Speakable and Unspeakable in Quantum Mechanics

Collected Papers on Quantum Philosophy

J. S. Bell, Introduction by Alain Aspect

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Chapter

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La nouvelle cuisine

Respectfully dedicated to the great chef

1 Introduction

There is an ongoing series of symposia, at Tokyo, on 'Foundations of Quantum Mechanics in the Light of New Technology'[1,2]. Indeed new technology (electronics, computers, lasers,…) has made possible new demonstrations of quantum queerness. And it has made possible practical approximations to old gedankenexperiments. Over the last decade or so have appeared beautiful experiments[1,2] on 'particle' interference and diffraction, with neutrons and electrons, on 'delayed choice', on the Ehrenburg–Siday–Aharonov–Bohm effect, and on the Einstein–Podolsky–Rosen–Bohm correlations. These last are of particular relevance for the particular themes of this paper. But those themes arise already in the context of technology which is neither new or advanced, as is illustrated by the following passage[3]:

> I want to boil an egg. I put the egg into boiling water and I set an alarm for five minutes. Five minutes later the alarm rings and the egg is done. Now the alarm clock has been running according to the laws of classical mechanics uninfluenced by what happened to the egg. And the egg is coagulating according to laws of physical chemistry and is uninfluenced by the running of the clock. Yet the coincidence of these two unrelated causal happenings is meaningful, because, I, the great chef, imposed a structure on my kitchen.

These notions, of cause and effect on the one hand, and of correlation on the other, and the problem of formulating them sharply in contemporary physical theory, will be the themes of my talk. I will be particularly concerned with the idea that effects are near to their causes[4]:

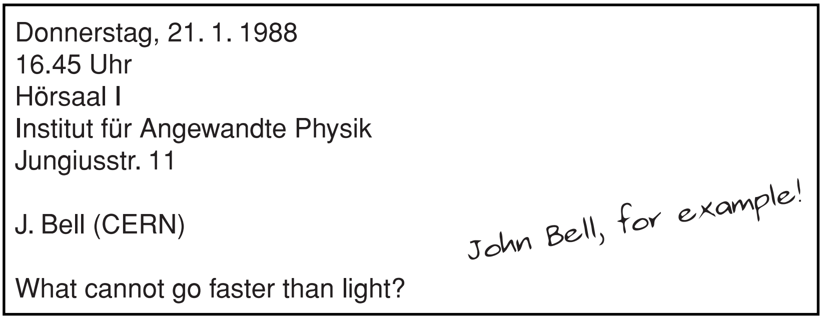
> If the results of experiments on free fall here in Amsterdam would depend appreciably on the temperature of Mont Blanc, on the height of the Seine below Paris and on the position of the planets, one would not get very far.

Now at some very high level of accuracy, all these things *would* become relevant for free fall in Amsterdam. However even then we would expect their influence to be retarded by at least the time that would be required for the propagation of light. I will be much concerned here with the idea of the velocity of light as a limit. What exactly does it limit?

2 What cannot go faster than light?

Once when I arrived to give a talk on this topic, at the University of Hamburg, it was pointed out to me that some graffiti had been added to one of the announcements (Fig. 1). To the question 'What cannot go faster than light?' had been volunteered the reply: 'John Bell, for example'. I have been wondering ever since what exactly that meant. When I walk, one foot remains planted on the ground, while the other advances. When I talk, I wave my hands (as you will see) and they have different velocities – from one another and from my head. Perhaps what was meant was that no *part* of John Bell can go faster than light. But that raises the question of how far I can be resolved into parts…legs and arms, fingers and toes,…cells,…molecules, atoms,…electrons. Was it meant that none of my *electrons*, for example, go faster than light?

The idea that no particle could go faster than light arose late in the nineteenth century, first for electrically charged particles, and then for all particles. Even then the 'particles' were envisaged as extended, and questions about their 'parts' could be posed…And now the sharp localization of objects in classical theory has been replaced by the fuzziness of wave mechanics and the complications of quantum field theory. The concept 'velocity of an electron' is now unproblematic only when not thought about.


Donnerstag, 21. 1. 1988
16.45 Uhr
Hörsaal I
Institut für Angewandte Physik
Jungiusstr. 11

J. Bell (CERN)

What cannot go faster than light?

John Bell, for example!

Fig. 1. 'What cannot go faster than light?'

The situation is further complicated by the fact that there *are* things which *do* go faster than light. British sovereignty is the classical example. When the Queen dies in London (may it long be delayed) the Prince of Wales, lecturing on modern architecture in Australia, becomes *instantaneously* King. (Greenwich Mean Time rules here.) And there are things like that in physics. In Maxwell's theory, the electric and magnetic fields in free space satisfy the wave equation:

$$\frac{1}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} - \nabla^2 \mathbf{E} = 0 \,, \tag{1}$$

$$\frac{1}{c^2}\frac{\partial^2 \mathbf{B}}{\partial t^2} - \nabla^2 \mathbf{B} = 0 \tag{2}$$

...corresponding to propagation with velocity c. But the scalar potential, if one chooses to work in 'Coulomb gauge', satisfies Laplace's equation

$$-\nabla^2 \phi = 0 \tag{3}$$

...corresponding to propagation with infinite velocity. Because the potentials are only mathematical conveniences, and arbitrary to a high degree, made definite only by the imposition of one convention or another, this infinitely fast propagation of the Coulomb-gauge scalar potential disturbs no one. Conventions can propagate as fast as may be convenient. But then we must distinguish in our theory between what is convention and what is not.

3 Local beables

No one is obliged to consider the question 'What cannot go faster than light?'. But if you decide to do so, then the above remarks suggest the following: you must identify in your theory 'local *be*ables'. The *be*ables of the theory are those entities in it which are, at least tentatively, to be taken seriously, as corresponding to something real. The concept of 'reality' is now an embarrassing one for many physicists, since the advent of quantum mechanics, and especially of 'complementarity'. But if you are unable to give some special status to things like electric and magnetic fields (in classical electromagnetism), as compared with the vector and scalar potentials, and British sovereignty, then we cannot begin a serious discussion. *Local* beables are those which are definitely associated with particular space-time regions. The electric and magnetic fields of classical electromagnetism, $\mathbf{E}(t, x)$ and $\mathbf{B}(t, x)$ are again examples, and so are integrals of them over limited space-time regions. The total energy in all space, on the other hand, may be a beable, but is certainly not a local one.

Now it may well be that there just *are* no local beables in the most serious theories. When space-time itself is 'quantized', as is generally held to be necessary, the concept of locality becomes very obscure. And so it does also in presently fashionable 'string theories' of 'everything'. So all our considerations are restricted to that level of approximation to serious theories in which space-time can be regarded as given, and localization becomes meaningful. Even then, we are frustrated by the vagueness of contemporary quantum mechanics. You will hunt in vain in the text-books for the local *be*ables of the theory. What you may find there are the so-called 'local observables'. It is then implicit that the apparatus of 'observation', or, better, of experimentation, and the experimental results, are real and localized. We will have to do as best we can with these rather ill-defined local beables, while hoping always for a more serious reformulation of quantum mechanics where the local beables are explicit and mathematical rather than implicit and vague.

4 No signals faster than light

The concept of particle is no longer sharp, so the concept of particle velocity is not sharp either. The answer to our question can no longer be: 'particles cannot go faster than light'. But perhaps it could still be; 'cause and effect'. As far as I know, this was first argued by Einstein, in the context of special relativity theory. In 1907 he pointed out[5] that if an effect followed its cause sooner than light could propagate from the one place to the other, then in some other inertial frames of reference the 'effect' would come before the 'cause'! He wrote[6]

> …in my opinion, regarded as pure logic…it contains no contradictions; however it absolutely clashes with the character of our total experience, and in this way is proved the impossibility of the hypothesis…

of a causal chain going faster than light.

The kind of thing that Einstein found unacceptable is illustrated in Fig. 2. If I had a 'tachyon' gun, i.e. one that could shoot bullets (or rays, or whatever) faster than light, then I could commit a murder without fear of punishment. This could be done by exploiting the relativity of time. I would lure my victim to the origin of coordinates O. Then I would run rapidly past, pulling the trigger at the appropriate moment P, shortly before time $t' = 0$ on my watch, and the deed would soon be done at time $t' = 0$. This would also be (by hypothesis) time $t = 0$, where t is Greenwich Mean Time, as used (at least during the winter in England) by the police, the courts of justice, and indeed all other institutions firmly planted on the English ground. But at time $t = \epsilon$ (where ϵ as usual is very small) the trigger has not yet been pulled, although the victim is dead. Indeed from this earthly point of view what happens at the origin of coordinates is that the unfortunate victim collapses spontaneously, with the spontaneous emission of an antitachyon. Happening to be passing, I catch the antitachyon into the barrel of my gun, and so prevent possible injury to other passers-by. I should get a medal.

Even Einstein would have hesitated to accept such relativity of morality. Most citizens will feel that such actions, if not against the laws of the land, should be excluded by the laws of nature. What we have to do then is to add to the laws of relativity some responsible causal structure. To avoid causal chains going backward in time in some frames of reference, we require them to go slower than light in any frame of reference.

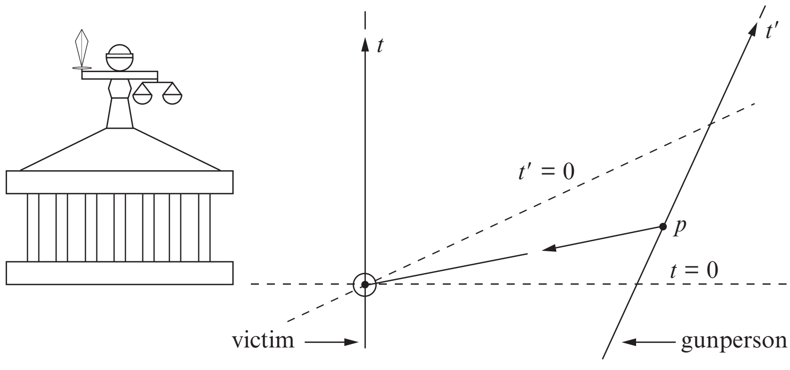


Fig. 2. Perfect tachyon crime.

5 Local commutativity

Ordinary 'local' quantum field theory does have a causal structure. As everyone knows, it gives rise to 'dispersion relations'. In their pioneering paper on dispersion relations in relativistic quantum field theory, Gell-Mann, Goldberger, and Thirring[7] write:

> The quantum mechanical formulation of the demand that waves do not propagate faster than light is, as is well known, the condition that the measurement of two observable quantities should not interfere if the points of measurement are space-like to each other…the commutators of two Heisenberg operators…shall vanish if the operators are taken at space-like points.

Thus for Heisenberg operators A and B for space-time points x and y,

$$[A(x), B(y)] = 0, \text{ for } (x_0 - y_0)^2 < (\mathbf{x} - \mathbf{y})^2 \tag{4}$$

…which is called 'local commutativity'.

The only way that I know to relate local commutativity to any sort of causality concerns the response of the quantum system to external interventions. Two sorts of external intervention are contemplated in ordinary quantum mechanics. They are the making of 'measurements', and the imposition of 'external fields'.

The 'non-interference' of 'measurements' of commuting 'observables' includes the following: the probability of any particular result for one of them is unaltered by whether or not the other is indeed measured, when all possible results for the latter (if indeed measured) are averaged over[8]. And so, in a theory with local commutativity, an experimental physicist cannot increase the probability that a rival will be 'measured' as dead in a space-like separated region, – by himself or herself making 'measurements'. The last sentence illustrates, by the way, the grotesque misuse of the word 'measurement' in contemporary quantum mechanics. The more careful writers use sometimes the word 'preparation' instead, and this would be less inappropriate here for whatever action the gunperson might take towards the desired end. Those actions will be in vain, in a locally commutative theory, if like 'measurements' and 'preparations' they result only in the 'collapse of the wavefunction' to an eigenstate of a nearby 'observable'.

An 'external field' is a c-number field on which the theory imposes no restrictions, i.e. about which it asserts no laws. The Lagrangian can be allowed to depend on such fields. The arbitrariness of such fields can be supposed to represent the freedom of experimenters, for example to do one variation of an experiment rather than another. Consider the effect of a small variation of such a field ϕ. The variation of the Lagrangian density will be of the form

$$\delta L(y) = Y(y)\ \delta\phi(y), \tag{5}$$

where, in 'local' theory, $Y(y)$ is some operator belonging to the space-time point y. Then it is an easy exercise in quantum mechanics to show that for a Heisenberg operator $X(x)$, the retarded change is given by

$$\frac{\delta X(x)}{\delta \phi(y)} = i\theta(x_0 - y_0) \ [X(x), \ Y(y)], \tag{6}$$

where θ is the step function, zero for negative argument. Then with local commutativity the statistical predictions of quantum mechanics, for 'measurement results', do not depend on external fields outside the backward light cone of the 'observables' in question. So, no superluminal signalling with external fields.

6 Who could ask for anything more?

Could the no-superluminal-signalling of 'local' quantum field theory be regarded as an adequate formulation of the fundamental causal structure of physical theory? I do not think so. For although 'local commutativity' has a nice sharp-looking mathematical appearance, the concepts involved in relating it to causal structure are not very satisfactory.

This is notoriously so as regards the notion of 'measurement' and the resulting 'collapse of the wavefunction'. Does this happen sometimes outside laboratories? Or only in some authorized 'measuring apparatus'? And whereabouts in that apparatus? In the Einstein–Podolsky–Rosen–Bohm experiment, does 'measurement' occur already in the polarizers, or only in the counters? Or does it occur still later, in the computer collecting the data, or only in the eye, or even perhaps only in the brain, or at the brain–mind interface of the experimenter?

The notion of external field is a more honourable one than that of 'measurement'. There are many cases in practice where an electromagnetic field can be considered, in an adequate approximation, to be classical and external to the quantum system. For example, a variation on the EPRB experiment involves neutral spin-half particles instead of photons. The polarization analysers can then be Stern–Gerlach magnets, and their magnetic fields can be treated as 'external'…in a good approximation. But an accurate treatment of the electromagnetic field involves its incorporation into the quantum system. And must we not also so incorporate the magnets, the hand of the experimenter, the brain of the experimenter? Where are truly 'external' fields to be found? Perhaps at the interface between the brain and the mind?

Who am I to deny that a sharp formulation of causal structure in physical theory requires reference to the minds of experimental physicists? Or that there just *was* no causal structure before the emergence of that profession (this might have interesting implications in cosmology). But before trying to figure out from which parts of their heads, and when, the fundamental causal cones emerge, should we not look for alternatives?

As a first attempt let us formulate the following…

7 Principle of local causality

> The direct causes (and effects) of events are near by, and even the indirect causes (and effects) are no further away than permitted by the velocity of light.

Thus for events in a space-time region 1 (Fig. 3) we would look for causes in the backward light cone, and for effects in the future light cone. In a region like 2, space-like separated from 1, we would seek neither causes nor effects of events in 1. Of course this does not mean that events in 1 and 2 might not be correlated, as are the ringing of Professor Casimir's alarm and readiness of his egg. They are two separate results of his previous actions.

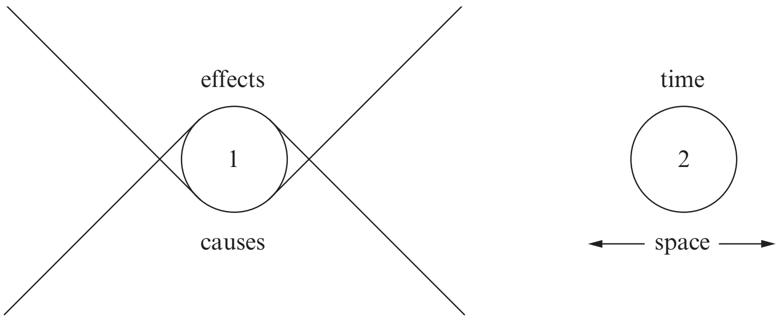


Fig. 3. Space-time location of causes and effects of events in region 1.

The above principle of local causality is not yet sufficiently sharp and clean for mathematics.

Now it is precisely in cleaning up intuitive ideas for mathematics that one is likely to throw out the baby with the bathwater. So the next step should be viewed with the utmost suspicion:

> A theory will be said to be locally causal if the probabilities attached to values of local beables in a space-time region 1 are

unaltered by specification of values of local beables in a space-like separated region 2, when what happens in the backward light cone of 1 is already sufficiently specified, for example by a full specification of local beables in a space-time region 3 (Fig. 4).

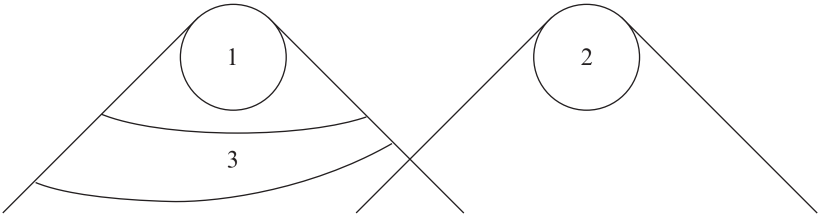


Fig. 4. Full specification of what happens in 3 makes events in 2 irrelevant for predictions about 1 in a locally causal theory.

It is important that region 3 completely shields off from 1 the overlap of the backward light cones of 1 and 2. And it is important that events in 3 be specified completely. Otherwise the traces in region 2 of causes of events in 1 could well supplement whatever else was being used for calculating probabilities about 1. The hypothesis is that any such information about 2 becomes redundant when 3 is specified completely. The ringing of the alarm establishes the readiness of the egg. But if it is already given that the egg was nearly boiled a second before, then the ringing of the alarm makes the readiness no more certain.

Consider for example Maxwell's equations, in the source-free case for simplicity. The fields **E** and **B** in region 1 are completely determined by the fields in region 3, regardless of those in 2. Thus this is a locally causal theory in the present sense. The deterministic case is a limit of the probabilistic case, the probabilities becoming delta functions.

Note, by the way, that our definition of locally causal theories, although motivated by talk of 'cause' and 'effect', does not in the end explicitly involve these rather vague notions.

8 Ordinary quantum mechanics is not locally causal

That ordinary quantum mechanics is not locally causal was pointed out by Einstein, Podolsky and Rosen, in 1935[9]. Their argument was simplified by Bohm[9] in 1951. Let the 'source' in Fig. 5 emit a pair of photons in opposite directions along the z-axis. Let them be in joint polarization state

$$\frac{1}{\sqrt{2}}\{X(1)X(2) + Y(1)Y(2)\}\ , \tag{7}$$

where X and Y are states of linear polarization in x and y directions. Let the polarizers be so oriented as to pass the X states and block the Y's. Each of the counters considered separately has on each repetition of the experiment a 50% chance of saying 'yes'. But when one counter says 'yes' so also always does the other, and when one counter says 'no' the other also says 'no', according to quantum mechanics. The theory requires a perfect correlation of 'yeses' or 'nos' on the two sides. So specification of the result on one side permits a 100% confident prediction of the previously totally uncertain result on the other side. Now in ordinary quantum mechanics there just *is* nothing but the wavefunction for calculating probabilities. There is then no question of making the result on one side redundant on the other by more fully specifying events in some space-time region 3. We have a violation of local causality.

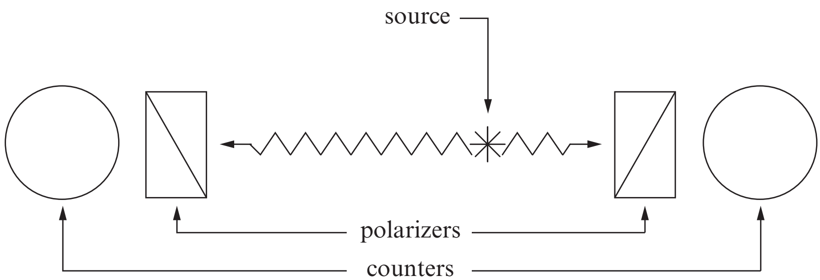


Fig. 5. Einstein–Podolsky–Rosen–Bohm gedankenexperiment.

Most physicists were (and are) rather unimpressed by this. That is because most physicists do not really accept, deep down, that the wavefunction is the whole story. They tend to think that the analogy of the glove left at home is a good one. If I find that I have brought only one glove, and that it is right-handed, then I predict confidently that the one still at home will be seen to be left-handed. But suppose we had been told, on good authority, that gloves are neither right- nor left-handed when not looked at. Then that, by looking at one, we could predetermine the result of looking at the other, at some remote place, would be remarkable. Finding that this is so in practice, we would very soon invent the idea that gloves are already one thing or the other even when not looked at. And we would begin to doubt the authorities that had assured us otherwise. That common-sense position was that taken by Einstein, Podolsky and Rosen, in respect of correlations in quantum mechanics. They decided that the wavefunction, making no distinction whatever between one possibility and another, could not be the whole story. And they conjectured that a more complete story would be locally causal.

However it has turned out that quantum mechanics cannot be 'completed' into a locally causal theory, at least as long as one allows, as Einstein, Podolsky and Rosen did, freely operating experimenters. The analogy of the gloves is not a good one. Common sense does not work here.

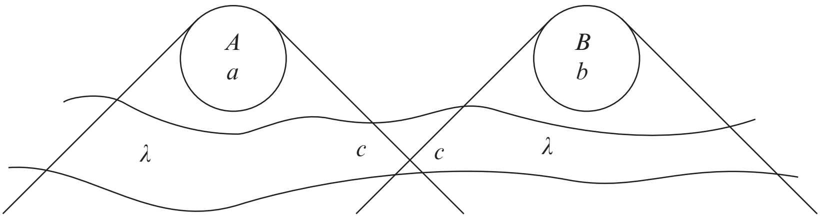


Fig. 6. Diagram for CHHS inequality derivation.

9 Locally explicable correlations

In the space-time diagram of Fig. 6 we denote by A (=+1 or –1) the output from the counter on the left ('yes' or 'no'). And B (=+1 or –1) is the output from the counter on the right. We denote by a and b the angles by which the polarizers are rotated from some standard positions in which they are parallel. We consider a slice of space-time 3 earlier than the regions 1 and 2 and crossing both their backward light cones where they no longer overlap. In region 3 let c stand for the values of any number of other variables describing the experimental set-up, as admitted by ordinary quantum mechanics. And let λ denote any number of hypothetical additional complementary variables needed to complete quantum mechanics in the way envisaged by EPR. Suppose that the c and λ together give a complete specification of at least those parts of 3 blocking the two backward light cones.

Let

$$\{A, B|a, b, c, \lambda\} \tag{8}$$

denote the probability of particular values A and B given values of the variables listed on the right. By a standard rule, the joint probability can be expressed in terms of conditional probabilities:

$$\{A, B|a, b, c, \lambda\} = \{A|B, a, b, c, \lambda\}\ \{B|a, b, c, \lambda\}. \tag{9}$$

Invoking local causality, and the assumed completeness of c and λ in the relevant parts of region 3, we declare redundant certain of the conditional variables in the last expression, because they are at space-like separation from the result in question. Then we have

$$\{A, B|a, b, c, \lambda\} = \{A|a, c, \lambda\}\ \{B|b, c, \lambda\}. \tag{10}$$

Now this formulation has a very simple interpretation. It exhibits A and B as having no dependence on one another, nor on the settings of the remote polarizers (b and a respectively), but only on the local polarizers (a and b respectively) and on the past causes, c and λ. We can clearly refer to correlations which permit such factorization as 'locally explicable'. Very often such factorizability is taken as the starting point of the analysis. Here we have preferred to see it not as the *formulation* of 'local causality', but as a consequence thereof.

10 Quantum mechanics cannot be embedded in a locally causal theory

Let us define a correlation function $E(a, b, c)$ as the expectation value of the product of A and B:

$$E = \sum_{\lambda} \sum_{A,B} AB\ \{A, B|a, b, c, \lambda\}\ \{\lambda|a, b, c\}. \tag{11}$$

Here we have introduced a probability distribution $\{\lambda|a, b, c\}$ over the hypothetical complementary beables λ, for given values of the variables (a, b, c) which describe the experimental setup in the usual way. Now we make an important hypothesis:

The variables a and b can be considered to be *free* or *random*.

In the application to the Einstein–Podolsky–Rosen–Bohm two-photon experiment, a and b are the polarizer settings. Then we may imagine the experiment done on such a scale, with the two sides of the experiment separated by a distance of order light minutes, that we can imagine these settings being freely chosen at the last second by two different experimental physicists, or some other random devices. If these last second choices are truly free or random, they are not influenced by the variables λ. Then the resultant values for a and b do not give any information about λ. So the probability distribution over λ does not depend on a or b:

$$\{\lambda|a, b, c\} = \{\lambda|c\}. \tag{12}$$

We will come back to this. Then, using also the factorizability consequent on local causality,

$$E(a, b, c) = \sum_{\lambda} \sum_{A,B} AB \, \{A|a, c, \lambda\} \, \{B|b, c, \lambda\} \, \{\lambda|c\}. \tag{13}$$

From this it is a matter of simple manipulation to derive the *Clauser–Holt–Horne–Shimony Inequality*:

$$|E(a, b, c) - E(a, b', c)| + |E(a', b, c) + E(a', b', c)| < 2. \tag{14}$$

But according to quantum mechanics, this expression can approach $2\sqrt{2}$. So quantum mechanics can*not* be embedded in a locally causal theory.

An essential element in the reasoning here is that a and b are free variables. One can envisage then theories in which there just *are* no free variables for the polarizer angles to be coupled to. In such 'superdeterministic' theories the apparent free will of experimenters, and any other apparent randomness, would be illusory. Perhaps such a theory could be both locally causal and in agreement with quantum mechanical predictions. However I do not expect to see a serious theory of this kind. I would expect a serious theory to permit 'deterministic chaos' or 'pseudorandomness', for complicated subsystems (e.g. computers) which would provide variables sufficiently free for the purpose at hand. But I do not have a theorem about that[10].

11 But still, we cannot signal faster than light

According to the above reasoning, the nonlocality of quantum mechanics cannot be attributed to incompleteness, but is somehow irreducible. It remains however that *we* are very much bound by time and space, and in particular that we cannot signal faster than light. Suppose that the two experimenters of the above were to try to communicate with one another by means of the apparatus in place. What could they do? We have supposed that one of them can freely manipulate the variable a, and the other the variable b. But each has to accept A or B as it appears from his equipment, and neither knows the hidden variables λ. Now it is readily verified from the explicit quantum mechanical predictions for the EPRB gedankenexperiment that

$$\{A|a, b, c\} = \{A|a, c\}, \{B|a, b, c\} = \{B|b, c\}. \tag{15}$$

That is to say that, when averaged over the unknown λ, manipulation of b has no effect on the statistics of A, and manipulation of a has no effect on the statistics of B. And this is quite generally a consequence of 'local commutativity' in so far as the variables a and b represent choices of 'measurements', or 'preparations', or 'external fields'.

12 Conclusion

The obvious definition of 'local causality' does not work in quantum mechanics, and this cannot be attributed to the 'incompleteness' of that theory[11].

Experimenters have looked to see if the relevant predictions of quantum mechanics are in fact true[1,2,9,12]. The consensus is that quantum mechanics works excellently, with no sign of an error of $\sqrt{2}$. It is often said then that experiment has decided against the locality inequality. Strictly speaking that is not so. The actual experiments depart too far from the ideal[13], and only after the various deficiencies are 'corrected' by theoretical extrapolation do the actual experiments become critical. There is a school of thought[14] which stresses this fact, and advocates the idea that better experiments may contradict quantum mechanics and vindicate locality. I do not myself entertain that hope. I am too impressed by the quantitative success of quantum mechanics, for the experiments already done, to hope that it will fail for more nearly ideal ones.

Do we then have to fall back on 'no signalling faster than light' as the expression of the fundamental causal structure of contemporary theoretical physics? That is hard for me to accept. For one thing we have lost the idea that correlations can be explained, or at least this idea awaits reformulation. More importantly, the 'no signalling…' notion rests on concepts which are desperately vague, or vaguely applicable. The assertion that 'we cannot signal faster than light' immediately provokes the question:

> Who do we think *we* are?

We who can make 'measurements', *we* who can manipulate 'external fields', *we* who can 'signal' at all, even if not faster than light? Do *we* include chemists, or only physicists, plants, or only animals, pocket calculators, or only mainframe computers?

The unlikelihood of finding a sharp answer to this question reminds me of the relation of thermodynamics to fundamental theory. The more closely one looks at the fundamental laws of physics the less one sees of the laws of thermodynamics. The increase of entropy emerges only for large complicated systems, in an approximation depending on 'largeness' and 'complexity'. Could it be that causal structure emerges only in something like a 'thermodynamic' approximation, where the notions 'measurement' and 'external field' become legitimate approximations? Maybe that is part of the story, but I do not think it can be all. Local commutativity does not for me have a thermodynamic air about it. It is a challenge now to couple it with sharp internal concepts, rather than vague external ones. Perhaps there is already a hint of this in 'quantum mechanics with spontaneous wavefunction collapse'[15, 16]. But that is another story. As regards the present situation, I end here with Einstein's judgement, as translated by Casimir[17], on the new cookery of quantum mechanics:

> …in my opinion it contains all the same a certain unpalatability.

Appendix: History

It would be interesting to know when and how the idea of the velocity of light as the limit developed. The earliest reference that I know is to a remark of G. F. FitzGerald, in a letter of Feb. 4, 1889, to O. Heaviside. Heaviside had calculated the electromagnetic field of a uniformly moving rigid sphere. He did this at first for velocity less than that of light. Writing to FitzGerald he said that he did not yet know what happened for motion faster than light. FitzGerald remarked '…I wonder if it is possible…'. Heaviside went on to solve the problem with velocity greater than c, and found that the solution is indeed rather different in character from that in the subluminal case. But he, at least at that time, saw no reason for not considering superluminal motion.

The idea of the velocity of light as the limit was one of the themes of Poincaré's famous address to the 1904 International Congress of Arts and Science at St Louis[19]. After reviewing the experiments and ideas that we now see as leading up to special relativity theory, he said[20]:

> …from all these results, if they were confirmed, would emerge an entirely new mechanics, which would be characterized by this fact that no velocity could exceed that of light any more than any temperature can fall below the absolute zero…

One of the reasons that he gave for this was the increase of inertia with velocity[21]:

> …perhaps we will have to construct a new mechanics, that we can only glimpse, where, inertia increasing with velocity, the velocity of light would become an uncrossable limit…

The advocates of 'tachyons' have since pointed out that one can imagine particles which are *created* moving faster than light, without having to be accelerated up from a subluminal velocity. Poincaré also had another argument, concerning signalling and the regulation of clocks[22]:

> …what would happen if one could communicate by signals whose velocity of propagation differed from that of light? If, after having synchronised clocks optically, one wished to verify the adjustment with the help of these new signals, one would find discrepancies which would show up the common motion of the two stations…

But in Switzerland you can set your watch by observing the trains go through the stations and looking up the timetable. Your watch is then synchronized with all the station clocks in Switzerland, and with the Federal Clock at Neuchatel. Although the trains do not go with the velocity of light, no discrepancies have ever been observed, and certainly none that would allow the detection of the motion of the stations, with the rest of Switzerland, through the aether[a]. The timetables allow for the finite propagation time of trains, but of course such allowance is necessary even with light. And clearly the same result will be obtained with any other method when proper allowance is made for the relevant laws of propagation, subluminal or superluminal, provided those laws are as regular as those of Swiss trains. I think that Poincaré nodded here. However he was not himself very convinced by his reasoning. Immediately after the last passage quoted he raises the possibility that gravitation goes faster than light. But a few pages later he is firmly maintaining that the motion of the stations will not be detected[23]:

> …Michelson has shown us, as I have said, that the procedures of physics are powerless to show up absolute motion; I am convinced that it will be the same for astronomical procedures however far the precision is pushed.

[a] At still higher accuracy, even with light-signal synchronization, small cumulative discrepancies should appear. They would show up, not the mere motion of Switzerland through the aether, but that that motion is not just one of uniform translation, and that gravitation is at work, and that these affect even *Swiss* clocks.

Notes and references

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