dilemmas, the patients with VMPFC lesions were more likely to choose the utilitarian option than were control participants and patients with lesions in other brain regions. This effect was particularly marked when there was high conflict between the utilitarian and the emotional component. The finding seems to be robust, as Ciaramelli *et al.*[4] report essentially the same results in a separate VMPFC patient group.

This result engenders a paradox. On the one hand, believing that emotion is the enemy of reason, our society still goes to great lengths to prevent emotional considerations from influencing important decisions, in particular moral decisions. Intriguingly, the result reported by Koenigs and colleagues[1] seems to show that damage to the VMPFC does not impair moral decision-making, but rather improves it through eliminating the effects of emotion. On the other hand, there is abundant evidence that decision-making in other spheres is severely impaired in these patients[5]. Indeed, it is on the basis of this latter evidence that Damasio[6] developed the 'somatic marker' theory, which affords a major role to emotions for making good decisions. Emotions clearly have a role in our moral intuitions, but do they improve moral decision-making, or impair it?

There is a similar conflict between reason and emotion when we make economic decisions. In the 'ultimatum game', player A is given $100 and can give a proportion of this to player B. Player B can accept the money, but, if B rejects it, neither A nor B get any money. Typically B will reject an offer of less than about $20. This behaviour does not accord with self-interest because B gets nothing rather than $20. It is also not utilitarian, as the two players, considered together, also get nothing rather than $100. Instead the behaviour is driven by the perceived unfairness of the offer. This is an emotional response because unfair offers elicit autonomic responses[7] and increased activity in brain regions associated with emotions[8].

Interestingly, Koenigs and Tranel[9] report that, relative to control participants, their patients with VMPFC lesions when playing the ultimatum game are influenced by emotion more strongly, in that they were more likely to reject low offers. This finding, in turn, is in line with findings that activation in the VMPFC is correlated with a reduced bias by the contextual framing of a decision[10]. Clearly, damage to this region disrupts the integration of emotion and reasoning, but it remains to be seen why this disruption takes different forms in different circumstances. Two critical differences between the paradigms Koenigs and his colleagues employed include the nature of the stimulus, which was either representational (emotional pictures, description of a dilemma)[1] or concrete (actual winning or losing a game)[9], and the procedure, which required a judgement with no direct consequences to the patient, or an active engagement[5]. Strategic planning may be needed both to stimulate an emotional response by calling forth previous experiences, and to tone down a reactive emotional response. A role for strategic planning in the emotional response that leads to the rejection of unfair offers is supported by findings[11] that disruption of function in the right prefrontal cortex reduces the effect of emotion, and biases participants towards a utilitarian response, in the ultimatum game.

Even though the precise role of VMPFC in the integration of emotion and reason remains unclear, these studies raise the perennial question as to whether emotion makes decisions better or worse. In the case of economic decisions, there is now considerable evidence that emotional rejection of unfair offers is a good strategy. Rejecting unfair offers in the ultimatum game is a form of altruistic punishment. With repeated economic encounters the use of altruistic punishment increases cooperation, resulting in greater benefits for the group[12,13]. By analogy, it may be possible to show that some moral decisions are improved when the emotional component is taken into account, rather than suppressed.

The challenge, then, is for decision-makers to cultivate an intelligent use of their emotional responses by integrating them with a reflective reasoning process, sensitive to the context and goals of the moral dilemmas they face. If decision-makers meet this challenge, they may be better able to decide when to rely upon their emotions, and when to regulate them. Indeed, such cultivation is already occurring in the legal system[14]. ■

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QUANTUM MECHANICS

To be or not to be local

Alain Aspect

The experimental violation of mathematical relations known as Bell's inequalities sounded the death-knell of Einstein's idea of 'local realism' in quantum mechanics. But which concept, locality or realism, is the problem?

The development of quantum mechanics early in the twentieth century obliged physicists to change radically the concepts they used to describe the world. The main ingredient of the first quantum revolution, wave–particle duality, has led to inventions such as the transistor and the laser that are at the root of the information society. Thanks to ideas developed by Albert Einstein and John S. Bell, another essential quantum ingredient, entanglement, is now leading us through the conceptual beginnings of a second quantum revolution — this time based on quantum information[1,2].

In contrast to wave–particle duality, which is a one-particle quantum feature, entanglement involves at least two particles. In entangled states such as those discovered by Einstein, Podolsky and Rosen (EPR)[3], quantum mechanics predicts strong correlations between measurements on two systems that have previously interacted but which are separated at the time of the measurement (Box 1). To interpret these correlations, Einstein said, one must accept the concept of local realism. This principle states that results of measurements on a system localized in space-time are fully determined by properties carried along by that system (its physical reality) and cannot be instantaneously influenced by a distant event (locality).

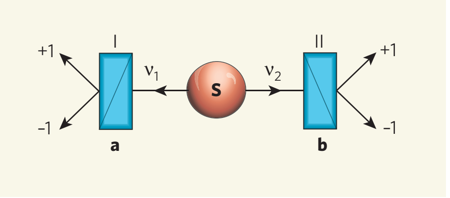
But after Bell's discovery that local realism entailed a limit on the correlations — a limit he expressed in his celebrated inequalities[4] — a series of ever more ideal experiments (ref. 5 and references therein) has led us to abandon the concept. It is then natural to raise the question of whether one should drop locality — which equates to the impossibility of any influence travelling faster than light — or rather drop the notion of physical reality.

There is no logical answer to that question: one can choose to abandon either concept, or even both. Tony Leggett has explored[6] one of these possibilities by considering a particular class of physically plausible theories that abandon locality, but maintain realism. He found these theories to be incompatible with quantum mechanics, and expressed the disagreement by new inequalities[6]. As there was no experimental

Box 1 | Thought made reality

As discovered by Albert Einstein, Boris Podolsky and Nathan Rosen[3], quantum mechanics predicts strong correlations between measurements on two particles in an entangled state. It is tempting to interpret these correlations as the result of shared properties determined at the time of their initial interaction and carried along by each particle. By analogy, similar sets of chromosomes in siblings allow one to understand correlations in their eye colour or other features.

Theories completed in such a way implement a view of the physical world called local realism, because individual physical properties are attributed to each of the separated partners. This type of interpretation was favoured by Einstein, but strongly opposed by another great early quantum physicist, Niels Bohr. For decades, however, the opposition between Einstein and Bohr seemed to be a mere epistemological debate, without any consequences for the predictions of the theory.



John Bell's formulation of his celebrated inequalities[4], which fix a limit to the correlations predicted by local realistic theories, made it possible to settle the debate by performing an experiment to test the inequalities. For a well-designed experiment[11], quantum mechanics predicts a violation of Bell's inequalities. There were thus two possibilities, both interesting: either the experimental results would obey Bell's inequalities, and thus exhibit a failure of quantum mechanics, or they would violate Bell's inequalities, and force us to renounce Einstein's local realist world view.

Starting with the pioneering work of John Clauser[12], a series of more and more refined experiments has brought overwhelming evidence that the actual degree of correlation found experimentally indeed violates Bell's inequalities[5]. In the basic experimental realization pictured here, a pair of photons, ν_1 and ν_2, is produced at source S in an entangled polarization state. Each photon is submitted to a measurement by a linear polarizer (I and II, in orientations **a** and **b**), giving a result +1 or −1. Quantum mechanics predicts that individual outcomes happen at random with equal probabilities at each polarizer, but that outcomes of both sides will be strongly correlated — as indeed they are.

The role of locality in these experiments has been underlined by changing the setting of the polarizers while the photons are in flight, and by making sure that the two measurements cannot influence each other according to relativistic causality[13–15]. The clear violation of Bell's inequalities leads to the conclusive rejection of theories that are simultaneously realistic and local. **A. A.**

result available to test Leggett's inequalities, a new type of measurement was necessary.

In experiments detailed on page 871 of this issue[7], Gröblacher *et al.* have carried out such measurements. They modified an experiment previously used to test Bell's inequalities through measurements on two photons (Box 1) by changing the original linear polarization measurement into an elliptical polarization measurement. This is readily done by inserting a quarter-wave plate in front of a standard (linear) polarizer. From an experimental point of view, however, the new test is more demanding, and requires almost ideal optical elements and a high signal-to-noise ratio. Thanks to their high-efficiency source of entangled photons, the authors meet these requirements, and find a significant violation of the generalized Leggett's inequalities that they have established. Following Leggett, they conclude by questioning realism rather than locality — at variance with the often-heard statement that "quantum mechanics is non-local".

Interesting as this conclusion is, it remains a matter of personal preference, not of logical deduction. The violation of Bell's inequalities implied that realism and locality are not simultaneously tenable. Violation of Leggett's inequalities implies only that realism and a certain type of non-locality are incompatible: there are other types of non-local models that are not addressed by either Leggett's inequalities or the experiment.

Consider, for instance, the experiment pictured in Box 1, and assume that a measurement is performed first on photon ν_1. This measurement gives either a result of +1 or −1; immediately after one of the two results is obtained, the quantum description of ν_2, which had not been favouring any precise polarization before the measurement on ν_1, collapses into a state of polarization identical to the one found for photon ν_1, from which one can readily derive the usual quantum-mechanical EPR correlations. If we take this description — based on standard quantum-mechanical calculations — as a model, it cannot be rejected by any experiment that is in agreement with quantum mechanics, including the more complex elliptical polarization measurements performed by Gröblacher *et al.*[7].

This model is clearly non-local in the relativistic sense, as we must invoke a particular frame of reference to give a sense to the statements that measurement on ν_1 happens first, and that its result immediately affects the state of ν_2. Can we say that the model is realist? In a sense yes, as we can qualify the individual polarization of each photon at each step. I must admit, however, that I am not comfortable with the notion of a physical reality that is instantaneously modified by something happening far away — not to speak of the problems related to breaking down explicit relativistic covariance[8]. In many of Einstein's writings[9], the notion of a physical reality describing completely the state of a system localized in space-time is clearly linked to the relativistic impossibility that this physical reality be instantaneously modified by a faraway event. To quote Einstein[10], the necessity of completing quantum mechanics in a local–realist way could be escaped "only by either assuming that the measurement of S_1 (telepathically) changes the real situation of S_2 or by denying independent real situations to things which are spatially separated from each other. Both alternatives appear to me entirely unacceptable."

Nobody knows what Einstein would have thought had he known of the violation of Bell's and Leggett's inequalities. I tend to accept the kind of non-local image sketched above as useful to stimulate my imagination, although I am aware that it implies renouncing the kind of realism I would have liked. The conclusion one draws is more a question of taste than logic, and one can argue that such a discussion is irrelevant to science. But I rather share the view that such debates, and accompanying experiments such as those of Gröblacher *et al.*[7], allow us to look deeper into the great mysteries of quantum mechanics. That, it is to be hoped, can contribute to transforming the second quantum revolution from the present stage of basic research to a fully fledged technological revolution. ■

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