledge. The subject naturalist instead maintains that philosophy needs to begin with what science tells us about ourselves—that we are natural creatures, and that philosophy must proceed by acknowledging this fact.

An object naturalist has a proto-theory about language involving the assumption of: *Representationalism*: The function of statements is to represent 'worldly' states of affairs and...true statements succeed in doing so. (Price (2013), p. 24)

This leads to problems in view of the striking mismatch between the rich world of ordinary

discourse and the sparse world apparently described by science. For there are many apparently true statements that don't seem to line up neatly with facts of the kind uncovered by natural science. These include not only normative statements, in ethics and elsewhere, but also statements about probability, possibility and causation—even when these occur within science itself.

Statements attributing quantum states to physical systems provide a striking illustration within fundamental science of the superiority of subject naturalism over an object naturalism burdened with Representationalism. For one who accepts quantum theory, the fundamental facts about the world are stated by magnitude claims. Truths about quantum states are not magnitude claims, although they supervene on them. The function of a statement attributing a quantum state is not to represent a 'worldly' state of affairs, even though many such statements are true. Representationalism fails for these statements.

The function of a quantum state is to offer good advice to any suitably-placed agent on how to set credences concerning magnitude claims whose truth-values they are not in a position to determine more directly. This function is exercised through application to the quantum state of the Born rule and adjustment of credences to match the probabilities it yields. Science tells us that we (and potentially other kinds of agents) are spatiotemporally localized natural creatures whose physical situation limits epistemic access to many physical states of affairs. Such an agent is able reliably to improve its epistemic state with respect to a physical system by applying the Born rule to the appropriate quantum state for one in the agent's physical situation. For each such situation this yields a plethora of probability distributions, each pertaining to a possible circumstance in which the system may find itself. By adjusting credences to match these probabilities the agent is better prepared to face the unknown.

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