Quantum Meaning

1. Introduction

On one view of quantum theory[1], a quantum state has the role of advising physically situated agents rather than representing the condition of physical systems. The advice concerns the cognitive significance of a magnitude claim S: **σ has (QεΔ)**, locating the value of magnitude Q on system σ in set Δ of real numbers. The quantum state offers advice both on the content of a magnitude claim S and on its credibility, provided it has enough content. The advice is authoritative—anyone who both accepts quantum theory and agrees on the correct quantum state is bound to heed it.

On this view, the content of a magnitude claim is a function of its place in a web of material inferences connecting it to other claims, and hence to perception and action. A quantum state offers advice on the content of a magnitude claim by controlling its place in this inferential web. It thereby adds a contextual element to the content even of claims about the properties of familiar objects like gross experimental apparatus and the moon. But by modeling the behavior of quantum states, quantum theory itself reassures us that only for claims about currently unfamiliar objects does the consequent modification of content amount to anything.

2. Two functions of the quantum state

The quantum state has one universally acknowledged function in quantum theory. When applied to a quantum state, the Born Rule yields probabilistic claims of the form $Prob(S)=p$, where S is a claim about a magnitude on a system (such as a component of its position, momentum, or spin).

The Born Rule also yields some joint probabilities $Prob(S_1,S_2, ..., S_n)=p$ where each S_i ($i = 1, 2, ..., n$) concerns a different magnitude: while different components of position have a well defined joint distribution, different components of polarization do not. A variety of "no-go" theorems show that, for most quantum systems, not all Born probabilities can be retrieved as marginals of any joint probability distribution for the simultaneous real values of all their magnitudes.[2] These results support the orthodox view that at no time does every magnitude on a quantum system have a precise value: in particular, no system ever has a precise position and a precise momentum.

But a single careful measurement of a magnitude always yields a precise value, and in measurements on many similar systems these values are distributed in close conformity to corresponding Born probabilities. This supports the orthodox view that the Born Rule specifies probabilities of measured values of magnitudes, not of values those magnitudes have whether or not some of them are measured. Born probabilities $Prob(S_1,S_2, ..., S_n)=p$ are then applicable only when n magnitudes are actually measured together on a system, in which case each S_i ($i = 1, 2, ..., n$) is a claim about the result of measuring the ith magnitude.

The problem with interpreting Born probabilities this way is that there is no precise specification of what a measurement is and when it happens. One might expect a fundamental quantum theory to be able to model, for each magnitude Q on a quantum system σ, a physical interaction between σ and a (quantum) measuring apparatus α suitable to serve as a measurement of Q as it correlates any initial value q_j of Q on σ with a corresponding final value p_j of a "pointer position" magnitude P on α. But a model of quantum theory merely specifies the behavior of a quantum state, whose main function is just to yield Born probabilities for what the orthodox view calls measurement results.

Many have been tempted to take a system's quantum state also to describe its properties. In effect they have adopted the semantic rule that system σ has a property that the value of magnitude Q lies in set Δ of real numbers ($Q\varepsilon\Delta$) iff application of the Born Rule to its quantum state assigns this property probability 1. But this rule establishing truth-conditions for a magnitude claim S leads directly to the notorious quantum measurement problem. The semantic rule proves to be incompatible with the observation that, no matter the initial quantum state of the measured system, an apparatus ready to record the result of a measurement always acquires a property recording some result or other.[3]

How else might one appeal to a quantum model to clarify the meaning and application of the Born Rule? One may use the quantum state not to determine whether a magnitude claim is true, but rather to decide what to do with such a claim.

One thing an agent may decide is to believe S. But if the Born probability of S is low that would be unwise. The way to conform one's epistemic state to a Born probability 0.1 of S is to form a corresponding partial belief–credence 0.1–in S. But it would be equally unwise to set one's partial beliefs equal to all Born probabilities generated by a particular quantum state: that would often render them incoherent.[4] A prior decision is required as to which Born probabilities are worthy of credence. Orthodoxy recommends restricting any belief to statements reporting measurement results. An agent needs guidance on which those might be. The system's quantum state is the only available adviser within a quantum model. But again that advice cannot come in the form of a semantic rule stating the truth-conditions of a statement that a measurement of specified magnitudes has occurred. Quantum theory neither contains nor accommodates any such rule. The needed advice must come in the form of a pragmatic rule for using a system's quantum state to judge when, and to which statements of the form S, it is advisable to apply the Born Rule.

Such a rule might do much more. It could contribute essentially to the general project of accounting for the determinateness of physical properties of a host of familiar physical objects besides measuring apparatus. To the extent that we are successful in describing these properties in terms of a classical state, this would help us to understand why we encounter an objectively existing, approximately classical, world.

The Born Rule can exercise its core function of guiding an agent in forming credences concerning a statement only if the statement is meaningful. So we are seeking a pragmatic rule for judging the conditions under which a magnitude claim *S* has sufficient content to be incorporated into an agent's epistemic state, as a partial or even full belief. This prompts the general question "What gives content to an empirical statement like *S*?" One can find a general answer in the pragmatist inferentialism of Brandom[5], who understands the content of such a claim in terms of its place in a web of theoretical and practical inferences. The theoretical inferences that contribute to the content of an empirical claim are not restricted to those that are formally valid: they importantly include what Sellars called material inferences.[6]

The quantum state, then, has two related functions, neither of which is to represent properties or relations of a system to which it is ascribed. Its primary function is to advise a user of quantum theory on the content of a magnitude claim attributing a property $Q \varepsilon \Delta$ to a physical system σ in a situation objectively characterized by quantum state ρ.[7] It does this not by specifying the claim's truth-conditions, but by modulating the inferential power of the claim in ways I am about to explain. On a traditional model of content, a claim is meaningful if it expresses a definite proposition when made in an adequately specified context: otherwise it is meaningless. An inferentialist approach to the content of an empirical claim accepts a role for context but replaces this "digital" view of content by an "analog" view. While a quantum state specifies the context for a magnitude claim, it does so by specifying the inferential power of particular magnitude claims in that context: inferential power comes in degrees, and so, therefore, does content.

The quantum state exercises its second, core function only for a magnitude claim with sufficiently high content. That function is to advise an agent to believe *S* to degree *p* iff *Prob*(*S*)=*p* is the probability that results from applying the Born Rule to this quantum state.

3. The content of magnitude claims

I shall consider a number of magnitude claims to show how a quantum state ρ may be taken to govern their content. In this section I consider only cases where ρ is ascribed to an independently designated physical object σ, and so plays no role in determining what that object is. This is particularly obvious in my first example, where σ is the moon!

In the 1980's, David Mermin wrote a pair of elegant little papers.[8] He had already answered the title question of one paper in the third sentence of the other: "We now know that the moon is demonstrably not there when nobody looks." (1981, p.397) Suppose, for the moment, that 'there' locates the moon within a "moon-sized" region *R* of space some 250,000 miles from the earth with cross-section *C* in a plane at right-angles to a line joining the centers of earth and moon. Choose Cartesian coordinates (x,y) in that plane and call *D* the diameter of *C* along the x-axis. Then the statement

S_1: The x-component of the moon's position lies in *D*

is of the form *S*.

Taken literally, Mermin's answer implies that S_1 is false when nobody looks (at the moon). But I doubt he means it literally: S_1 functions as a metaphor for him, suggested by a rhetorical question of Einstein to which I shall return.[9] The demonstration Mermin appeals to concerns not the moon and its position, but the spin of a spin ½ particle (such as an electron or a silver atom). S_1 is a metaphor for:

S_2: The x-component of the particle's spin is r.

It is S_2 that Mermin designs his demonstration directly to refute (for any x axis and any real value r) if no-one measures the x-component of the particle's spin, even though a measurement of its spin x-component always yields one of two real values (about $\pm 0.50 \times 10^{-34}$ in appropriate units).

S_1 and S_2 don't just ascribe different magnitudes: they ascribe them to very different systems. Mermin could just as well have appealed to a more complex demonstration to argue for the falsity of the statement

S_3: The x-component of the particle's position lies in d

(where d is any sufficiently small interval of real numbers) if the x-component of the particle's position is not measured. But while that demonstration also could be given "with an effort almost certainly less than, say, the Manhattan project" (Mermin (1981), p. 398), the moon so differs from an electron or atom that quantum theory itself gives us overwhelming reason to think a similar demonstration that S_1 is false unless the moon is "observed" will forever exceed the powers of human or any other physically instantiated agents.

For quantum theory, the key difference between the moon and an electron or silver atom is their disparity not in size but in interactions with their physical environment. Perhaps surprisingly, while an electron or atom is sometimes so isolated that its environment can be neglected, that is never true of the moon. Newtonian physics gave an excellent model of the moon by neglecting all effects of the sun's illumination and impacts by stray matter and taking the moon's environment to affect its state only through gravitational forces. In classical physics, the way to incorporate these effects into an even better model is as additional external forces on a system (the moon) that can affect how its state changes, but not what counts as its state at any moment—they affect its dynamics but not its kinematics. In quantum theory, taking account of a system's interactions can alter the nature of its momentary state, as well as how its state changes.

Schrödinger[10] introduced the term 'entanglement' to make this point as follows:

> When two systems, of which we know the states by their respective representatives, enter into temporary physical interaction due to known forces between them, and when after a time of mutual influence the systems separate again, then they can no longer be described in the same way as before, viz. by endowing each of them with a representative of its own. I would not call that *one* but rather *the* characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought. By the interaction the two representatives have become entangled. (*op. cit*, p. 555)

I have used the symbol 'ρ' to stand for a quantum state without saying what kind of mathematical object that is. In this quote, the author of wave-mechanics used the term 'representative' to refer to a wave-function $\psi(\boldsymbol{r}_1,\ldots,\boldsymbol{r}_n)$—a (paradigmatically) complex-valued function of the positions of the *n* particles in a system. It is often more convenient to regard a wave-function as a vector $|\psi\rangle$ in an abstract vector space. Schrödinger's point, then, is that almost any interaction between two quantum systems with vector quantum states will result in a joint state in which neither system has a vector state.

But a system may have a different kind of quantum state. When a composite of two or more quantum systems has vector state $|\psi\rangle$, each of its subsystems may still be assigned a state, since there is a distinct mathematical object—a density operator—qualified to be its quantum state. Suppose a composite system Σ has vector state $|\psi\rangle$. Then, for each subsystem σ of Σ, $|\psi\rangle$ defines a unique density operator ρ with the following property: when applied to ρ, the Born Rule gives the same probability distribution for every magnitude on σ as it does when applied to $|\psi\rangle$. In so far as generating Born probabilities is the core function of a quantum state, this makes the density operator the quantum state of σ. The notation ρ subsumes vector states as a special case, since each vector state $|\psi\rangle$ uniquely corresponds to a density operator state $\rho=|\psi\rangle\langle\psi|$. An electron or atom is sometimes sufficiently isolated from its environment to be ascribed a vector state, at least for a while. The moon's constant interactions with sunlight and stray matter may be weak, but they ensure that the moon always has only a density operator quantum state.

We are almost in a position to see why quantum theory permits an agent to claim S_1 whether or not anyone is looking, while forbidding any claim of the form S_2 or S_3 for an atomic or subatomic particle except while it is subjected to the right kind of measurement. Very roughly, the answer is that the moon's position is constantly being measured by its environmental interactions with sunlight and stray matter, while a measurement of the particle's spin or position occurs only under very specific circumstances which don't always obtain. But we need to explicate such talk of "looking" and "measurement" to re-express this answer in kosher quantum-theoretic terms. This requires a quantum model of measurement. Section 2 noted that attempts to model measurement quantum-theoretically that give the quantum state a descriptive role founder on the quantum measurement problem. So the quantum state in the model must be understood to function non-descriptively.

It is natural to model the moon's interaction with its environment as a continual series of collisions with small particles.[11] Even if the moon and each of these particles had a vector state before the collision, that would not be so afterwards. Detailed models of this type use plausible assumptions to show that whatever its hypothetical initial quantum state, the moon would extremely rapidly assume a density operator state ρ of a particular form, and then stay in such a state.[12] This is not a state in which the semantic rule of section 2 assigns the moon a precise position. But at every moment t, $\rho(t)$ will define a set of vector states $|\psi_x(t)\rangle$ ($x \in \mathbb{R}$) with several special features: *i*) It is stable—if $|\psi_x(t_1)\rangle$ is an element of the set $\rho(t_1)$ defines at t_1 then $|\psi_x(t_2)\rangle$ is an element of the set $\rho(t_2)$ defines at t_2; *ii*) $|\psi_x(t)\rangle$ approximates a classical state in the following sense: the Born probability distributions it yields for x-components of position and momentum are each concentrated around precise values (x, p_x respectively) and are consistent with the corresponding marginal probability of a joint probability distribution on a space of classical states for a system of precise but unknown position and momentum; *iii*) the classical state with values x, p_x obeys classical equations of motion.

These features suggest the following pragmatic rule for assigning content to each statement S_{1x} that locates the moon's center of mass not within D but at position x: Assign a high content at t to each statement S_{1x} if the $|\psi_x(t)\rangle$ have features *i-iii*. Applied to $\rho(t)$, the Born Rule generates a probability distribution over the statements S_{1x}. Given their high content, quantum theory now advises an agent applying the model to believe S_1 to the degree corresponding to its probability under this distribution. Since this probability will be indistinguishable from 1, an agent is certainly entitled to claim S_1, whether or not (s)he is looking at the moon.

Whether an agent is similarly entitled to make a claim of the form S_2 or S_3 concerning a particle depends on how it interacts with its environment. For Mermin's demonstration to work, the particle's interaction with its environment cannot significantly affect the spin aspect of its quantum state before it is measured. But that state does not define a set of vector states with the special features that would justify application of a pragmatic rule for assigning significant content to a statement of the form S_2. Bluntly put, an agent should regard S_2 as devoid of empirical content when the particle has such a quantum state. Even though a mechanical application of the Born Rule to its quantum state will associate a number between 0 and 1 with S_2, an agent should not base partial belief in S_2 on this number.

Measurement of a particle's spin requires an external interaction. This will change its quantum state in a way that can be modeled quantum-theoretically. A suitable interaction will transform the spin aspect of the particle's quantum state so it defines a set of vector states with special features that justify application of a pragmatic rule for assigning a statement of the form S_2 a high degree of empirical content. Application of the Born Rule to the particle's quantum state now yields a non-zero probability for two statements of the form S_2. An agent who accepts quantum theory but does not know the result of the measurement should use these as an authoritative guide in forming a partial belief in each statement. If the probability of one statement is near 1, an agent may feel entitled to make that claim: if not, the agent should suspend judgment concerning a fact of which (s)he is currently ignorant.

Some recent experiments on fullerene molecules nicely illustrate the role of the environment in giving content to claims of the form S_3. A fullerene is a form of carbon in which a large number of carbon atoms bond together in the shape of a football—soccer for C_{60}, rugby for C_{70}. While a fullerene is a fairly large molecule with considerable internal structure, it seems reasonable to call it a particle since its diameter of around 1 nanometer makes it over ten thousand times smaller than any visible speck of dust. But if passed through a carefully aligned array of narrow slits, a beam of fullerenes can display behavior typical of a light or water wave that passes through a number of slits (so that the parts going through different slits either cancel or reinforce each other) by forming an interference pattern on a detection screen. Such behavior may be understood quantum-theoretically by assigning the same quantum wave-function to each beam molecule and then using the Born Rule to calculate the probability of statements of the form S_3 locating a fullerene in a small region of the screen, where the *x*-axis is at right-angles both to the slits and to the beam axis.

This assumes such statements have a high degree of empirical content here. The assumption is justified since interaction with the screen changes the fullerene's quantum state into a form suited for applying basically the same pragmatic rule that assigned high empirical content to the statements S_{1x} about the position of the moon. In one recent experiment, the positions of C_{60} molecules on the screen were indirectly observed after they had landed on it and adhered to the screen like a fly on fly paper. Their positions were imaged using a scanning tunneling electron microscope, thereby providing strong evidence for many claims of the form S_3 about fullerenes in which *d* is an interval of only a few nanometers

But a fullerene usually interacts in this way only with the screen. The beam passes through a dark, high vacuum in the apparatus so hardly any fullerenes interact with gas molecules or light, while the material in which the slits are cut just constrains the fullerenes' vector quantum state to produce interference at the screen. So at no time before reaching the screen is a fullerene's quantum state of the right form to assign high empirical content to any statement of the form S_3, if *d* is an interval comparable to the separation between the slits. No statement that a fullerene passed through a particular slit has any empirical content.

Feynman said this about an electron as it passes through an analogous 2-hole interference experiment:

> if one has a piece of apparatus which is capable of determining whether the electrons go through hole 1 or hole 2, then one *can* say it goes through either hole 1 or hole 2.

> [otherwise] one may *not* say that an electron goes through either hole 1 or hole 2. If one *does* say that, and starts to make any deductions from the statement, he will make errors in the analysis. This is the logical tightrope on which we must walk if we wish to describe nature successfully.[13]

In the C_{60} experiment there was no piece of apparatus capable of determining which slit each fullerene goes through. But one cannot say which slit it goes through for a different, though related, reason: the environmental conditions for such a statement to be empirically significant are not met for these fullerenes. Such conditions are relevant to the possibility of determining which slit a fullerene goes through because if they were met, the environment itself could be so affected by its interaction with the fullerene as to incorporate a "record" that it went through one slit rather than the others. The presence of such a "record" in the environment would be a marker for the kind of environmental conditions required for a statement of the form S_3 to be empirically significant for a fullerene at the slits, whether or not any apparatus is capable of "reading" it. This is shown by another experiment in which a beam of C_{70} molecules was sent through a similar array of slits after first passing through a series of laser beams to heat the molecules to a high temperature.

A molecule that has absorbed energy from a laser may later radiate that energy as light. Just as one can track a firefly from the light it emits, the light emitted by a hot fullerene might be used to try to find out which slit it went through. But the slits are very closely spaced, so the emitted light would need to have a short enough wavelength to resolve the distance between them. A hotter fullerene emits more light and of a shorter wavelength than a cooler fullerene. Whether or not one sets up apparatus to collect any light to try to see through which slit a heated fullerene passes, the emitted light produces a “record” of its passage in the environment. As the beam is heated, the interference pattern a cold beam would produce gradually disappears.

At first sight, emission of light into a vacuum may seem not to involve interaction with a fullerene’s environment. But this is not true in a quantum-theoretic model of the fullerene’s environment as the vacuum state of a quantized electromagnetic field. The effect of this electromagnetic environment is to change the fullerene’s quantum state so that while each statement of the form S_{1x} about its position at the screen still has high empirical content, the Born probability density of that statement corresponds not to the low temperature interference pattern, but to the pattern observed at a higher temperature. As the beam’s temperature is increased, this approaches the “smoothed” shape one would expect to observe if each molecule passed through just one slit. At the same time, the fullerenes’ increased interaction with their environment affects their quantum state so as to increase the empirical content of a claim of the form S_3 for a fullerene at the slits, where *d* is an interval comparable to the slit separation. One is entitled to claim that each sufficiently hot fullerene passes through just one slit, and to apply the Born Rule to its quantum state to form credences about which slit the fullerene goes through.

I anticipate two objections to this account of the content of a claim of the form S_3 and other claims of the form **σ has (*Q*εΔ)** in which σ is an independently designated object such as the moon, an electron, an atom or a molecule.

First objection: A claim has significant content iff it expresses a determinate proposition. While what content a claim expresses may depend on the context to which it relates (loosely, to the context in which it is made), context merely determines what proposition a claim expresses. Any variation of content with context can be represented by a function from context into proposition expressed. An adequate analysis of a claim’s content must then supply an account of the content of each proposition in the range of that function in a referential semantics that provides its truth-conditions: if the function is only partial, the claim has no content in a context in which it expresses no determinate proposition. So an adequate analysis of the content of a magnitude claim *S* will either assign it some specific content (varying from context to context) or no content at all (in other contexts). No analysis is adequate according to which what varies with context is not simply the specific content of the claim but also how much content it has.

Reply: One can give an account of the truth-conditions of a claim of the form *S*: **σ has (*Q*εΔ)** but this is trivial. For example: *S* is true iff the system to which 'σ' refers has a value for the magnitude to which '*Q*' refers that lies in the set of real numbers to which 'Δ' refers.[14] These truth-conditions are independent of context, since the claim contains no indexical elements. The problem with this referential approach is not that it is wrong but that it is too shallow to be helpful: it fails to illuminate the different ways a claim of the form *S* functions in different contexts. The claim functions within a web of inferences, and the extent of its content depends on the context provided by the presence of other claims in the web—in this case, a claim about the quantum state of σ is critical to determining the content of a claim of the form *S* about σ.

Second objection: The proposed inferentialist alternative seeks to specify the empirical content of a claim of the form *S* by locating it in a web of material inferences—what other claims would entitle one to claim *S*, and what other claims one would be committed to by claiming *S*. But this would qualify as a serious analysis only if backed up by a complete specification of these inferences, and none has been offered. Indeed, it is doubtful that any such complete specification could be given, and even more doubtful that different agents could come to share the same web and so associate the same content with any particular claim of the form *S*.

Reply: To understand the function of a claim of the form *S* within quantum theory, it is not necessary to undertake the quixotic task of fully specifying a web of material inferences in which it is located. Claims of this form were used and understood well enough by scientists and others prior to acceptance of quantum theory. The task is merely to clarify the changes in use and understanding accompanying acceptance of quantum theory. We can rely on our previous understanding while characterizing these changes by showing how acceptance of quantum theory alters patterns of inference that grounded that understanding.

This second reply sets a task without accomplishing it. I begin that task in the next section by showing how acceptance of quantum theory affects the inferential function of analogous pairs of incompatible claims about three kinds of physical systems.

4. Some conceptual mutations[15]

How does quantum theory displace key material inferences that contribute to the content of magnitude claims?

These statements are readily recast as magnitude claims like S_2:

S_{red}: The *red* traffic light is on. S_{green}: The *green* traffic light is on.

S_{one}: The computer memory bit stores *one*. S_{zero}: The computer memory bit stores *zero*.

If a traffic light and computer are operating normally, exactly one of each pair is true (assuming the traffic light has no orange, and neglecting the brief period during which the lights and memory record are changing). A driver may defend his entitlement to claim S_{green} by appeal to his current visual experience or his memory of how the light looked a moment ago. Such inferences are fallible: someone may have secretly covered the illuminated red light with opaque material while strong reflected sunlight makes the green light appear to be on when it is off, or the driver's eyesight, memory or cognitive functioning may have been rendered unreliable.

Conclusively to establish the truth, either of S_{red} or of S_{green}, one would arrange close examination of the condition of the traffic lights by multiple observers with sense organs, cognitive skills and measurement equipment subjected to rigorous testing. An examination could include direct visual and tactile inspection of the bulbs and filters, measurement of the intensity and spectral profile of the emitted light, measurement of the bulbs' temperature, of the current flow through the bulbs and the rest of the circuit, and so on.

Suppose that such test results always provide overwhelming evidence for one of S_{red}, S_{green}, but a skeptic objects that this shows only that one or other of these claims is true whenever tests are performed, but that neither S_{red} nor S_{green} is true when no test is performed—in fact the traffic lights are red or green only when "someone looks". In response one can appeal to an account of how the lights work, according to which the tests performed have no effect on whether the lights are on or off.[16] Call a measurement of the lights' status *non-invasive* if it has no effect on their subsequent on/off status.

The skeptic may press his objection by questioning the evidence for this account. But then his skepticism becomes global in form as well as content. The account is embedded in general theories of how devices like light bulbs shine when an electrical current is passed through them, and how devices as diverse as human eyes and hands, thermometers, spectro-photometers and ammeters function. Our confidence in those theories rests on much more than their ability to account for the operation of the traffic lights. To question those theories, the skeptic must indulge in a general inductive skepticism, either about the support relation between the evidence and these theories, or about that evidence itself. The former kind of "merely philosophical" skepticism may be set aside as irrelevant here. But a skeptic may question the account because he doubts whether observations or measurements on a system ever provide evidence as to how it is when unobserved: his doubt that the traffic lights are red or green "when no-one looks" is simply an instance of this general kind of philosophical skepticism.

One can reply to such a skeptic who questions a claim S_{green} about an unmeasured traffic light by asking him what he takes to be the content of his doubt. We can at least begin to give a detailed account of evidence justifying an inference to the statement S_{green} that entitles one to make that claim: and we can embark on a detailed account of what is materially implied by S_{green} and so to what one is committed by claiming it. The latter might involve inferences, e.g. from only the green light's being on at time t_1 to only the red light's being on at t_2, but only the green light's being on at t_3, regardless of whether the lights are measured at or between any of those times. Observations confirming the inferences' conclusions lend support both to particular claims S_{red}, S_{green} at those times and to the general claim G: either S_{red} or S_{green} is true at any time the lights are operating. Indeed, on an inferentialist account of content, its place in such a smoothly-functioning web of belief is what gives G its content. To simply replace G by the claim G^*: either S_{red} or S_{green} is true at any time the lights are observed but neither S_{red} nor S_{green} is true at other times, will cut so many inferential connections as to render the web useless. The alternative, of restoring all the inferential connections by making compensating modifications in the statements they connect, would simply produce a functionally equivalent web within which G^* mimics the role of G in the original web and so has essentially the same content. Neither option yields a genuine skeptical rival to the original account incorporating G.

Our unaided sense-organs do not help us observe the status of a particular bit of static random access memory in a contemporary electronic computer. But there are many ways of measuring and recording whether it stores one or zero, and it is essential to the efficient functioning of the computer both that it always stores one or the other and that some of these measurements are non-invasive in the sense defined earlier. According to an inferentialist, each of S_{one} and S_{zero} gets its content from an inferential web connecting it to evidence for the claim and to what the claim commits one, and the general "shape" of the web is closely analogous to that which confers content on S_{red} and S_{green}. The conferred content warrants the exclusive disjunction $G^{\dagger}$: S_{one} or S_{zero} at any time the computer is operating. There is likely less reason to doubt that $G^{\dagger}$ is true when the bit status is unmeasured than to question whether the traffic light is red or green "when no-one is looking".

While the operation of traffic lights and memory elements in digital computers can be understood quite well (at least in general terms) without quantum physics, that is certainly not true of the analog to a single memory element in a quantum computer. The set of values available to a logical bit in a classical digital computer has two elements {0,1}. But the set of values available to a logical qubit in a quantum computer corresponds to the infinite set of elements of a 2-dimensional complex vector space in which the vector quantum state of a system (such as an electron's spin) may be represented. However, a measurement of the contents of a qubit always gives one of two values {0,1} of a magnitude *Q*.

A qubit must be realized physically in a quantum computer, just as a bit must be realized physically in a classical computer. One candidate for realizing a single qubit memory element is the focus of an experimental program designed to test what is called macro(scopic)-realism.[17] A key tenet of macro-realism (for a two-state system) is macro-objectivity

(*MO*) Any system which is always observed to be in one or the other of two macroscopically distinguishable states is in one of those two states at any time t, even if no measurement on that state is performed at time t.

The system in question is a kind of superconducting quantum interference device (SQUID). When operating, measurements on this device always find it in one of two states:[18] in one state a small current is flowing clockwise around a ring, while in the other state the same current is flowing anti-clockwise around the ring. This small current is readily measurable: it is associated with the coordinated motion of a very large number (well over a million) of electrons. So these two states are plausibly considered macroscopically distinguishable—perhaps no less so than the *one*, *zero* states of a classical computer memory element.

We can define a magnitude Q for the SQUID as taking value 0 if the current is circulating clockwise and 1 if it is circulating anticlockwise. For this SQUID to realize a qubit, there are times at which one must be able to associate with it one of a variety of vector quantum states. Given its instantaneous vector state, the Born Rule specifies a probability p for value 0 of Q, and probability (1-p) for 1. Much of the time, the Born Rule applied to its vector state yields a p-value between 0 and 1. But according to (*MO*), exactly one of these statements is true at any time the device is operating:

S_c: The current is circulating clockwise. $S_{ɔ}$: The current is circulating anticlockwise.

Even if we assume that a measurement of Q at t reveals the value Q has at t, any apparent tension between this consequence of (*MO*) and Born probabilities outside {0,1} for S_c, $S_{ɔ}$ is easily relieved by recognizing that the value of Q may change in an unknown and even objectively random way between measurements. But if one makes a further assumption of non-invasive measurability, one can show that the exclusive disjunction $S_c \underset{\cdot}{\vee} S_{ɔ}$ is inconsistent with certain consequences of the Born Rule as applied to the vector states quantum theory prescribes for the SQUID at various times. Here that assumption is

(*NIM*) Consider a system which is always observed to be in one or the other of two macroscopically distinguishable states. No matter what quantum state that system is ascribed at *t*, there exists a non-invasive procedure for measuring which of its two macroscopically distinguishable states it is in at *t*: i.e. a procedure that does not disturb the system's subsequent behavior, at least as far as concerns which of these states it is in.

This does not demonstrate the falsity of (*MO*) for two reasons. Since no practicable experiment has yet collected statistics to test the relevant consequences of the Born Rule, this application may prove to be quantum theory's Achilles heel. But even if such statistics accord with quantum theory, one could consistently uphold (*MO*) by rejecting (*NIM*). Leggett (1998) argues that the dilemma as to which of these assumptions to jettison is a false one:

> Frankly I am not sure that this question is really very meaningful. The everyday language we use to describe the macroscopic world is based on a whole complex of implicit, mutually interlocking assumptions, so that once the complex as a whole is seen to fail it may not make much sense to ask which particular assumption is at fault. I am not sure, myself, that I could give a lot of meaning to [(*MO*)] under conditions where I had to admit that [(*NIM*)] fails. (*op. cit.* p.20)

As I understand him, Leggett does not claim that (*MO*) logically implies (*NIM*), but rather that by rejecting (*NIM*) one cuts key links in the inferential web that gives (*MO*) its content, with no clear way to patch up the web and imbue (*MO*) with any consequent new content.

Accepting quantum theory commits one to rejecting (*NIM*). (*MO*) does not logically imply (*NIM*), so one may try to retain (*MO*). But what could be the content of (*MO*) without (*NIM*)? How could one try to insert (*MO*) into the inferential web quantum theory weaves? Quantum theory here predicts probabilistic correlations between measured values of Q at two times, provided no measurement occurs in the interim. A natural way to make (*MO*) relevant to these values is to assume that a careful measurement of Q at t reveals which of S_c, $S_ɔ$ was true at t. But rejecting (*NIM*) blocks inferences from the direction of the current at t either to its direction at any later time or to the result of measuring Q at any later time. So even if one does assume that a careful measurement of Q at t entitles one to claim that a particular one of S_c, $S_ɔ$ was true at t, that claim commits one to nothing to which one is not already committed by applying quantum theory's probabilistic correlations between the measured values of Q at t and at a later time. For one who accepts quantum theory as applied to this SQUID, there is simply no content to the claim that one of either S_c or $S_ɔ$ is true at any time. By contrast with the traffic lights and (classical) computer memory bit, in this case it is the "skeptic" who insists on the truth of this exclusive disjunction in the face of quantum theory who has failed to give content to his claim.

This section has shown in some detail how acceptance of quantum theory affects the content of some claims of the form S by altering the inferential web that gives them content. I followed Leggett in making use of a binary distinction between times when a system is undisturbed and times when it is measured. That idealization employs the problematic term 'measurement'. In a quantum model not using that term, the SQUID's quantum state is briefly affected by some external device suited to record the result of this interaction as a value of Q at some time t. It is the form of this quantum state that governs the content of claims about the value of Q. In the SQUID qubit that content "crystallizes" then "redissolves" extremely rapidly during the brief external interaction. Quantum theory justifies the assumption that a classical computer memory element always reliably stores either a 0 or a 1 because constant strong interaction with its environment maintains the content and warrant of the claim that it does.

5. The content of denoting terms

Einstein did not ask Pais whether he believed the moon is there when nobody looks, but whether he believed the moon exists only when he looks at it. Taking Einstein's reported question literally, he was worried that Pais's understanding of quantum theory would remove the empirical credentials of every claim about the moon by undermining the objectivity of the moon's existence.

In an inferentialist account it is claims or statements that serve as the primary vehicle of content. I have so far assumed that the variation of content with quantum state for a magnitude claim **σ has (QεΔ)** afflicts only the property $Q\varepsilon\Delta$ of a fixed system σ as it interacts with other quantum systems. But the forms of quantum theory currently considered fundamental—relativistic quantum field theories—raise questions about the content of the term 'σ' in a magnitude claim.

In discussing the meaning of a term like 'electron' or 'photon' one commonly distinguishes its denotation (the extension of a general term or the referent of a singular term) from its sense, intension or stereotype. From this point of view, the inferential role in a quantum theory of a magnitude claim containing a term 'σ' would affect neither the reference of 'σ' nor the truth-conditions of S. But the ontological status of "elementary particles" like electrons and photons in a relativistic quantum field theory is problematic.

This may seem surprising, since the relativistic interacting quantum field theories of the Standard Model provide our deepest current understanding of phenomena involving the detection of elementary particles including electrons and photons when beams of electrons or protons from a particle accelerator collide at high energies. Nevertheless

> The notion that QFT can be understood as describing systems of point particles has been all but refuted by recent work in the philosophy of physics.[19]

and

> ...because systems which interact cannot be given a particle interpretation, QFT does not describe particles.[20]

Such recent arguments by philosophers support the views of some, though not all, physicists:

> Quantum field theory is a theory of fields, not particles. Although in appropriate circumstances a particle interpretation of the theory may be available, the notion of "particles" plays no fundamental role, either in the formulation or interpretation of the theory.[21]

Wald suggests here that while particles are not included in the fundamental ontology of a quantum field theory they somehow emerge in certain circumstances from the theory's fundamental ontology of fields. But this suggestion fares no better.

> If the particle concept cannot be applied to QFT, it seems that the field concept must break down as well.[22]

So what does a quantum field theory describe? What are the systems that interact in an interacting quantum field theory if they are neither fields nor particles? We seem to have arrived at an impasse.

I believe there is a way to break the impasse on this view of quantum theory. In serving as a source of sound advice to a physically situated agent on the content and credibility of magnitude claims about physical systems, a quantum state does not describe these physical systems, and need not be ascribed to them. In a quantum field-theoretic model, a quantum state is ascribed to some abstract mathematical system, such as a quantized electromagnetic field or an electron field. By ascribing a quantum state to such a system, one undertakes no commitment to the physical existence of that system. So while one can say that quantum field theory is about quantum fields, accepting a quantum field theory does not mean believing the world contains such things.

Quantum fields and their quantum states function within a mathematical model whose application is funneled through the Born Rule, which assigns probabilities to statements of the form *S*: **σ has (*Q*εΔ)**: call σ the *target* of *S*. The primary function of the quantum state of a quantum field is to provide advice on when a statement *S* has enough empirical content to be an appropriate object of an epistemic state of partial belief: only then should an agent base credence on the Born probability of *S*. No statement of the form *S* whose target system is a quantum field has any empirical content, since quantum fields are not physical systems. But the quantum state of a quantum field sometimes assigns a high degree of empirical content to a claim of the form *S* about particles, such as the claim that a high energy positron and electron with equal and opposite momenta will be converted into an oppositely charged muon pair with equal and opposite momenta. In other circumstances the quantum state of a quantum field assigns a high degree of empirical content to a claim of the form *S* about classical fields.

As in section 3, it is the "interactions" between a quantum field and its "environment" in a model that determines whether the state of that quantum field licenses claims about particles, about classical fields, or about neither.[23] In quantum optics, some models of systems involving the quantized electromagnetic field license claims of the form *S* about photons, such as a claim that two photons have the same energy but opposite polarizations: other models license claims of the form *S* about classical electromagnetic fields, such as a claim about the frequency of electromagnetic radiation emitted by a laser. These models of quantum theory neither describe nor represent interactions between physical systems. Even when a model involves quantum fields that are said to interact, it neither describes nor represents a physical interaction between physical systems. Though they form the basis for our deepest understanding of "elementary" particles and "fundamental" force fields, the interacting quantum field theories of the Standard Model in fact describe neither.

One can believe that some claims about electrons, electric fields or photons sometimes have a high degree of empirical content without believing those claims. If no quantum field theory describes such things (or anything else that could constitute them) one may wonder how it can give us any reason to believe claims about them, including claims that they exist. Such reasons are provided by applications of the Born Rule in circumstances that assign probability at or close to 1 to a significant claim of the form *S* about things like electrons, electric fields or photons. But just as this sometimes gives us no reason to entertain a claim locating an electron or photon in some small region or roughly specifying the value of an electric field, there are circumstances in which we can have no reason to form a belief about whether electrons, photons or electric fields are present. So while accepting a quantum field theory can justify one in believing that things like electrons, electric fields and photons exist, on the present view it also gives one reasons to deny that a specification of their features could constitute a complete and fundamental description of the world.

[1] I advocate this view in [ ]. Here I trace some implications for meaning and reference.

[2] See especially Simon Kochen and Ernst Specker, "The problem of hidden variables in quantum mechanics", *Journal of Mathematics and Mechanics*, **17** (1967): 59-87. Arthur Fine, "Joint distributions, quantum correlations, and commuting observables", *Journal of Mathematical Physics*, **23** (1982): 1306-10.

[3] See, for example, Arthur Fine, "Insolubility of the quantum measurement problem", *Physical Review* **D**, **2** (1970): 2783-87. Harvey Brown, "The insolubility proof of the quantum measurement problem", *Foundations of Physics*, **16** (1986): 857-70.

[4] This follows as a simple corollary of Fine (1982).

[5] Robert Brandom, *Making it Explicit* (Cambridge: Harvard, 1994).

[6] Wilfrid Sellars, "Inference and meaning", *Mind*, **62**, Number 247 (July 1953): 313-338.

[7] The quantum state ρ of a system is a mathematical object. While one can often take ρ to be the quantum state of σ, section 5 argues that this is not always right.

[8] N. David Mermin, "Quantum mysteries for anyone", this JOURNAL, LXXVIII, 7 (July 1981): 397-408; "Is the moon there when nobody looks?" *Physics Today*, April 1985, 38-47.

[9] "...during one walk Einstein suddenly stopped, turned to me and asked whether I really believed that the moon exists only when I look at it." Abraham Pais, *Reviews of Modern Physics*, **LI**, 4 (1979): 863-914, p.907.

[10] Erwin Schrödinger, "Discussion of Probability Relations Between Separated Systems," *Proceedings of the Cambridge Philosophical Society*, **31** (1935): 555-63.

[11] The assumption that these include photons—particles of light—is in need of justification, as we shall see in section 5.

[12] Its center of mass position density matrix would become approximately diagonal.

[13] Richard Feynman, *The Feynman Lectures on Physics*, **III** (Reading, Mass.: Addison-Wesley, 1963): 1.9.

[14] A committed extensionalist could drop talk of magnitudes in favor of an analysis in terms of the extension of a predicate that applies to an object iff the value of Q on that object lies in set Δ.

[15.] "It is characteristic of modern science to produce deliberately mutant conceptual structures with which to challenge the world." (Sellars, *op. cit.*, p.337)

[16] While some tests could have a small effect on the current flow through the lights, the account could allow for this in determining the current flow in their absence. In any case, the effect is too small to alter their on/off status.

[17] See Anthony Leggett, "Macroscopic realism: What is it and what do we know about it from experiment?", in Richard Healey and Geoffrey Hellman eds. *Quantum Measurement: Beyond Paradox* (Minneapolis: University of Minnesota Press, 1998): 1-22; "Testing the limits of quantum mechanics: motivation, state of play, prospects", *Journal of Physics: Condensed Matter*, **14** (2002): R415–R451 for further details and proof of the claimed inconsistency.

[18] On rare occasions it is observed to be in some *other* macroscopically distinguishable state.

[19] David Baker, "Against field interpretations of quantum field theory", *The British Journal for the Philosophy of Science*, **60** (2009): 585-609, p.585.

[20] Doreen Fraser, "The fate of 'particles' in quantum field theories with interactions", *Studies in History and Philosophy of Modern Physics*, **39** (2008): 841-59, p.842.

[21] Robert Wald, *Quantum Field Theory in Curved Spacetime and Black Hole Thermodynamics*, (1994), p.2.

[22] Baker, *op. cit.*, pp.585-6. The existence of inequivalent representations of the canonical commutation relations poses parallel problems for field and particle ontologies: see Laura Ruetsche, *Interpreting Quantum Theories* (Oxford University Press, 2011).

[23] The scare quotes are a reminder that quantum fields, their states, environment and interactions, are here just *abstract* objects in mathematical models.