truth that is presently good enough for us, has also played a positive role in the history of science. Thus Copernicus found a more intelligible pattern by placing the sun rather than the earth at the center of the solar system. I can well imagine a future phase in which this happens again, in which the world becomes intelligible to human beings, even to theoretical physicists, when they do not imagine themselves to be the center of it."

It was our good fortune to have spent a week last June with John and Mary in a workshop at Amherst College, where these issues were discussed at leisure and at length. Afterwards, driving back to Ithaca, we agreed that John was truly unique in the world of physics, as a personality and as an intellect — at once scientist, philosopher and humanist. He was a person to whom deep ideas mattered deeply. Fate has been most cruel to steal him from us when he was still so brimful of vitality. But he will live on through his profound and timeless work. That, and the privilege of having known him, must be our solace.

ADDITIONAL REFERENCES

[1] [page 72, 2]: Bell listed his physics speciality in an official CERN document as "quantum engineering" (p. 12) and averred that "I am not like many people I meet at conferences on the foundations of quantum mechanics ... who have not really studied the orthodox theory [and] devote their lives to criticizing it ... I think that means that they haven't really appreciated the strengths of the ordinary theory. I have a very healthy respect for it. I am enormously impressed by it." (p. 85).

[2] Most of Bell's shots across the bow of orthodoxy are collected in [page 72, 1].

[3] [page 72, 3]: this and [page 72, 1] were actually written at about the same time.

[4] Bell J.S., *Phys. World* **3** (1990) 33.

[5] Other words that Bell sought to ban from the formulation of the theory (as compared to discussions of its applications) are system, apparatus, environment, microscopic, macroscopic, reversible, irreversible, information, and observables, the latter term to be replaced by a favorite concept, beables.

[6] *The Ghost of the Atom*, Eds. P.C.W. Davies and J.R. Brown (Cambridge University Press, 1986) 50.

[7] See, in particular, Ghirardi G.C., Rimini A. and Weber T., *Phys. Rev. D* **34** (1986) 470; **36** (1987) 3287; and [2, pp. 201-212].

[8] [4, p. 40]: note the stress here on *or* in contrast to *and*.

[9] John Bell (and Michael Nauenberg) expressed this same point with zest in a paper bearing the same title as this essay: "We emphasize not only that our view is that of a minority, but also that current interest in such questions is small. The typical physicist feels that they have long been answered, and that he will fully understand just how if ever he can spare just twenty minutes to think about it." [2, p. 28].

Bell's Early Work

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John Bell came to my department in Birmingham in October 1953 on a year's leave from the Atomic Energy Research Establishment, Harwell, UK. Technically his status was that of a graduate student, but he was evidently much more mature than his 25 years. He also had already had substantial research experience for in his four years at Harwell he had worked on accelerator design, particularly on aspects of particle orbits and focussing. It may well be that this experience, of approaching physics through work on concrete problems relating to hardware, influenced his later style. When dealing with abstract problems he would always find some simple, tangible example to test his ideas.

He quickly became popular in the department, and it did not take long before we were impressed with his ability and the clarity of his thoughts. We became accustomed to his way of speaking, which at first may have sounded pedantic but on closer acquaintance revealed care to get the essential points across.

Time Reversal and Field Theory

He had come to Birmingham to learn about modern theoretical physics: he started studying field theory and in a short time acquired an up-to-date knowledge of the subject. At the time we heard of experiments which seemed to reveal evidence for a negatively charged particle which was stable, but with a mass less than that of the proton. The experimenters asked us whether this could possibly be the antiproton. This seemed unlikely, but could it be firmly ruled out? Everybody expected particle and antiparticle to have the same mass, but was this strictly necessary?

This was a problem after his heart. He did not like to take commonly held views for granted, but tended to ask "How do you know?". In due course he came up with the "CPT theorem", that the results of any field theory must remain unchanged if one reverses the sign of the space coordinates and of time, and interchanges particles and antiparticles. (He said cautiously, "in any theory of the present form", but nobody has yet given an example of a sensible theory in which the theorem would not hold). The theorem ensures, in particular, that any particle and antiparticle must have the same mass.

Sir Rudolf Peierls was Professor of Mathematical Physics at the University of Birmingham, UK from 1937 to 1963 and the Wykeham Professor of Theoretical Physics at Oxford from 1963 to 1974, when he retried.

John Bell in 1956 in front of one of the post-war prefabricated homes at Chilton, UK where he lived with his wife Mary when they were first married.

Any evidence contradicting the theorem would be very hard to reconcile with our present basic physics; so far no such evidence has been found. Indeed, the experiment which had raised the question was not confirmed.

The proof of the theorem formed the basis of John's Ph.D. thesis [page 72, 8] completed after his return to Harwell. Before he had completed writing it the same result was published by Lüders. So John lost priority, but this did not diminish the merit of his insight.

After returning to Harwell, he retained his interest in problems relating to time reversal. He showed [1] that time-reversal arguments cannot be strictly applied to β decay because the inverse reaction is not in practice observable, but that useful conclusions can be drawn provided first-order perturbation theory is applicable, which of course it is to high accuracy. He also continued to think about field theory. He developed a formalism proposed by Skyrme [2] and together with him applied it to an attempt to calculate the magnetic moments of nucleons [3].

Nuclear Physics

But his main effort went into problems of nuclear physics which came up in the work at Harwell. Here again he was never satisfied with routine applications of standard methods, but always went back to foundations. For example, he showed [4] how the spin-orbit term in the shell-model potential could be derived from the spin-orbit force in the two-nucleon interaction.

He discussed how far β decay would be influenced by taking place in a many-body situation [5], and with Blin-Stoyle he considered the effect of virtual mesons in the nucleus of β decay [6]. Two papers with Mandl [7] discuss the identity relating polarization and asymmetry in scattering, and show that this is valid if longitudinal polarization plays no part, but needs correcting if there is longitudinal polarization, which is always possible because of parity violation.

Another fundamental problem is bremsstrahlung in multiple scattering [8]. A characteristic approach adopted by John Bell was to solve a many-body problem in a one-body potential [9], because this can serve as a model for genuine many-body problems.

Charge conjugation in the shell model [10] yields simple rules which lead to simple deviations of results which had been obtained beforehand using more cumbersome methods.

This is only a short selection from the many important and original contributions he made between 1954 and 1960 when he moved to CERN, where after a short period of adjustment he stared contributing to particle physics. It may be worth noting, however, that his command of nuclear physics put him in a strong position to deal with problems straddling the borderline between nuclear and particle physics, such as muon capture in heavy nuclei [11], or the nuclear optical modes for pions [12].

In recent years he has spoken out strongly against the usual interpretation of quantum mechanics, and this was also expressed in his last paper [page 72, 5]. Some, including myself, do not agree [13] with his views, but we respect his arguments as raising and clarifying important issues and provoking serious thought. The issue he has defined will be debated for many years.

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Later Contributions

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John Bell is widely known even among non-physicists for his work [1-5] on the foundations of quantum mechanics (see page 67), while high-energy physicists also recognize his important contributions to that subject with his discovery, together with R. Jackiw [6], of the chiral anomaly (see page 76). The consequences of this discovery for gauge theory have been profound. However, these celebrated examples are but two of the many important fundamental contributions that John made to physics, and to elementary particle physics in particular. It is a reflection of his modesty that other aspects of his research are not more widely known.

Hawking Radiation

I first met John in 1978 and maintained contact during occasional visits to CERN until 1982 when I held a two-year fellowship at CERN. John was working at the time with J.M. Leinaas on a problem in quantum gravity relating to Hawking radiation from black holes and the Unruh effect (see page 78). It had been shown that if an observer carries a particle detector with him, he finds that the vacuum state of quantum field theory contains a thermal distribution of quanta, in direct analogy with Hawking radiation from a Schwarzschild black hole. Bell and Leinaas argued that this temperature should be present for circular as well as linearly accelerated detectors. They then showed that the thermal radiation would be detectable if the spin of an electron in a storage ring was used as a thermometer [7].

One of the paradoxical aspects of Unruh radiation is that the accelerated observer perceives a pure state (the quantum field theory vacuum) to be mixed (thermal). The resolution of this paradox is that there are correlations in the vacuum state over space-like intervals, but the accelerating observer is unable to detect them when they extend over his event horizon, which ultimately leads to his characterization of the state as mixed. The existence of quantum correlations over space-like intervals has obvious parallels with the Einstein-Podolsky-Rosen (EPR) paradox, and this was the subject of one of my few discussions of quantum mechanics with John. He felt that many of the interpretational problems of this aspect of quantum mechanics come from the idealized notion of the pure state. As John put it. "How would you ever make a pure state in the laboratory?"

Generally speaking, however, John was somewhat reluctant to discuss his work on the foundations of quantum mechanics with me. He believed that this subject was "not suitable" for a young physicist to work on, while he referred to his own involvement with it as a hobby, which he described, with his characteristic sense of humour, as "quantum theology" in a 1984 list of CERN research interests.

Another example of John's research accomplishments is his independent discovery of the CPT theorem (see page 69) while working on his Ph.D. thesis [8]. I learnt about this work because the over-the-event-horizon space-time of a uniformly accelerating observer can be mathematically accessed by the operation of inversion of space-time coordinates through the origin, which is closely related to the CPT operation in quantum field theory [9].

Classical Mechanics and Special Realtivity

I shall now try to describe some of John's less well-known research accomplishments that I have learnt about during our conversations. These will illustrate, I think, the incisiveness and precision that was so characteristic of his approach to physics.

Possibly the best illustration of John's wide ranging interests comes from his research in accelerator physics (see page 72) which he worked on throughout his career (he had recently collaborated with his wife Mary on the problem of brems-

John Bell in one of CERN's experimental halls in 1988. The photograph was taken to illustrate a British Council exhibit describing physics.

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