The Sudbery interpretation of quantum mechanics

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Abstract. In this paper I review Tony Sudbery's foundational work with a view to tracing the evolution of his ideas about the measurement problem and the interpretation of quantum mechanics.

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Introduction
In this paper I review Tony Sudbery's foundational work with a view to tracing the evolution of his ideas about the measurement problem and the interpretation of quantum mechanics. I also discuss briefly what I learned about the question of whether quantum mechanics is nonlocal under Sudbery's supervision.1 In Section 1, I discuss Sudbery's critique of the application of the standard theory of quantum measurement to continuous observation. In Section 2 I briefly explain Sudbery's refutation of Karl Popper's claim that his purported experiment could be used to experimentally test the orthodox Copenhagen interpretation of quantum mechanics. In Section 3 I describe Sudbery's account of the measurement problem and the taxonomy and evaluation of interpretations of quantum mechanics in his earlier work especially in his 1986 book. In Section 4 I explain Sudbery's current defence of the Everett interpretation. Finally in Section 5 I briefly address the vexed question of whether quantum mechanics is nonlocal.

1. Discrete versus Continuous Observation
Sudbery points out at the beginning of his paper ‘The Observation of Decay’ [1] that time evolution in quantum mechanics is seemingly governed by two very different laws. The first is the Schroedinger equation according to which quantum systems evolve deterministically and reversibly. The second, the projection or collapse postulate is used to describe the abrupt change that occurs when a measurement is made and a system that may have been in a superposition with respect to the relevant observable is found to have a particular value. Much debate in the philosophy of quantum mechanics concerns whether one should regard collapse as a genuine

1 I studied pure mathematics (main) and philosophy (subsidiary) at the University of York with Tony Sudbery as my supervisor graduating in 1992. I carried out a theoretical physics project with him in my final year on nonlocality in quantum mechanics and this inspired me to study philosophy of science which became my academic speciality. I am profoundly grateful to Tony for the wonderful example he set as to how to conduct oneself in academic life. He approached teaching and research in the same spirit of collective enquiry, and exhibited contagious enthusiasm and all-encompassing intellectual curiosity, as well as giving me personally great support and encouragement.
physical process (dynamical collapse theories), an expression of our limited state of knowledge
(hidden variable theories), or as a perspectival illusion consequent on our experience being of
only a single branch of the multiverse (Everettian theories). However, in the above paper,
Sudbery discusses a fundamental problem with the collapse theory of measurement that is more
rarely discussed, namely that it does not account for measurement that is passive and continuous
rather than active and discrete. Consider, for example, the observation of a radioactive isotope
with a Geiger counter. The system is coupled to the apparatus and simply left to decay at its
own rate. There is no particular point at which a measurement is made, rather the system is
continuously monitored and decay events are recorded when they happen spontaneously. The
observer does not intervene actively, as in a projective measurement of the spin of an electron
by passing it through a Stern-Gerlach device, but rather simply

“waits for an event to happen” ([1], p 515).

If this kind of observation is modelled with the standard formalism one considers a number
of discrete measurements with some small time interval between them and takes the limit as
the time interval goes to zero. However, applying the projection postulate to each measurement
in this model and then time-evolving the state to obtain the transition probability for the next
measurement, leads to the conclusion that the difference in the probabilities of finding the system
in a given state at different times tends to zero. Hence, the problem is that the famous ‘watched-
pot theorem’ applies, and the model implies that no change occurs in the system at all. In the
case of our radioactive element this result is of course in conflict with experience since (almost
always) there will be sufficient decay events so that half the material is left after the observer
has waited for the half life of the substance in question. There are various ways to resolve the
paradox for many situations, for example, by supposing a finite cut-off in the limit of continual
measurement, or by not modelling measurements as precise, but these do not seem to get to the
heart of the problem for the case described above since the measurement is not imprecise nor
is the problem well modelled by a series of measurements at discrete times. Since there is not
a time-dependent interaction Hamiltonian but a time-independent one to describe continuous
coupling of the system and the device a very different approach is needed.

Sudbery proposes a model of continuous observation in which the system and an apparatus
are coupled and evolve in time together, hence “continuous observation is not continual
measurement” ([1], p 513). He adopts a new form of the projection postulate formulated in
terms of density operators. According to his Postulate A: Suppose $D$ is an observable being
continuously observed and $P_k$ are the projection operators onto the eigenspaces of $D$. If $\rho_0$ is
the density matrix of the system at time $t = 0$ its density matrix at time $t$ is:

$$T_t(\rho_0) = \sum_k P_k e^{-iHt} \rho_0 e^{iHt} P_k.$$ 

This can be considered as a supplement to the standard projection postulate to deal with
continuous measurement or as a replacement for it. Sudbery’s Postulate B then asserts that
density operators will evolve according to the above equation for a privileged class of observables
that form the relevant eigenspaces of $D$ and the projectors onto them.

The measurement problem will not go away however. Sudbery demonstrates that although
probabilities are independent of exactly where the line between system and observer is drawn,
but that nonetheless some such line must be drawn (this result is due to von Neumann and
gives rise to what is known as the von Neumann Chain). It is left open how we are to interpret
the density matrix of a system. Sudbery points out that the problem of what kinds of physical
process count as measurements remains in his approach, as does the problem of what exactly
the privileged observables in postulate B are. Furthermore, with Postulate B the symmetry of
Hilbert Space is broken because some observables are regarded as special. This is analogous to classical mechanics in which there is symmetry between position and momentum under canonical transformations but an asymmetry in them when they are related to observation. Sudbery flirts with the Bohrian claim that the apparatus must be described in classical terms. He posits a sharp quantum/classical spit in return for which we only have one kind of dynamics, and we can suppose that transitions (e.g. decay) take place at definite times. In a 1986 paper Sudbery says that the above paper is part of a “general programme of showing that all interpretations of quantum mechanics are saying the same thing in different ways” ([4], p 82). This is a striking claim that comes close to positivism in so far as the seeming great metaphysical differences between dynamical collapse theories, Everettian interpretations and hidden variable interpretations are regarded as merely verbal.

This aside it is worth reiterating the conceptual distinction that Sudbery introduced in his 1984 paper. ‘Measurement’ is the active process of taking a system and subjecting it to an interaction that will result in the coupling of some property of the system with degrees of freedom in the measuring device. Both measurements of the first kind such as spin measurements using a Stern-Gerlach device that would result in the same outcome if repeated on the same system, and measurements of the second kind such as momentum measurements that change the momentum and hence would not result in the same outcome if repeated on the same system, are examples of ‘measurement’ in Sudbery’s sense. On the other hand, ‘observation’ is when a measuring device is coupled to a system in such a way that it will not precipitate an immediate outcome, but rather will record a change in the system when it occurs such as a decay event resulting in the emission of radiation. In his most recent work Sudbery still cites the importance of recovering transition probabilities for systems that are ‘passively measured’, that is ‘observed’ not ‘measured’ in his 1984 terminology. Now, his explanation for the choice of basis is very different and the interpretation of the density matrix and the measurement problem are faced head on. I return to this below.

2. Sudbery falsifies Popper
In the 1982 preface to Quantum Theory and the Schism in Physics, Karl Popper proposed an experiment based on the EPR set-up that he claimed could be used to test the then standard Copenhagen interpretation of quantum mechanics. Popper argued that a strong form of action at a distance could be observed due to the increase in the spread of one particle’s momentum due to the decrease in the spread in the other particle’s position. In his paper ‘Popper’s variant of the EPR experiment’ [3] published in Philosophy of Science, Sudbery shows decisively that the derivation is mistaken and that the Copenhagen interpretation cannot be tested by the experiment in the way Popper suggests.

Popper considers a pair of particles propagating in opposite directions along the x-axis such that they each have zero momentum in the y-direction, and each being passed through a slit of variable width beyond which are a semi-circle of particle detectors. He then imagines changing the sit width of particle A thereby gaining increased knowledge of its position in the y-direction, and consequently because of the entanglement of particles A and B, decreasing the spread in particle B’s position too and therefore by the uncertainty relation increasing the spread in particle B’s momentum. So he argues that the latter ought to be observable by the different pattern of detection in the semicircle of detectors and so the Copenhagen interpretation produces an empirically detectable form of action at a distance. However, as Sudbery shows, particles in eigenstates of y-momentum as required will not be in the entangled state of position that would lead to the prediction of a change in which counters fire because of a narrowing of the slit on the other wing.

In the commentary Sudbery endorses Hans Reichenbach’s claim that the attribution of both position and momentum to a quantum particle is not a ‘scientific statement’ because it cannot
be tested. Here again he seems to lean towards positivism as he goes on to castigate Popper for querying what can be meant by the claim that a particle cannot simultaneously have values of both position and momentum. Sudbery points out that statements about both quantities cannot be tested simultaneously, but of course this would cut no ice with Popper who thought testability was a condition for a statement being scientific but not (unlike the positivists) for it being meaningful.

In the context of discussing realism, Sudbery says there is “no more reason to think that a real particle must have a definite position and momentum than there is to think it must have a definite colour or smell” ([3], p 475). This is interesting because he here contrasts properties that are classically considered to be ‘primary’ with those that are classically considered to be ‘secondary’ in the sense defined in the scientific revolution by John Locke following Descartes, Galileo and the Greek atomists. The primary properties are defined to be those that are objectively possessed by objects as we conceive of them whereas the secondary properties are such that what the object objectively possesses is merely a configuration of primary properties that give it the stable disposition to produce in us experiences as of the secondary properties as we conceive of them. For example, it is said by the Greek atomists that honey is not really sweet but its particles are arranged in such a way as to give rise to the taste of sweetness in our perception. Sudbery is therefore suggesting that the traditional primary properties of position and momentum are on a par with paradigmatic secondary properties leaving us with the question as to what the true primary properties of particles are. Of course, mass and charge and the like may still be objectively possessed by them but they are state independent properties and so cannot be the basis for the contingent differences we observe between particles such as their apparent different spatial locations. If the quantum state is taken to be a primary property we are left with the problem of how it relates physically to the observations we make. Sudbery says that “a particle does not in general have definite values of position or momentum but it does have propensities to take up particular values of either” ([3], p 476). This replaces one mystery with another for of course we have no account of under what circumstances propensities turn into actualities.

### 3. The Interpretation of Quantum Mechanics

In his 1988 paper ‘Testing Interpretations of Quantum Mechanics’, Sudbery endorses falsificationism saying that the function of experiments is to disprove not to confirm. He goes on to distinguish three kinds of interpretation of a physical theory and how each relates to the criterion of testability.

(i) Operational interpretation This is a way of specifying the meaning of mathematical symbols or entities in terms of experimentally measurable quantities. For example, we may operationally interpret $|\psi|^2$ either as the charge density of a quantum system (Schrödinger), or as the probability of finding a particle as a given location (Born). The point about operational interpretations is that they must be testable. Without an operational interpretation we do not have a physical theory at all but only a mathematical one.

(ii) Physical interpretation Physical interpretations go further than operational ones by giving physical meaning for terms that have no direct operational interpretation. While such interpretations may be important for the development of further theoretical advances they are not themselves necessarily testable. For example, Planck interpreted his radiation law in terms of quantum oscillators with energy states in integer multiples of the product of his constant $h$ and the frequency, and de Broglie-Bohm interpreted the phase of the wave function in terms of particles with definite trajectories and momenta.

(iii) Metaphysical interpretation This is the conceptual analysis of terms such as space and time (Einstein), probability, Bohr’s complementarity and so on. According to Sudbery,
disputes about which metaphysical interpretation of a theory to accept cannot be resolved by physics but are philosophical. Metaphysical interpretations are not testable, although they may get more or less plausibility from the role they play in the guiding the heuristics of those developing physical theories.

Sudbery goes on to summarise various interpretations of quantum mechanics that are explained in more depth in his book Quantum Mechanics and the Particles of Nature: an outline for mathematicians. The latter remains an excellent way to learn about quantum physics despite its relative age. The book goes a long way into the advanced topics of quantum field theory, symmetry groups and particle physics for an introductory text, and so it takes one a long way to what remains the cutting edge of fundamental physics that has actually been applied to experiments\(^2\). One thing that makes it particularly ahead of its time is the prevalence given to foundational issues. There are four chapters that introduce quantum phenomena, quantum statics, quantum dynamics and then a selection of standard quantum systems, and then the fifth chapter is ‘Quantum Metaphysics’. It is a tour de force of the philosophy of quantum mechanics into which a huge amount of important material is packed.

It is notable that the first thing in the chapter is the explanation of the distinction between pure and mixed states and the density matrix formalism. Sudbery explains and contrasts the way probability measures over classical phase space differ from the statistical operators of quantum mechanics. A table very neatly sets out the fundamental foundational differences between classical and quantum mechanics with respect to pure states, general states, the equation of motion, observables and expectation values. This forms the framework for the rest of the discussion.

When it comes to the quantum theory of measurement, Sudbery emphasises the way that measurement plays a fundamental role in the postulates of the theory, and then repeats and augments his earlier criticism of the projection postulate. His main objections to it are that:

(a) It is ill-defined since no definition of measurement is available. (It is “at worse inconsistent” ([5], p 186))
(b) It is dualistic because it splits time evolution into deterministic and probabilistic parts.
(c) It is anticausal since there is no explanation of what causes collapse and it appears to make “physical events consequences of their observation” ([5], p 212).
(d) No account of continuous measurement is possible (as we saw in 1 above).

Although Sudbery does not do so, it is possible to formulate the measurement problem in the form of three premises that are together inconsistent in the spirit of his remark quoted in (a) above.

Consider the following three propositions all of which there is reason to believe.

(I) A system has a definite value for an observable \(O\) if and only if it is an eigenstate of the corresponding hermitian operator on the Hilbert space of the system. (This is often called ‘the e-state/e-value link’. It expresses the usual connection between quantum states and values of observables from right to left, and the completeness of the quantum state from left to right.)

(II) All time evolution is in accordance with the Schrödinger equation and is therefore described by a linear and unitary operator on the Hilbert space of the system.

(III) Measurements have unique outcomes, for example, a spin half system will always be found to be up or down if its spin in a particular direction is measured.

\(^2\) It was the basis of a course given for many years by Sudbery at the University of York to third year mathematicians over three terms that managed to get those of us with very little physics to the doorstep of quantum chromodynamics.
These cannot all be true for a quantum system that is initially in a superposition of what is being measured. Consider a quantum system $S$ described by a two-dimensional Hilbert space $H$ which has two possible eigenstates $\psi_+, \psi_-$ of an observable $O$ associated with the eigenvalues $+1$ and $-1$. Suppose the measuring device $M$ faithfully measures $O$ for systems like $S$. This means that if (when $M$ is in its ready state $M_0$) $M$ interacts appropriately with $S$ when $S$ is in the state $\psi_+$, $M$ will evolve into a state $M_+$. Similarly for $\psi_-$ and $M_-$. The states $M_+$ and $M_-$ are distinguishable by us (hence the idea of a measurement device as opposed to any other physical system that could interact with $S$).

The argument is as follows: Suppose $S$ is initially in the superposition $(\psi_+ + \psi_-)/\sqrt{2}$. Since time evolution $U$ is linear and unitary:

$$U\left(\frac{1}{\sqrt{2}}(\psi_+ + \psi_-) \otimes M_0\right) = \frac{1}{\sqrt{2}}(U(\psi_+ \otimes M_0) + U(\psi_- \otimes M_0)) = \frac{1}{\sqrt{2}}(\psi_+ \otimes M_+ + \psi_- \otimes M_-).$$

But the latter state is not an eigenstate of either $S$ or $M$. Therefore, by the e-state/e-value link, neither $S$ nor $M$ have a definite value after the measurement.

The standard options for the interpretation of quantum mechanics can be classified according to which of (I) to (III) they deny. To deny (I) is usually thought to mean the positing of hidden-variables, and of course Bell’s theorem tells us any such hidden variable theory must be nonlocal like de Broglie-Bohm theory. It is worth noting that quantum mechanics would also be incomplete if it did not apply to macroscopic objects and required a classical/quantum cut so that the states of the measurement device could be definite without there being corresponding quantum mechanical eigenstates. (II) would be false if the collapse of the wavefunction is a real process whether a random physical process as in dynamical collapse theories, caused by observation as in Wigner’s interpretation, or caused by interaction between quantum and classical systems in line with some version of the theory of decoherence. Denying (III) gives us some version of the Everett interpretation. The other alternative is to reject the whole framework above and adopt some form of antirealism according to which the wavefunction represents only our knowledge of the system and all the probabilities in quantum mechanics are subjective.

Having explained the quantum theory of measurement, the measurement problem in the form of the cat paradox and the problem of continuous measurement and the ‘watched pot theorem’, Sudbery beautifully explains the EPR paradox in the context of a spin $1/2$ system using to motivate the following explanation of de Broglie-Bohm theory. The latter is presented in terms of a continuity equation in terms of the probability current and density, and it is immediately apparent that the current for one particle will depend on the wavefunction of both and hence that the velocity of each particle depends on the other’s position. Sudbery then shows that this manifest action at a distance in Bohm theory must be a feature of all hidden variable theories by proving a version of Bell’s theorem. In his philosophical commentary, Sudbery begins by discussing indeterminism and arguing that it is straightforward to accept it but that it violates the idea that every event has a cause. This would be contested by many people; the literature in causal inference, Bayes nets and so on is replete with models of probabilistic causation (although these may not be well suited to quantum mechanics). He then says that indeterminism raises “no conceptual problems which are peculiar to quantum mechanics” ([5], p 211). I am not sure if he would now agree with this claim. It seems problematic in the light of the fact that many people argue that the principle of the common cause is false in quantum mechanics and one may connect worries about causation and determinism in quantum mechanics to the very subtle issues concerning locality discussed below. Sudbery is careful to distinguish indeterminism from indeterminacy, and notes that a system could have definite values at all times that evolve stochastically. He points out that the fact that if quantum mechanics is complete then particles cannot have definite trajectories in space over time conflicts with the “deep seated feeling that position and momentum are essential properties” of particles ([5], p 211). More generally we
can ask about the physical state of a system with respect to some observable when it is not attributed an eigenstate of the corresponding operator, and the eigenstate-eigenvalue link tells us that in these circumstance the system’s state with respect to the observable in question is indeterminate.

Sudbery outlines nine interpretations of quantum mechanics as follows.

1. The **minimal interpretation** was “consistently promulgated by Bohr” ([4], p. 271) (it was notoriously not consistently promulgated consistently). It amounts to giving up on attributing states to quantum objects and on trying to say what the quantum state vector describes. Both pure states and general statistical operators refer to state preparation.

2. The **literal interpretation** supposes that quantum states are descriptions of the properties of physical systems and there really are collapse events sometime during the measurement process as described by the projection postulate (von Neumann).

3. The **objective interpretation** features stochastic jumps due to some physical process that is not peculiar to measurement. This is associated with Bell and with contemporary dynamical collapse theories.

4. The **epistemic interpretation** regards quantum states as descriptions of our state of knowledge of quantum systems. This has been developed in recent years by many people working in quantum information theory, notably Carlton Caves and Chris Fuchs.

5. The **ensemble interpretation** was favoured by Einstein and treats quantum states as descriptions of a collection of systems, and projection as shifting attention to a subensemble.

6. The **many-worlds interpretation** due to Everett treats the state vector after projection as describing a branch in a multiverse in which collapse never objectively happens. It is now usually referred to as the ‘Everett interpretation’ because many people think talk of ‘many worlds’ is misleading.

7. The **quantum-logical interpretation** is associated with Hilary Putnam. It is based on taking state vectors to describe propositions obeying a non-distributive logic.

8. **Hidden-variable interpretations** deny that the quantum state is a complete description of the physical states of systems.

9. The **stochastic interpretation** exploits the formal analogy between Schrödinger’s equation and stochastic differential equations that describe processes like Brownian motion.

While (1) is subject to the challenge that it gives up on the aim of science “to understand the physical world” ([5], p 214), it is at least consistent. (2) is undermined by (a)-(d) above. The main problem with (3) is making collapse relativistically invariant. (4) is argued to be unstable between interpretations that resolve into a version of either (2) and (3). (5) is undermined by the fact that measurement involves “an objective change in the ensemble which cannot be explained away in terms of a shift of attention on the part of the observer” ([5], p 220). The Everett interpretation (6) is said to face all the same problems as the literal interpretation since the alleged splitting of the universe would occur when collapse occurs in the latter, hence we are equally owed an account of when and why it happens. (7) is allegedly based on “nothing but a mathematical pun” ([5], p 222). (8) is criticised both for requiring a distribution of hidden variables exactly matching the state vector, and for being in conflict with relativity. Finally, (9) is problematic because the motions of particles will depend on the motions of distant particles and on the form of the wavefunction at the initial time coordinate.

Sudbery recommends a choice of three (1), (3) or (8) among these nine interpretations but claims that ultimately it is a matter of individual preference since (1) is “boring”, (3) is “puzzling” and (8) is “implausible” ([5], p 224). It is interesting that the interpretation that he eventually comes to advocate and does still at the time of writing is the Everett interpretation, and that it is not among those he earlier considered seriously. This perhaps reflects the fact that
developments in the elucidation of the Everett interpretation seem to have made real progress with respect to the basis problem and the problem of how to interpret probability if all events happen.

4. Sudbery on Everett
By 2000 Sudbery has converted to the Everett interpretation and wants to “bring us all together to share the experience of summoning up a vanished tension and watching it relax” ([7], p.2). In fact he has in mind four tensions:

(i) The existence of spacetime versus the passage of time
(ii) Determinism versus free will
(iii) The physical description of brain states versus conscious experience
(iv) Duty versus ‘why should I?’

Each of these involves the relationship between a universal third-person statement based on rational reflection and a perspectival first-person statement based on personal experience. In each case he maintains there is no genuine contradiction between them and his hope is that by treating the relationship between universal linear time evolution and the projection postulate as analogous to them he can show that there is no contradiction between them either. In short, the idea is that the projection postulate applies within a branch of the wavefunction while universal linear time evolution applies to the whole wavefunction.

His inspiration for this way of looking at the matter comes from an essay by the philosopher Thomas Nagel who distinguishes between what he calls ‘internal’ and ‘external’ questions. From an internal perspective it makes sense to ask ‘why am I me?’ meaning why do I have the subjective point of view that I in fact do have. From the internal perspective there is only one experiencing subject and from this perspective it is contingent who that subject is. From an external perspective it makes no sense for the question is equivalent to ‘why is James Ladyman James Ladyman’ and one cannot explain why a tautology is true.

In relation to (i), Sudbery argues that it is wrong to think that the perception of the flow of time is an illusion because there is no mistaken belief that we have when we experience time passing. The temporal ordering of events is no less real for being frame dependent. The way that experiences at different times seem to contradict each other is captured by thinking of the state of having a certain experience as being some quantum state that is indexed to a time. Then one cannot be in both states. The problem with the flow of time is, according to Sudbery, dissolved, when we realise that from the internal perspective time flows, while from the external perspective it does not. Internal statements are necessarily relative to a particular perspective that includes a conscious system, an instant of time and an eigenstate of experience. The latter change stochastically according to the transition probabilities given by quantum mechanics. Probability is here understood to be relative to an internal perspective, that is an Everett branch, and to be the degree of expectation of the event which is rational for a fully informed observer. From the external perspective on the other hand statements are about quantum states as functions of time where such states obey unitary dynamics. When it comes to the basis problem for the Everett interpretation which basis in Hilbert space is to be used to define the branching structure? Sudbery seems to ally himself with those like Michael Lockwood who suggest that the relevant basis is defined by the way that brain states give rise to conscious experiences. This is in contrast to those like Simon Saunders and David Wallace who think that decoherence theory suggests the emergence of a quasi-classical basis in which macroscopic objects behave quasiclassically. The latter has the disadvantage that it defines at best an approximate basis and hence an approximate branching structure, whereas the former has the disadvantage that it relies upon a promissory note about an as yet unknown science of the mind.

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5. Does quantum mechanics require an Action at a Distance?

For a third year undergraduate project Sudbery gave me two papers, one by Henry Stapp and one by Karl Kraus (in *The Symposium on the Foundations of Modern Physics* edited by Lahti and Mittelstaedt), and asked me to answer the above question. The former claimed to prove that quantum mechanics is nonlocal, and the latter that it is compatible with special relativity’s local causal structure based on the light cones of events. As is well known, the EPR-Bohm experiment can be carried out when the detection events on the left and right wings of the apparatus are spacelike separated. It follows that if there is a causal influence between them, such that say, the result on the left wing affects that on the right, then there are frames of reference in which the cause would occur after the effect in time. Since this seems to imply the possibility of causal loops and other problems it is usually ruled out by fiat and most physicists accept that causally connected events are in each other’s light cones. Indeed, recently David Albert [2] has recently pressed the argument that quantum mechanics is incompatible with special relativity. On the other hand, physicists in general deny this and often follow Abney Shimony and talk of ‘peaceful co-existence’ between quantum theory and special relativity. The situation is particularly puzzling because relativistic quantum theory exists in the form of quantum field theory into which Lorentz covariance is normally explicitly built. There is a long history of controversy about action at a distance in physics. It seems fair to say that the insistence on local mechanisms to explain physical events has been extremely successful. Examples include theories that looked for intermediary carriers for the propagation of heat, sound, light, magnetic attraction and repulsion and electromagnetic induction. The field concept and its incredible fecundity may be regarded as the greatest triumph of the locality principle. While Newtonian gravitation remains a compelling counterexample, there are ways in which it respects some of the intuitions about local action. After all, the gravitational force falls off very quickly with the distance from a source, leading the conclusion that at large enough distances bodies do not affect each other gravitationally. The inverse square law can also be related to the area of an expanding sphere centred on the mass that causes the force of attraction, hence suggesting that the latter is mediated by something that propagates outwards from the source. By the time of General Relativity the idea of the finiteness of the speed of propagation of effects was fully established for all physical interactions. If it were really true that quantum mechanics was a nonlocal theory this would be a huge upset for physics.

Stapp proved a version of Bell’s theorem, Krause a version of the no-signalling theorem. The task I faced was to reconcile the claims. The obvious way to do this is to disambiguate the notion of locality. If one defines locality to be the claim that experimental results are not affected by distant events except via some mechanism of contiguous intermediary processes, then I see no reason to deny that quantum systems are local, for orthodox physics posits no causal influences between spacelike separated events. While it is certainly true that the correlations exhibited by entangled systems would require action at a distance if there was a definite value for every observable for each system independently, such definite values are not a feature of the quantum formalism. I concluded in my project that some form of holism or nonseparability about the quantum world should be adopted to avoid the positing of action at a distance. Certainly one cannot prove that the quantum world requires action at a distance without assuming something like counterfactual definiteness. There is, as far as we know, complete symmetry between the two wings of the EPR-Bohm experiment. We have no more reason to believe that the left hand side result influences the right hand side result than vice versa. Hence, talk of action at a distance is misleading in this context. We have a strange kind of correlation at a distance but nothing like an ordinary interaction between the wings.
6. Conclusions
To conclude, it seems that several clear foundational commitments are constantly upheld in Sudbery’s work on quantum mechanics, prior to and after his conversion to the Everett interpretation. These are as follows:

(1) There is no physical process of collapse.
(2) There is no gross nonlocality: “Quantum mechanics is not incompatible with the principle of locality, but with the conjunction of this principle and the existence of hidden variables” [1].
(3) The interpretation of quantum mechanics should be approached using the density matrix formalism and in terms of the recovery of transition probabilities, including from continuous observation.

Finally, Sudbery has always avowed and exemplified the importance and value of the philosophy of physics.

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