The Impact of Modern Scientific Ideas on Society

In Commemoration of Einstein

Edited by Colette M. Kinnon
with A.N. Kholodilin and J.G. Richardson

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ON SOCIETY

Papers presented at the Unesco Symposium on
The Impact of Modern Scientific Ideas on Society,
Munich-Ulm, 18–20 September 1978,
and the addresses delivered on the occasion of
Unesco's celebration of the hundredth anniversary
of Einstein's birth, Paris, 9 May 1979.

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* Delivered on the occasion of Unesco's celebration of the one hundredth anniversary of Albert Einstein's birth, Paris, 9 May 1979

** Delivered in Munich, 18 September 1978

*** Delivered in Ulm, 19–20 September 1978

Preface

Albert Einstein was not only the greatest figure in twentieth century physics, he was also a symbol of achievement in the new field of interactions between science and society.

In addition to paying homage to Einstein as an individual, numerous celebrations of either a scientific or a social character were organized by different bodies to celebrate the centennial year of his birth, 1979. Unesco took an active role in these activities, beginning with the organization of a symposium on the Impact of Modern Scientific Ideas on Society, held in Munich and Ulm (Federal Republic of Germany), 18–20 September 1978. Eight months later, Unesco celebrated the Einstein centennial year at its Headquarters in Paris with talks, music, and the projection of a film on the life of Einstein. Unesco also took part in the Second Marcel Grossmann Meeting on the Recent Developments in General Relativity, held in Trieste (Italy) to honour the hundredth anniversary of the birth of Albert Einstein. Similar meetings were held, variously, in Berlin-Babelsberg, Berne, Calcutta, Jerusalem, Moscow, Princeton, Washington and West Berlin.

Furthermore, Unesco collaborated with the International Commission on Physics Education (part of the International Union of Pure and Applied Physics) in the preparation of *Einstein – A Centenary Volume* [1], published in March 1979. This book describes Einstein's life, his major contributions to physics, his work in the cause of peace, and the wide-ranging effect of his ideas on some of the major educational, philosophical and other cultural issues of the twentieth century; the volume also contains personal reminiscences by people who knew Einstein, remarks made by the great savant, extracts from his own writings, as well as many photographs and other illustrations. Unesco also published, as the January-March 1979 issue of its quarterly journal, *Impact of Science on Society*, a commemorative collection of original articles concerning Einstein, his life and times, and the sociocultural consequences of his work.

Albert Einstein was born on 14 March 1879 in Ulm. He was to become one of the most creative intellects in the history of man. Among the research papers he published in 1905, there were four great discoveries in the field of physics. These were the photon theory of the structure of light (quantum physics), an explanation of Brownian motion (atomic physics), the special theory of relativity, and the equivalence of mass and energy (electromagnetism). It is interesting to note that another work published in 1916, and somewhat obscure in significance at the time, is now unquestionably recognized for its practical value in applications to lasers.

Between 1913 and 1915, Einstein evolved his general theory of relativity, postulated to express all the laws of physics by means of 'covariant' equations – that is, by equations having the same mathematical form, irrespective of systems of reference or of the space-time variables used. This theory had already predicted, in 1911, the bending of light beams from stars in passing near the surface of our sun, and the red-shift of light emitted by a source situated in a strong gravitational field; it also explained (1915) exactly the previously unaccounted for discrepancy in the advance of the perihelion of Mercury. Einstein sought to combine the four force-fields into a single, unifying theory, an endeavour in which he did not succeed.

Einstein also contributed greatly to the development of quantum physics with his theories concerning the photoelectric effect (1905), the specific heat of solids (1907), the emission and absorption of radiation (1916), and with the development of Bose-Einstein statistics (1924–1925). He contributed as well to the atomic theory of matter by offering the first demonstration (1905) that macroscopic observations (those of Brownian movement) could prove or disprove the molecular kinetic hypothesis of Maxwell and Gibbs, which explained macroscopic thermodynamics in terms of the mechanics of large numbers of particles. Einstein laid the foundations of the modern study of cosmology in 1917, but (for lack of observations) the subject lay dormant for about fifty years. The new cosmology has only recently become active as a consequence of new discoveries in particle physics and astronomy.

In discussing the singularly significant role that Einstein played in science, the Director-General of Unesco, Mr. Amadou-Mahtar M'Bow, said in his address of 9 May 1979: 'The reason for the prominence of Albert Einstein in the history of science is that he was not content to add one or two facts to our knowledge of the world, but reorganized the whole field of our knowledge and reconstructed it, adding to it a new dimension. And the quintessence of his imagination is perhaps to be found above all in his ability to see the connection between concepts which until then had been thought incompatible or contradictory, to restructure the field of physics by bringing increasing coherence and harmony into it'.

Albert Einstein was not a scientist working in an ivory tower. He recognized the practical implications of scientific advance. He himself stated, 'The source of all scientific achievement is . . . the ceaseless quest for knowledge of the experimenter and the creative fantasy of the engineer and inventor' [2].

The present work includes papers based on an interdisciplinary approach to research, written by scientists with different backgrounds, reflecting the impact of Einstein's ideas on a complexity of problems. Among the authors, the reader will find P. A. M. Dirac and Piotr L. Kapitza, both Nobel Prize winners (1933 and 1978, respectively) and the first Nobel Prize laureate from Pakistan, Abdus Salam (1979). These authors and their colleagues, whose contributions comprise this modest testimonial to the greatness of Albert Einstein, reflect ever so clearly the international character of science today. Unesco, because of its own international mandate, has collected these essays in its continuing effort to insure a free flow of information round the world, the promotion of human rights and the maintenance of peace. These are ideals, to be sure, but they are ideals to which Einstein harnessed his own burning zeal. Today these aims have become the essential foundations of the global humanism inspiring the mission and activities of Unesco and of men and women of the same good faith, all over the world.

Unesco acknowledges the invaluable contributions made to the organization of the first symposium in Munich and Ulm by Dr. Kurt Müller of the Ministry of Foreign Affairs of the Federal Republic of Germany, Prof. Hans Maier, Minister of Education and Cultural Affairs of the State of Bavaria, Dr. Mathilde Berghofer-Weichner, Secretary of State at the Bavarian Ministry of Education and Cultural Affairs, Prof. Dr. Nicholas Lobkowicz, president of the Ludwig-Maximilians University in Munich, Dr. Hans Lorenser, Lord-Mayor of Ulm, Dr. Gerhard Stuber, Vice-Mayor of Ulm, Prof. Dr. Ernst-F. Pfeiffer, rector of the University of Ulm, and Prof. Dr. Theo Nonnenmacher, director of the Department of Theoretical Physics in the same university. Without their dedication and perseverance, neither the inaugural ceremonies marking the centenary of Albert Einstein's birth nor this volume could have been prepared.

The Editors

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Introduction

In September 1978, Unesco honoured the Federal Republic's largest university (founded in 1472) by organizing on its premises a long-planned symposium to commemorate the centenary of Albert Einstein's birth. This symposium continued its meetings in Einstein's birthplace, Ulm, also in the Federal Republic.

It was no coincidence that, in addition to a detailed appreciation of Einstein's work, the symposium should have devoted itself to the theme 'The Impact of Modern Scientific Ideas on Society'. Not only would it be hard to find another scientist in our own century whose work has had a greater impact upon our overall understanding of nature and, indeed, of the world in which we live, but one would have to go back to the seventeenth century – to Newton – to find a scientific development with as far-reaching effects in modern times.

At the same time, however, Einstein's thinking bears witness to the fact that scientific ideas do not always have purely positive effects on our world. Towards the end of his life, Einstein came to see this more clearly than many of his fellow scientists. In fact, he serves as an example to all scientists in this respect: although the scientist's sole aim is to gain a better understanding of reality, he cannot wholly evade responsibility for the consequences his theories may have for the world in which we live.

For this reason, the symposium to commemorate the anniversary of Einstein's birth was of great significance, not only for the participants and organizers but also for Ludwig-Maximilians University itself. The occasion served to remind us, on the one hand, of the enormous impact which theoretical thought has on society and, on the other hand, of the moral problems that can come in its wake.

I should like to thank Unesco, and in particular its Director-General, Mr. Amadou-Mahtar M'Bow, as well as all the participants in the symposium, for having elected to hold the symposium at a German university, this despite the fact that Germany, and specially the University of Munich, did anything but justice in the 1930s to the most renowned physicist in our century. In this important respect, the symposium also proved to be an occasion of international understanding, indeed, of reparation and reconciliation in the spirit of that great Western culture that has today spread throughout much of the world, and in which are rooted those values for which the international community of nations is indebted.

Prof. Dr. Nicholas Lobkowicz
President of Ludwig-Maximilians University, Munich

PART I

PRESENTATION

Presentation at Munich by the Director-General of Unesco

Einstein's career is much too well known for me to need to recapitulate it here. You will however allow me to recall in a few words the role which Munich, Ulm and their universities, which are honoring his centenary, played in the life of the great physicist.

Albert Einstein was born on 14 March 1879 in Ulm, whose long history goes back to the ninth century. His family originally came from Buchau. His father, Hermann Einstein, who had a gift for mathematics, wished, after completing his studies at the Gymnasium, to enrol at Stuttgart University, but had to go into business instead. In 1878 he married Pauline Koch, the daughter of a rich grain merchant of Stuttgart, and the young couple settled in Ulm where Hermann Einstein's parents had been living for the past ten years and where they had a fairly large number of relatives. In Ulm, Hermann Einstein ran an electrical supplies shop, but one year after Einstein's birth the family moved to the suburbs of Munich.

Einstein began his schooling at a primary school in Munich and it was also in Munich, at the Luitpold Gymnasium, that he did his secondary school studies. He remained there until the age of fifteen, when his parents, whose business was doing none too well, moved to Milan. It was therefore at Munich that Einstein's first years were spent, the decisive formative years when he discovered mathematics and music which were to occupy such a place in his life.

In his autobiography, Bertrand Russell wrote that his life had been lit by three passions – the thirst for knowledge, the search for love, and communion with human suffering. Einstein could well have subscribed to this profession of faith by a man who, like him, was endowed with exceptional talent and breadth of mind. But perhaps, when we consider his life, we could today ascribe to him three ruling passions: the bold search for what was scientifically new, a deep faith in the harmony of the universe and the ardent aspiration for concord among men. It is on these three themes that I would like to centre this brief address.

Bohr, whose vigorous but friendly controversy with Einstein constitutes one of the most admirable pages of contemporary science, voiced the following superb thought regarding the unitary field of elementary particles proposed by Heisenberg, another giant of physics from the soil of Munich: 'This theory is manifestly observed. The question remains whether it is sufficiently observed to be true.' He could just as well have used these words to describe Einstein's whole work. Einstein, who in his youth discovered the photon and developed the special theory of relativity and finally the general theory of relativity, and who devoted his life to unifying the theory of physical interactions, never ceased to be a bold explorer of the mysteries of nature. With humour and modesty, going against received ideas, and taking a stand against orthodoxy, he enabled science to make its greatest leap forward since the time of Newton.

His immense intellectual courage derived its strength from the profound conviction that the physical universe was governed by a harmony which man could grasp and reflect in a mathematical model. This fascination for harmony recurs in Einstein's love of music, in which he saw, like Leibnitz, ' . . . the imitation of that universal harmony which God has conferred upon the world'. Music was for him, with physics, one of the royal roads open to man to explore the beauty towards which he strives with all his mind and all his heart.

However, the harmony of the universe must be matched by concord among men. The aspiration to such concord was Einstein's third great passion. No one has described it as well as Leopold Infeld who was the great scholar's closest collaborator. In pages of almost filial piety, he wrote that while it was certainly from Einstein that he had learnt the essential part of all he knew in physics, what he was most indebted to him for was his moral and ethical example. For Einstein, continued Infeld, was quite simply the most generous-minded man he had ever known: his whole life was an ardent communion with others, that communion which nurtured all that was great and noble in man and which came both from the soul and from the intellect; he felt with all his heart and mind that the serenity of each of us is determined by the accomplishment of one's duty towards all one's fellows and above all those who are suffering.

Thus it was that this man who had so acute a sense of the necessity of natural laws was inspired by an equally strong passion for the inalienable liberty of man. On the one hand a systematic search for the intimate order of things, against any margin of uncertainty, and on the other a systematic defence of the creative genius of man, against any form of servitude or coercion. It is because he was convinced that this liberty, and this liberty alone, was capable of penetrating the organized mystery of the world that he never dissociated the adventure of the mind from that of human emancipation and never spared either his time or his energy in proving it by his acts.

Typical of this was his entry in 1922 into the League of Nations Committee on Intellectual Co-operation. Despite his misgivings concerning group work and discipline in general, he took part in its meetings for as long as he felt that by so doing he could help to give practical form to the contribution of intellectuals to world understanding and peace. Once he acquired the conviction that the League of Nations, heavily dependent on the great powers, was impotent to respond to the hopes placed in it by the peoples of the world, he tendered his resignation.

He did not hesitate, however, in May 1946, just after the Second World War, to chair the group of atomic scientists which conceived its duty as being to alert world opinion to the formidable dangers of using the new source of energy represented by atomic fission for purposes of extermination.

'Our world', he was to proclaim, 'is faced with a crisis which has never before been envisaged in its whole existence. It gives the power to make far-reaching decisions on good and evil. The release of atom power has changed everything except our way of thinking, and thus we are being driven, unarmed, towards a catastrophe.' And he concluded with these words, which are a good summary of the importance he attached to man's responsibility for his own destiny: 'The solution of this problem lies in the heart of human kind.'

In April 1955, a few days before his death, he added his signature to the appeal by eleven leading world figures which Lord Bertrand Russell was to launch to Heads of State, as well as to the conscience of the world, in favour of disarmament and the peaceful settlement of disputes.

As he saw it, the protection of mankind against the threat posed to it by nuclear weapons was inseparable from the protection of the individual against the threat posed to him by dictatorship and arbitrary rule. These were, in fact, but the two faces of one and the same deep regard for man.

His aversion for any repressive system was rooted in the conception that the first and foremost of the individual's responsibilities was a moral responsibility towards the community, not a political responsibility *vis-à-vis* the State. As he put it, 'The State is there for man and not man for the State'. *A fortiori*, he condemned any violation of the basic rights of the individual, committed in the name of some *raison d'Etat*.

This is clear from his attitude in March 1954, when Oppenheimer, the Director of the Institute for Advanced Study, was abruptly dismissed from all the positions he held in the field of official atomic research. That very night, in spite of his already precarious health, Einstein summoned the press in order to make a public defence of his colleague's integrity – although he did not share all the latter's scientific views.

The freedom of man and the peace of the world – these ideals to which Einstein's burning zeal was harnessed – have today become the essential foundations of the global humanism that inspires the action of Unesco. These are, precisely, the first two chapters of its Medium-Term Plan, guiding both its overall theoretical approach and its principal practical activities in the field of culture and science.

The United Nations system has been preparing one of its most ambitious undertakings – a world conference on science and technology for development, to be held in the very year of the centenary of Einstein's birth. Allow me then, in conclusion, to draw from a life, exemplary in so many respects, a few essential guidelines for the Conference's work.

The first concerns the place of the scientist in society. The scientist no longer has an ivory tower in which to shut himself away from his contemporaries. For better or for worse, his work has a more or less direct influence upon the intellectual and material production of his time. His ethical responsibility towards his fellow-citizens is involved from the outset – and grows with the fame and authority he acquires. In the overall struggle for human progress, well-being and dignity, the scientist, less than anyone, has the right to desert; and, more than anyone, the duty to play an active part.

In direct descent from the ideal which inspired the League of Nations Committee on Intellectual Co-operation, Unesco aspires to be the leading international tribune at which thinkers and scientists, of all countries and of all schools, may gain a hearing for their collective views regarding the great challenges facing the consciousness of mankind. Moreover, the time has already come, as I see it, to create within the Organization the permanent instrument for this dialogue. It is hence with pleasure that I announce the creation of a group of scientific advisers, which is due to hold its first meeting at the beginning of 1979.

The second guideline concerns the role of research in scientific work. The present tendency is to limit this role, at least in the choice of fields where research can be carried out, under the pressure of immediate demands deriving from the requirements of technological development within the framework of short- or medium-term production programmes. Admittedly, fundamental and applied research can no longer be dissociated in many fields, but there is a real danger of witnessing an impoverishment of fundamental research and a dwindling of credits – seriously compromising the longer-term future. It suffices to look back to the sources of Einstein's inspiration for us to realize that the majority of his discoveries would have been impossible if he had from the outset set himself utilitarian objectives in his research, if he had been fascinated by anything other than knowledge of the laws of the cosmos. It is hardly necessary to add that today it is as vital as ever, for science, that the area of pure research be preserved and defended.

The third guideline, finally, concerns the teaching of sciences and, in particular, the relationship between teacher and learner, between scientist and layman. Einstein himself described with bitterness the inhibiting, sterilizing conditions of schooling in his time: 'In the school, the main emphasis was placed on the inculcation of obedience and discipline. The pupils were required to stand to attention when addressed by the teacher and were not supposed to speak unless asked a question'. The situation has admittedly improved since then, and the systems are fortunately becoming less rigid; but essential problems remain, concerning, in particular, the special measures needed in order to free the imagination of those pupils with exceptional scientific gifts – and to establish between these pupils and their teachers links which would encourage them to open up new horizons.

But that is not all. Outside the school, university and research institutes, it is the entire intellectual community, it is the population as a whole, that is concerned by the work of ~~men~~ ppl of science. Today it is a fact that most people cannot keep up with the rapid progress of knowledge and many live in ignorance of essential truths. Great numbers of people are deeply conscious of the current breakdown in communication between them and the scientific *élite*. And it is a fact that without some knowledge, however general it may be, of what is happening along the present frontiers of learning, the general public is not only powerless to derive any benefit from the evolution of learning, but is also incapable of influencing the direction of scientific policy. This is a problem to which, as I see it, we shall have to apply ourselves without delay, since it concerns, in the final analysis, one of the foundations of democracy in modern society.

Between the age of Einstein and our own, the ability of society to absorb new, disturbing and revolutionary ideas has profoundly changed. In its time, the theory of relativity was fiercely contested on all scientific fronts.

Nowadays invention and innovation are not only much more warmly welcomed by the scientific community as a whole, but are generally looked for and fostered by society. Scientific research has become the driving force of progress. The danger now threatening it arises less out of incomprehension or intellectual rigidity than from the attempt to subordinate it too closely to technological imperatives.

This reversal of attitudes closely mirrors the fantastic trajectory described in half a century by the human intellect. And among those who have made the most towering contribution to this process, none, without a doubt, occupies a more important place than the son of Ulm and Munich, the old sage of Princeton, in whose memory we are here gathered and who remains, to this day, the only man entitled to say, in all simplicity: 'Newton and I'.

Amadou-Mahtar M'Bow

PART II

SPECIAL PRESENTATIONS

P. A. M. Dirac

Einstein and the Development of Physics

I am very happy to have this opportunity of paying tribute to Einstein. Einstein has had an enormous effect on the development of physics and I would like to try to give you some idea of the nature of this effect.

Einstein was greatly interested in the foundations of physics, in the fundamental laws, and here he revolutionized our way of thinking completely. Before Einstein, people worked just with the ordinary ideas of space and time. They set up structures in this space and time and tried to find the laws governing these structures, just working from the results provided by experiment. Now Einstein had quite a different method of procedure.

Einstein had a fundamental belief that the laws of nature had to be expressible in terms of beautiful equations. That was quite imperative with Einstein. It formed the basis of all his methods of work. Agreement with experiment was not a dominant feature at all in Einstein's work.

His main contributions consisted of his two theories of relativity, the special theory and the general theory. I would like to try to explain how these two theories drastically influenced our lines of thought.

THE SPECIAL THEORY

Let us first take special relativity. One can best understand special relativity as a symmetry principle. It was evident from earliest times that space has a two-dimensional symmetry, referring to the two horizontal directions. But actually there is a three-dimensional symmetry in space; there is the vertical direction which is symmetrical with the two-horizontal directions. I believe it was Newton who first understood this symmetry. Newton showed how there exist basic laws of dynamics which are symmetrical between these three directions of space, and the only reason why the vertical direction appears to us differently from the horizontal directions is because of the gravitational force which is exerted by the earth below us.

We thus had this primitive two-dimensional symmetry which was converted into a three-dimensional symmetry by Newton. The three-dimensional symmetry was then converted into a four-dimensional symmetry by Einstein. Einstein showed how the time dimension was basically symmetrical with relation to the three spatial dimensions.

Now this symmetry is not quite so easy to understand because it involves a departure from the geometry which we have got used to from Euclid. It involves a different kind of geometry in which the velocity of light appears as an absolute quantity. However, this new geometry can be worked out fairly simply. Its basic ideas were formulated by Minkowski and it is usually referred to for that reason as Minkowski space. Einstein had the belief that space with this symmetry was really the dominant space-time of the natural world, and it became necessary to set up physical laws in this space.

The transformations which correspond to making rotations in this four-dimensional space had been worked out previously by Lorentz – they are called Lorentz transformations. Lorentz got these transformations just by working from the equations of the Maxwell theory, the equations which describe electric and magnetic fields. Studying these equations, Lorentz found that they could be transformed in a certain way. But Lorentz considered these transformations only as mathematics and did not really have a proper understanding of their fundamental physical importance. He did not realize the basic four-dimensional symmetry of space-time. This was realized only by Einstein.

Einstein had a quite different approach to the problem, in which he felt a compelling reason to believe in the four-dimensional symmetry. This dominated his whole line of thought.

Poincaré was also working on these transformations and did very much the same as Lorentz. But Poincaré looked upon his work as flowing from experiments and, like Lorentz, did not understand that a fundamental new physical principle was involved. The difference in the attitudes of Lorentz and Poincaré, on the one hand, and Einstein, on the other hand, is shown by their different reactions to experimental results.

These questions were very much under discussion in the year 1905. The best experimenter at that time was Kaufmann. Lorentz had set up a model for the electron, a model which was subject to his transformations and was also therefore in agreement with the four-dimensional symmetry which Einstein required. Lorentz proposed this model to replace the previous model of the electron based on a rigid sphere, called the Abraham model of the electron. Kaufmann did experiments in 1906 to try to decide which model of the electron was correct. Kaufmann reported that the Abraham model was the correct one.

When Lorentz heard this result, he was completely knocked over by it. He said, 'All my work has gone for nothing.' Poincaré just accepted it as a limitation on his scheme of transformations. When Einstein heard the result his reaction was different. Einstein felt that his four-dimensional symmetry was such a beautiful thing mathematically that it just *had* to be correct and, if the experiments gave a different answer, one should just wait and see — maybe there was something wrong with the experiments. So

Einstein was not so much perturbed. He felt a quiet confidence in the correctness of his own point of view and adopted a wait-and-see attitude with regard to the experiments.

The experiments were repeated a few years later, and the later experiments were found to support the Lorentz-Einstein model against the Abraham model. Some years after that, it was noticed that there was a flaw in the apparatus which Kaufmann had been using.

So Einstein had the correct attitude. This attitude is really characteristic of him. It requires that one should place more faith in one's fundamental ideas if they are based on sound beautiful mathematics than one should place on experimental results. Experimenters always overestimate the accuracy of their results and are inclined to make mistakes. One should thus not allow oneself to be too much perturbed by them.

That was the beginning of Einstein's special relativity. As it became accepted, physicists were faced with the problem of putting all physical laws into a form in which they showed the four-dimensional symmetry between the three space dimensions and the time dimension. That was a problem which usually proved to be not very difficult and provided quite an interesting game.

I was a young student at that time and, some time later, I joined in this game. It was possible to do good work and publish a paper, using rather straightforward methods of taking a physical process which was already well explained in terms of the old ideas of space and time, and expressing it in terms of the new four-dimensional symmetry.

I would like to mention in particular the work of Louis de Broglie. De Broglie was led by his study of the Einstein equations to postulate waves associated with particles. These waves appeared to be quite unphysical things: they travelled faster than light. According to Einstein, nothing could travel faster than light and so it would seem that they were just a mathematical fiction and did not correspond to any physical reality.

De Broglie showed that if you take the group velocity connected with these waves, that is to say the velocity of a packet of these waves, the group velocity was less than the velocity of light; it was equal to the velocity of the particle. And if one were to use these waves for the purposes of signalling, it would be the group velocity which is important. The rough statement that nothing can travel faster than light should be refined to the statement that no signal can be transmitted faster than light, and if you use the de Broglie waves for signalling purposes, you find that your signals would not travel faster than light. Thus there would be no contradiction with the basic Einstein idea.

The waves introduced by de Broglie were later on very much developed by Schrödinger and later by Klein and Gordon, and they were found to be very important for explaining quantum effects. Essentially it was Einstein's genius which led to these waves. Einstein's insistence on the importance of this four-dimensional symmetry led de Broglie to think of these waves associated with the particles.

There is another respect in which this theory of Einstein proved to be important. With this new four-dimensional symmetry, one had to develop the whole of mechanics to fit with it. The mechanics of Newton had to be changed. The change led to some surprising conclusions, which had to be accepted.

Take the energy of a particle. The change required by the passage to the Einstein picture leads to the formula that everyone knows, $E = mc^2$. That means there is a large amount of energy associated with each piece of matter. This formula, $E = mc^2$, applies to matter at rest. If the matter is moving, the formula has to be modified to read: $E = \sqrt{m^2c^4 + c^2p^2}$, where p is the momentum of the particle and c is still the velocity of light.

THE GENERAL THEORY

I would now like to move on to say something about the general theory of relativity. Einstein's contributions to this are very different from those of his special relativity. Here, Einstein was working alone. He was not working in conjunction with Lorentz and Poincaré, with equations which other people had obtained. He was working entirely on his own: he had to set up his own equations right from the beginning.

Einstein made a very profound change in the ideas of physicists. Previously to general relativity, there were two essential lines of thought possible with regard to the fundamental laws of nature. One could say that interaction occurs either through a field or action-at-a-distance. Action through a field appears to be the superior point of view in the case of electromagnetic theory because it leads to the prediction of electromagnetic waves. This was quite a definite advantage over the action-at-a-distance view. But for physics in general, one had to take into account also gravitation. Here the situation was not at all clear until Einstein came forward with his new theory of gravitation, which insists on a field theory. It was no longer possible to have action-at-a-distance.

Einstein now changed our whole idea of space. Previously space was considered flat. A new space was introduced with curvature, and this curvature provided a description of the gravitational field.

It was found to work wonderfully well in describing the solar system. It provided small effects by which the Einstein theory differed from the Newtonian theory – small effects concerning the motion of the planets and the deflection of light passing close by the sun. The new theory was always verified.

Now you are forced to accept this formula if you take Newton's laws and modify them to fit Einstein's ideas of the symmetry between space and time. This formula has the feature that there is a square root in front of the expression for the energy. Where there is a square root, it means mathematically that one can take a positive or a negative value, so that the general formula leads to possible negative values for the energy of a particle.

This at first is really hard to understand; one never sees these negative values for the energy. Still, the mathematics insists that they are possible.

To begin with, it was not a physical problem, because one could say that the negative values do not happen to occur in nature and this is why we do not see them. There was a big development in mechanics, however, when the quantum theory was introduced. With the quantum theory, dynamical variables can jump from one value to another, and if one starts off a particle in a state of positive energy it may jump into a state of negative energy. These jumps are predicted by the quantum theory. One can calculate the probability of their happening. Under these conditions, we can no longer just close our eyes to negative values for the energy.

We are then forced to look at them again and to try to find some physical interpretation for them. It turns out that one can find a physical interpretation for them without too much difficulty. They can be interpreted in terms of states of antimatter. So one can say that Einstein's discovery of special relativity leads to the prediction of antimatter. There is a continuous line of argument leading up to antimatter. The real credit for it comes from Einstein's basic mechanical equations, designed to replace the equations of Newton.

I mentioned before the problem of taking the standard equations of physics and putting them into a form which shows the symmetry between space and time required by Einstein's picture. This problem can usually be solved without too much trouble, so long as one keeps to the ideas of classical mechanics. But with the quantum mechanics introduced about 1925 by Heisenberg and by Schrödinger, the situation became different. One was then led to have basic equations of dynamics involving differentiation with respect to the time variable. The time appeared on quite a different footing from the three spatial dimensions. It became a very serious problem to try to restore the four-dimensional symmetry for these equations of quantum mechanics.

It turned out that it was possible to do so in the case of a single particle. However, when one has several particles in interaction, the difficulties are more serious. People tried in a straightforward way to solve this, and were led to equations which were not really sensible equations: when one tried to get solutions to them, one found infinite terms appearing – and that of course was nonsense.

The problem of getting a general quantum mechanics in agreement with the four-dimensional relativity of Einstein, I would say, is still an unsolved problem. A very great deal of work is being done on it but, apart from simple applications dealing essentially with a single particle, the problem is unsolved. Modern physicists have been ingenious in turning a blind eye to the infinities which naturally appear when one goes ahead in a straightforward way, but I feel that this work is basically wrong. It is the kind of work which Einstein would not have liked at all.

But it was a definite advance, and quite a new line of thought, to develop the ideas that we had of space itself. We no longer keep to the flat space of Euclid or as it was modified to four dimensions by Minkowski; one thinks of a curved space. Once mathematicians are set on a new idea like this, they can continue to work on it, introducing more elaborate kinds of curved space.

Einstein himself realized that his space was perhaps not really adequate, because it put such a big difference between the gravitational field and the electromagnetic field. These two fields both involve long-range forces, forces that are inversely proportional to the square of the distance. So it would seem that they should be closely coupled, and the idea naturally suggests itself that some more general kind of space than the one which Einstein originally used would describe the electromagnetic field also. The problem was to find this more general space.

A solution was very soon found by Weyl, which gave some of the equations very nicely, but Weyl's solution was found to be in disagreement with the quantum theory and was abandoned for that reason.

The hunt was on again. Since then, the world's best mathematicians have been trying to find a better space for describing nature than the one originally used by Einstein. Einstein himself spent the rest of his life on that problem, without success. It is still one of the fundamental problems of physics to try to describe a space which will unify the gravitational and electromagnetic fields.

In more recent times, there are other fields which have been discovered which are important in atomic physics for describing the interactions between the particles in the nucleus of an atom. There are new forces, called the strong force and the weak force, so that there are altogether four known forces in physics. One would like to unify all the four.

This is a big problem, and a great deal of work has been done on it. But I don't think the work is altogether along the correct lines. I am rather opposed to this kind of work while the fundamental difficulty that I mentioned previously of reconciling even special relativity with the laws of quantum mechanics remains unsolved.

INDETERMINACY

The laws of quantum mechanics have been very much developed, and they require at their present stage of development an interpretation in terms of probabilities. One cannot calculate just what happens under certain conditions; one can only calculate the probability of a certain event happening.

Physicists have got quite used to this probabilistic interpretation of quantum mechanics. Most physicists are fairly happy with it.

But Einstein was, all along, opposed to it. Einstein felt that the basic laws of physics would have to have the determinism of classical mechanics.

One can understand Einstein's point of view because he had had so much success with his modifications of space. When one has had an enormous amount of success with one particular line of development, one has a tendency to think that one has to go further and further in the same direction to solve all the problems. So Einstein spent the rest of his life working alone these lines. Thus he was hostile to the standard interpretation of quantum mechanics.

This standard interpretation is usually called the Bohr interpretation; it was very much emphasized by Bohr's school in Copenhagen. So there arose a big controversy between Einstein and Bohr. It dominated physics right from the time when quantum mechanics was first expressed in a general form, around 1927.

With regard to this controversy, I would like to emphasize that the Bohr interpretation is the one which you have to accept if you are working with the standard quantum theory. All physicists, who are working on real problems, have to use the Bohr interpretation. However, one may very well believe that the Bohr interpretation is not the last word on the subject.

One can believe this because the equations of the standard quantum mechanics are illogical, in the sense that they lead to infinities when one tries to apply them to particular examples. One has to learn certain rules which effectively turn a blind eye to the infinities. People have learned these rules with a very great thoroughness. They turn a suitably blind eye to the infinities and calculate what is left over, and then get agreement with observation to an extremely high accuracy.

Most physicists are very happy because of this accuracy. But Einstein was not content; he knew about this great accuracy, but he felt that the theory was basically wrong and that no really big advance could be made in physics on these lines.

I am inclined rather to agree with Einstein, with respect to this controversy. I think that Einstein might turn out to be correct in the end, although one will not be able to assert it until one has obtained a better quantum mechanics than we have at the present time. Such a better quantum mechanics will have to differ in its foundations from the present quantum mechanics.

In conclusion, I would like to emphasize the new point of view which Einstein introduced, namely, that it is imperative to have great beauty in one's basic equations. Einstein introduced this and has had more influence than anyone else in emphasizing the importance of the great beauty of the basic equations.

You might ask, 'Why should the equations have this great beauty?' We cannot give a definite answer to that. We can say that it is a principle which has been extremely successful, especially successful in the hands of Einstein. One must accept that God made the world like this. He has provided a challenge to us to find the mathematics which underlies physics. We should realize that of course this problem is not yet solved and that all the faults, the blemishes, in the present theory should be ascribed to imperfections in it. They are what we should study and try to eliminate.

Abdus Salam

Einstein's Last Dream: The Space-Time Unification of Fundamental Forces

Professor Dirac has given us a beautiful survey of Einstein's work. I shall touch on just the last part of his survey and speak of Einstein's last dream – to which he devoted half of his working life. This is a dream which continues to inspire the present generation of physicists, by the work done since Einstein's death. The dream is the dream of unification of the fundamental forces of nature.

From earliest times, man has tried to understand the complexity of nature in terms of as few fundamental concepts as possible. So far as physics is concerned, this unification, while an ideal, has been achieved successfully only a few times. Among the few unifiers over the centuries, Einstein stands absolutely supreme.

The first name that occurs to us in physics as that of one of the great unifiers is Al-Biruni, in the 11th century. He stated that the laws of physics are universal, here on earth and in the rest of the universe. The same theme was later taken up independently and forcefully by Galileo, towards the end of the 16th century. By observing the shadows cast by the mountains on the moon, through his telescope, Galileo experimentally showed the unity of laws governing phenomena on earth with those on the moon.

The next great unification was that of Newton, a hundred years after Galileo. Newton recognized that the force which makes the apple fall on earth is the same force that keeps the earth circling round the sun. Newton unified terrestrial gravity with celestial gravity.

Two hundred years elapsed. Then Maxwell, the hundredth anniversary of whose death falls in November 1979, accomplished one of the greatest unifications in human knowledge. Building on the ideas of Faraday, he unified the forces of electricity and magnetism. We all know that if we take a solenoid and move a magnet through it, a current is produced, and conversely a current passing through a solenoid can produce a magnetic force in the space around it. One consequence of this unifying work of Maxwell was the discovery and the drawing together of the phenomena of light, radiant heat, X-rays and radio waves.

Thus, at Maxwell's death, physics recognized two fundamental forces: Newton's gravity and Maxwell's electromagnetism. A further synthesis occurred in the early part of this century. With the coming of quantum theory, through Dirac and his contemporaries, it was realized that the force which keeps atoms together, as well as the chemical force which binds them together as a molecule, is nothing but another manifestation of electromagnetism. Electromagnetism, then, is also the force which governs all the phenomena of life.

In Dirac's lecture, we heard of Einstein's unification of space and time in his theory of special relativity. It was this unification which led inevitably to the recognition that mass and energy represent different aspects of the same entity ($E = mc^2$). But Einstein did not stop there. In his general theory of relativity, Einstein endowed space-time with dynamical properties. As a consequence, he could comprehend Newton's gravity as a manifestation of the curvature of space and time. This unification of a fundamental force (gravity) and its comprehension as an aspect of the properties of space-time certainly remains perhaps one of the greatest achievements of human thought.

In our day, dramatic experimental confirmation of these ideas of the dynamical role of space and time in making a theory of the universe has come in the form of the discovery of 3° Kelvin radiation (microwave background of radiation), signalling the beginning of space-time. A second and related confirmation of Einstein's ideas is the expansion of the universe, which is manifested by the red-shift of the stars.

As I said, these are high achievements, but Einstein was not content with them. His dream from 1919 onward, pursued with unrelenting devotion, was to try to unite the two forces of gravity and magnetism in a single whole, so that one could understand the two as facets of the same entity. Since he had already accomplished an understanding of Newtonian gravity as a property of space-time, a unified gravity and electromagnetic force would then also be understood as representing a still more comprehensive aspect of space-time curvature. He derived thus a triple unification: gravity with electromagnetism with space-time.

As we heard from Dirac, Einstein, particularly around 1919, was not so aware of nuclear forces. These have acquired an enhanced importance in the work of the physicists since Einstein's time. We know now that there are two types of nuclear force, the weak nuclear force which helps to make heavy elements (like carbon, iron, uranium) from primordial hydrogen, and the strong nuclear force responsible for fission and fusion and for making stars shine. Thus physics today recognizes four basic forces: gravity (Newton and Einstein); electromagnetism (Maxwell); the weak nuclear force; and the strong nuclear force.

The question then arose: how are we to reformulate the vision of Einstein which sought to unite two of these forces (gravity and electromagnetism) in order that the final unification embraces the totality of the four forces? This has been the problem which has faced our generation.

The problem has been simultaneously worked upon in Europe and the United States during the last decade. It has been suggested that electromagnetism and the weak nuclear force resemble one another closely and the unification of these two will be observed, first, in terms of the energies with which we experiment. Then will come the unification of this new force, which one might call the electroweak force, with the strong nuclear force. Finally will come a unification of this electronuclear force with gravity.

Although the suggestion was made in the last decade, the first indication that this suggestion might be correct, came from the great nuclear accelerator laboratory of the European Organization for Nuclear Research (CERN) in Geneva, in 1973. The second crucial experiment, which appears to clinch the unification of the weak electromagnetic forces, came in June 1978 from the Stanford Linear Accelerator Laboratory in the United States. In this experiment, polarized electrons were scattered off heavy water. If the two forces – the weak and the electromagnetic – are indeed facets of the same fundamental force, then in phenomena that one traditionally ascribes to electromagnetism there should be observed traces of the weak force. These traces were searched for at a level hitherto experimentally never attempted – one part in ten thousand – and they were found: just as the theory had predicted.

This is, of course, indirect evidence. There should also be direct evidence for the unification of the two forces. This direct evidence would consist of making quanta of the weak force similar to the quanta of the electromagnetic force (the familiar particles of light – the photons). The quanta of the weak force have been called heavy photons. It has been predicted what the mass of these quanta should be, and the CERN laboratory is preparing to try to see if it can produce these heavy quanta around 1982. The same attempt will be made with the new accelerator at the Brookhaven National Laboratory, U.K., in 1986 and at Serpukhov in the U.S.S.R. in 1988.

For experimenting with these particles, one will need a new accelerator, one which is being projected for CERN for 1990. The fact that electromagnetism is a long-range force, while weak forces are short in range, is ascribed to the epoch in which we happen to live. From evidence gathered observing the red shift, we believe that the universe is now 10^{10} years old. If we were observing it one-tenth of a second after its birth, we would find both forces – electromagnetic and weak – to be long-range forces, with no distinction between them.

To summarize, this unification – whose indirect evidence we already possess and whose direct evidence is awaited – is in line with the inspiration given to us by Einstein. The questions arise: What about the strong nuclear force? Does this also combine with the electroweak? Suggestions have already been advanced as to how to check on this. One only needs 10,000 tons of water, shielded one mile deep in a cave. Then surround the system in the cave with photo-multipliers. There will be one tiny burst of light once a year, amplified by the photo-multipliers. *If* this happens, it will be the indication that the strong nuclear force is the same as the weak or the electromagnetic. These three forces will have united into one – the electronuclear force.

To summarize again, the vision of Einstein which has inspired all this work goes like this. At the beginning of the Seventies, we knew four forces of nature: electromagnetic, weak nuclear, strong nuclear and gravitational. We already have indirect evidence for the electromagnetic and the weak being unified into one, single force. We may be fortunate to acquire evidence, perhaps in a few years, for the unification of the electroweak with the strong. And at that stage we shall line up with Einstein directly. It is this force which might unite with gravity into one super-unified force which would have its deeper basis, according to Einstein's vision, within the geometry of space and time.

What can this deeper basis be? Einstein taught us that gravity is the manifestation of the curvature of space-time. What property of space-time could the electronuclear force manifest? There are two rival suggestions. Perhaps the electronuclear force is connected with the topological structure of space and time in smallness; it tells us of the granular structure of space and time, of wormholes and other topological characterizations. A second suggestion is that the electronuclear pertains to extra dimensions of space and time far beyond the four that we are conscious of.

These are problems which I am sure the physics of the twenty-first century will be grappling with. But whatever ideas prove correct and win through in the end, it will always be recognized that the grand vision and its inspiration were Einstein's.

Before I conclude, I wish to take up another thought which I would like to share with you. Unquestionably, there has been no one like Einstein in physics in this century, but one has to reflect on how easily Einstein might have been lost, particularly if he had been born in a developing country. At the age of sixteen and a half, Einstein wanted to enter the Zurich Polytechnic. He took the entrance examination for engineering and (very fortunately for physics) failed. A year later he succeeded, entering to study physics this time, and graduating in the year 1900. Like every good student, he sought a university position. He failed in this effort, 'for I was not in the good graces of my former teachers.' Einstein maintained himself by finding temporary jobs, doing private tutoring at three Swiss francs an hour, teaching school.

In November 1901, he submitted a research paper as thesis for his doctorate. A doctorate was the necessary passport for university teaching. Zurich University rejected the thesis. According to Banesh Hoffmann, Einstein's assistant, collaborator and biographer, this rejection combined with his joblessness made Einstein feel that he was sinking hopelessly in a world having no place for him.

An episode during 1901 further illustrates this. In that year Einstein sent a copy of his first paper to Professor Wilhelm Ostwald, later a Nobel laureate, together with a letter which said, 'Since I was inspired by your book on general chemistry, I am taking the liberty of sending you a copy of my paper . . . I venture also to ask you whether perhaps you might have use for a mathematical physicist, for I am without means.' There was no reply.

At this stage Einstein's father, an unsuccessful merchant in ill health, a stranger to the academic community, took it upon himself to write to Ostwald. Here is his letter: 'I beg you to excuse a father who dares to approach you, dear Professor, in the interest of his son . . . My son, Albert Einstein, is 22 years old. Everyone who is able to judge praises his talent . . . My son is profoundly unhappy, and every day the idea becomes more fully implanted in him that he is a failure in his career. Because, dear Professor, my son honours and reveres you, I request that you read his article, and hopefully write him a few lines of encouragement so that he may regain his joy in life and in his work.' There was no reply.

Eventually in 1902, Einstein did secure a job, at the Swiss Patent Office as a probationary technical expert, third-class. There, in 1905, as is well known, Einstein produced two of his revolutionary papers. But before these, he was still without the precious Ph.D. 'I shall not become a Ph.D., the whole comedy has become a bore to me'. This he wrote in 1905 after a second attempt at the degree, which also failed. A third attempt, the same year, succeeded, but by then he did not need doctorates. He had become world famous.

I have related this story in detail for the simple reason that every one of the discouragements that Einstein suffered from are a norm for a scientist in a developing country. If what I have related can happen in one of the most developed countries on earth, think what can and does happen in the developing parts of the world.

As a second thought, let me ask another question. Would an Einstein – with his total commitment to science for its own sake – fare any better in the climate of today, even in a developed country? According to Einstein, 'My scientific work is motivated by an irresistible longing to understand the secrets of nature and by no other feeling. My love for justice and striving to contribute towards the improvement of the human condition are quite independent from my scientific interests.' In March of this year, at the Berne conference celebrating Einstein's birthday, Professor Lüst, president of the Max Planck Society, after reading this quotation from Einstein, made the following pertinent comment: 'Einstein's words may sound strange to the ears of those who are responsible for science policy all over the world today, looking for social relevance, immediate applicability, and cost-benefit analysis in supporting scientific research.'

While I rejoice that Unesco, representing the world community of culture and scholarship, is celebrating Einstein's birthday in such a befitting manner, I hope – and I am sure – that Unesco will not forget Einstein's words regarding the preciousness of research for knowledge for its own sake. Nor, I am sure, will Unesco forget the comments of Professor Lüst, when Unesco's counsels are sought on science policy, particularly for developing countries.

Amadou-Mahtar M'Bow

Einstein: Man of Peace

The one hundredth anniversary of the birth of Albert Einstein offers an opportunity for us all to pay a solemn tribute to the memory of a man whose thinking has influenced his century so deeply that the life of every one of us has been modified by it in one way or another.

Looking back on man's voyage of discovery of the secrets of the universe, as far as its oldest known traces – carved in stone or sculptured in wood, written on papyrus or drawn on the walls of grottoes – we see few names whose glory equals his among the names of those who, having begun by examining the questions at issue in their day, finally apprehended one of those great truths which transcend the boundaries of time and which are the source of increasing knowledge, of constantly renewed meaning.

What such thinkers did was much more than to formulate an idea or elaborate a theory already dimly discerned by their contemporaries. They opened up to human intelligence a new domain whose originality met no particular need and which, had it not been for them, might have remained hidden for ever in the mists of the potential. Their discoveries are not the fruit of a mere accumulation of facts drawn from experience, but involve a measure of intuition, a leap in the dark, the flash of inspiration through which the mind suddenly penetrates one of the mysteries of the world.

This is why they are not subject to the laws of historical gravitation, according to which the work of the average man remains valid for only a limited specific time. This is why they are always in advance of questions we ask several centuries after they have died, and always will be so.

The reason for the prominence of Albert Einstein in the history of science, is that he was not content to add one or two facts to our knowledge of the world, but reorganized the whole field of our knowledge and reconstructed it, adding to it a new dimension. And the quintessence of his imagination is perhaps to be found above all in his ability to see the connection between concepts which until then had been thought incompatible or contradictory, to restructure the field of physics by bringing increasing coherence and harmony into it.

In the last analysis, what he revealed to us was not a particular property of matter; it was the relation between space and time, which he makes us think of in a way we are not used to, upsetting some of the most basic and everyday notions of our lives.

However, the paradoxical force of discoveries of this kind is such that their first effect is to reduce the validity of what we had previously considered as established fact. Thereafter, they open up a whole new horizon to our wondering eyes. Three quarters of a century after the famous articles by Einstein were published in the *Annalen der Physik*, and sixty years after the publication of his general theory of relativity, his hypotheses continue to inspire the most daring research.

As we all know, Einstein was not only a very great scientist. There was in him a man of freedom and peace, who gradually showed himself to be of the same stature as the man of science, and who led the latter, as it were, to sponsor Unesco, after having been a member of the International Committee for Intellectual Co-operation set up by the League of Nations.

After the Second World War, he wrote in the December 1951 issue of the Unesco Courier:

A world federation presupposes a new kind of loyalty on the part of man, a sense of responsibility that does not stop short at the national boundaries. To be truly effective, such loyalty must embrace more than purely political issues. Understanding among different cultural groups, mutual economic and cultural aid are the necessary conditions. Only by such endeavours will the feeling of confidence be established that was lost owing to the psychological effect of the wars and sapped by the narrow philosophy of militarism and power politics. No effective institution for the collective security of nations is possible without understanding and a measure of reciprocal confidence.

This man, who was keenly aware of the necessity of natural laws, was moved by an equally strong passion for human freedom. On the one hand, there was the systematic effort to discover the hidden order of things, leaving no margin for uncertainty and, on the other, the systematic defence of the creative genius of man against all forms of servitude. It is because he was convinced that this freedom, and it alone, could uncover the secrets of the universe that he never dissociated the adventure of the mind from that of the emancipation of man.

He fought to his last days for disarmament, especially nuclear disarmanent. And he passionately defended the idea of conferring on the United Nations the prerogatives of a supranational system, the only system, in his view, which could establish and administer a just and lasting peace.

He always considered such peace from the most positive viewpoint, not merely as the suspension of hostilities, but as the extirpation of their causes, as a new state of mutual tolerance and respect among peoples which would at last replace the logic of power relations and confrontations.

Then again, Einstein reflected at length on the problems of education, which he considered to be of fundamental importance in the life of society. Having himself suffered the disadvantages of a cramped and pedantic school system, he reflected upon the conditions required for a new kind of education, in which the creative spirit of the child would awaken as he absorbed facts and acquired standards.

He held that it was for the educational system to search out, discern and develop the abilities of every person, for the benefit of the individual and also of society. Thus Unesco pays tribute to Einstein as to a forerunner; it is doing so in a formal meeting which has brought together an eminent group of personalities, and in a three-day consultative meeting* for the purpose of ensuring progress in scientific co-operation for peace. These meetings reflect those aspects of the life of Einstein from which we could learn something of value for our work in the future, which have been developed in the presentation at Munich. They concern particularly the scientist's place in society, and the consideration that those responsible for world affairs should give his ideas; the importance given to basic research, which must go hand in hand with applied research for each is of benefit to the other; and, finally, the relation both between the teacher and the pupil, and between the scientist and the lay public, through which the people of a country can acquire the ability to exert an influence, in full knowledge of the facts, on the direction taken by its scientific policy.

* 'New perspectives in international scientific and technological co-operation: UNCSTD and beyond', Unesco, Paris, 8–10 May, 1979.

PART III

INTRODUCTORY LECTURES

P. A. M. Dirac

The Excellence of Einstein's Theory of Gravitation

Einstein gave us a new theory of gravitation connected with the curvature of space. He started a whole new line of activity for physicists. He set them working with non-Euclidean space. The particular kind of space that Einstein introduced was Riemann space, a space that can be embedded in a flat space of a larger number of dimensions. Under the stimulus of Einstein various people have considered introducing other kinds of space into physics, but so far without any real success. So far as is known at present, the space introduced by Einstein is the one used by nature.

Einstein's theory of relativity remained unknown, except to a few specialists, until the end of 1918, when the First World War came to an end. It then came in with a terrific impact. It presented the world with a new style of thinking, a new philosophy.

It came at a time when everyone was sick of the war, those who had won as well as those who had lost. People wanted something new. Relativity provided just what was wanted and was seized upon by the general public and became the central topic of conversation. It allowed people to forget for a time the horrors of the war they had come through.

Innumerable articles about relativity were written in newspapers, magazines and everywhere. Never before or since has a scientific idea aroused so much and such widespread interest. Most of what was said or written referred to general philosophical ideas and did not have the precision required for serious scientific discussion. Very little precise information was available. But still people were happy just to expound their views.

I was an engineering student at Bristol University at the time, and of course the students took up this subject and discussed it extensively among themselves. But the students as well as the professors did not have precise information about it and knew nothing of the underlying mathematics. We could only talk about the philosophical implications and accept the universal belief that it was a good theory.

In England we had one man, A. S. Eddington, who really understood relativity and became the leader and the authority on the subject. He was very much concerned with the astronomical consequences of the theory and the possibilities of checking it by observations. There were three possibilities for testing the theory, which everyone soon became familiar with from the publicity given by Eddington.

Test number 1 involves the planet Mercury. It had been known for a long time that there was a discrepancy between the motion of this planet and the Newtonian theory. Its perihelion was observed to be precessing by the amount of 42″ of arc per century, which could not be explained by the Newtonian theory. The Einstein theory required such a precession and gave the correct amount, 42″ per century. It was a wonderful success for the theory. It is said that Einstein himself was not unduly elated when he heard of this success. He was so confident that his theory had to be right.

The Einstein theory of gravitation requires that light passing close by the sun shall be deflected. The Newtonian theory also requires a deflection, but only half the amount of the Einstein theory. So by observing stars on the far side of the sun, whose light has passed close to the sun to reach us, we can test the Einstein theory. This is test number 2.

The observations can be carried out only at a time of a total eclipse of the sun, otherwise the sun's light makes it impossible to see the stars. There was a suitable eclipse in 1919. Two expeditions were sent out to observe it, both organized by Eddington, and one led by Eddington. Both expeditions obtained results supporting the Einstein theory and against the Newtonian theory. The accuracy of the confirmation was only moderate owing to the inherent difficulty of the observations. Since then similar observations have been made at various later total eclipses. Einstein's theory has always been confirmed, although the accuracy has not been as great as one would desire.

The discovery of radio stars provided an alternative way of checking on test number 2, using radio waves instead of light waves. One needs a radio source behind the sun. One just has to wait until the sun passes close in front of a radio star and then observe whether the apparent position of the star is deflected. One does not need a total eclipse for such observations, as the sun is not a strong radio source.

The use of radio waves instead of light waves brings in a complication because radio waves are deflected by the sun's corona. But one can make observations for two different wavelengths, for which the deflection caused by the corona is different, so that it can be separated from the Einstein effect. The result is that the Einstein theory is confirmed, with an accuracy much greater than that attainable with light waves.

The third effect which provides a means of testing the Einstein theory is the red-shift of spectral lines caused by a gravitational potential at their point of origin. The obvious place to look for this effect is in light from the surface of the sun. But the effect here is obscured by the Doppler effect coming from motion of the emitting matter. By estimating the Doppler effect one gets rough support for the Einstein theory, but it is too rough to be an effective test.

The discovery of white dwarf stars provides a better way of testing for this effect. In a white dwarf the matter is so highly condensed that the gravitational potential at the surface is very large, and so the Einstein red-shift is large. When one knows enough about the white dwarf to determine its mass and radius one can make a good test of the Einstein theory. One finds that the theory is well confirmed.

This effect can also be checked by terrestrial experiments, as was shown by R. L. Mössbauer. One sets up in the laboratory an emitter of electromagnetic waves and observes them at a place lower than the place of emission, where the gravitational potential is less. It is best to use γ-rays of a definite frequency for this experiment. One finds that the frequency is increased by the change in gravitational potential. The amount of this increase confirms the Einstein theory, with an accuracy greater than any astronomical test for this effect.

Recently a fourth test has been added to the three classical ones. This is concerned with the time taken by light to pass close by the sun. The Einstein theory requires a delay. This can be observed if one projects radar waves to a planet on the far side of the sun, and then observes the time taken for the reflected waves to get back to earth. With the use of radar waves the retardation is affected by the sun's corona and again one has to use two different wavelengths to disentangle the corona effect from the Einstein effect. The observations have been carried out by I. I. Shapiro and he gets good confirmation of the Einstein theory.

One can also get evidence about the Einstein theory from the observation of binary pulsars. A pulsar emits pulses of radio waves which normally have extremely high regularity. However if the pulsar forms part of a binary system, its rotation around the other star introduces irregularities, coming from the Doppler effect associated with its motion and also from the Einstein precession effect, like the effect in test number 1, in the orbit of the pulsar around its companion. This effect is very large, much larger than in the case of Mercury.

The observations give qualitative support to the Einstein theory, but one cannot make a quantitative check because one does not know enough about the parameters of the binary system.

I have enumerated the successes of the Einstein theory of gravitation. It is a long list, quite impressive. In every case the Einstein theory is confirmed, with greater or lesser accuracy depending on the precision with which the observations can be made and the uncertainties that they involve.

Let us now face the question, suppose a discrepancy had appeared, well confirmed and substantiated, between the theory and observations. How should one react to it? How would Einstein himself have reacted to it? Should one then consider the theory to be basically wrong?

I would say that the answer to the last question is emphatically *no*. The Einstein theory of gravitation has a character of excellence of its own. Anyone who appreciates the fundamental harmony connecting the way nature runs and general mathematical principles must feel that a theory with the beauty and elegance of Einstein's theory *has* to be substantially correct. If a discrepancy should appear in some application of the theory, it must be caused by some secondary feature relating to this application which has not been adequately taken into account, and not by a failure of the general principles of the theory. One has a great confidence in the theory arising from its great beauty, quite independent of its detailed successes. It must have been such confidence in the essential beauty of the mathematical description of nature which inspired Einstein in his quest for a theory of gravitation.

When Einstein was working on building up his theory of gravitation he was not trying to account for some results of observations. Far from it. His entire procedure was to search for a beautiful theory, a theory of a type that nature would choose. Of course it needs real genius to be able to imagine what nature should be like, just from abstract thinking about it. Einstein was able to do it.

Somehow he got the idea of connecting gravitation with the curvature of space. He was able to develop a mathematical scheme incorporating this idea. He was guided only by consideration of the beauty of the equations. Of course one is free to choose equations as one likes, subject only to the rigours of the mathematics, but these set a strong limitation on one's freedom.

The result of such a procedure is a theory of great simplicity and elegance in its basic ideas. One has an overpowering belief that its foundations must be correct quite independently of its agreement with observation. If a discrepancy should turn up, one cannot let it interfere with one's confidence in the correctness of the general scheme. One must ascribe it to some detail of the nature of an incompleteness rather than a failure.

Any theory that we can construct is probably incomplete. There is so much that is still unknown. So one need not be too much disturbed by a discrepancy. It should not be considered as detracting from the excellence of a theory that has been put forward on the basis of an inspired feeling of what nature is like.

I can illustrate these remarks by referring to another important physical discovery of recent times, Schrödinger's discovery of the wave equation of quantum mechanics. Schrödinger was working with de Broglie waves, the waves which de Broglie had postulated, simply on grounds of mathematical beauty, as being associated with the motion of any material particle. Schrödinger generalized the idea so as to obtain an elegant equation for waves associated with an electron moving in an electromagnetic field. He applied his equation to the electron in a hydrogen atom and worked out the spectrum of hydrogen. The result was not in agreement with observation.

Schrödinger was then very dejected. He lacked faith in the excellence of his basic ideas and assumed his whole line of approach was wrong. He then abandoned it. Only some months later did he recover from his dejection sufficiently to go back to this work. He then noticed that his theory was in agreement with observation in the approximation in which one neglects effects associated with the special theory of relativity, and he published his equation as a non-relativistic theory of the hydrogen atom.

The discrepancy was later on explained as arising from the spin of the electron, which was unknown at the time Schrödinger did his pioneering work. The moral of the story is that one should be dominated by considerations of mathematical beauty and not be too much perturbed by discrepancies with observation. They may very well be caused by secondary effects which get explained later.

A discrepancy with the Einstein theory of gravitation has not yet arisen, but it may arise in the future. It should then be interpreted, not in terms of the basic ideas being wrong, but as a need to supplement the theory with further developments in it.

There are two directions in which such further developments may be needed: (a) the method by which electromagnetic fields are brought into the theory; (b) cosmological requirements affecting the conditions at great distances in any application of the equations. Einstein himself was well aware of these problems.

There is an obvious way of applying the standard equations of electromagnetic theory to a Riemann space so that they can be fitted in with Einstein's theory of gravitation. But does the resulting theory really apply to nature? One has doubt about it because it leaves the electromagnetic field as something detached, which is only added on afterwards. The gravitational field and the electromagnetic field are the only fields with long-range forces and one is led to believe that the connection between them must be very intimate. Maybe one of them cannot be conceived without the other and one needs a more general kind of geometry that handles both together. Einstein himself had ideas of this kind and spent decades looking for an improved field theory that would unify gravitation and electromagnetism. He did not find a satisfactory result and the problem of (a) must be considered as still unsolved.

With regard to (b) one can make some progress. One needs a cosmological model for the universe, applicable when one considers local irregularities associated with the existence of stars and galaxies to be smoothed out.

A model was soon provided by Einstein himself, call it model 1. Einstein's model gave a static universe of uniform density, closed in spatial directions. It required a constant, the cosmological constant, to be brought into the field equations. It was not an acceptable model because of its static character, which conflicted with the observations that the galaxies are receding from us, with velocities that increase as their distance from us increases.

A second model was provided by de Sitter, model 2. De Sitter's model does lead to a recession of distant matter, as required by observation. It also involves a cosmological constant in the field equations. However, de Sitter's model gives zero density of matter in the smoothed-out universe, so it is not acceptable.

A third model was proposed jointly by Einstein and de Sitter in 1932, model 3. This model involves the line element

$$\text{(1)} \qquad ds^2 = dt^2 - t^{4/3}(dx^2 + dy^2 + dz^2).$$

It requires no cosmological constant. It gives correctly the recession of distant matter, and it gives the correct order of magnitude for the density of matter. It also gives zero for the pressure, which is what one would require with the approximations involved in this kind of a model. It is thus an acceptable model.

Various other models consistent with Einstein's field equations, with or without a cosmological constant, have been worked out by Friedman, Lemaître and others. One may use any of these models as a supplement to Einstein's field equations to fix the conditions at $r = \infty$. The changes that they would give rise to in the applications of Einstein's equations to the solar system would be too small to affect the successes discussed earlier.

There is a development which I would like to bring to your attention as a supplement to the Einstein theory. This is the Large Numbers Hypothesis (LNH) which asserts that all the very large numbers that can be constructed from the various 'constants' of physics and astronomy are really not constant, but are connected with the epoch, the time since the creation of the universe, by simple equations with coefficients close to unity. They are thus varying with the epoch, according to a law which is determined by their size.

If one adopts this LNH, one finds that the only permitted cosmological model is model 3 above. One is no longer bothered by having many acceptable alternatives.

The microwave radiation that is observed to be coming from space uniformly in all directions and that is interpreted as the remains of a primordial fireball agrees with the LNH when combined with model 3. It provides strong evidence in favour of both the LNH and model 3.

The LNH leads to the requirement that the $\mathrm{d}s$ of Einstein's theory, call it $\mathrm{d}s_E$, is not the same as the $\mathrm{d}s$ measured by atomic clocks, call is $\mathrm{d}s_A$. They are related by

$$(2) \qquad \mathrm{d}s_E = t_A \, \mathrm{d}s_A,$$

where t_A is the epoch as measured by an atomic clock. This is an effect which can be checked by observation. Van Flandern has been searching for this effect for some years, comparing observations of the moon referred to ephemeris time with observations referred to atomic time, but he has not yet got a reliable result.

Some evidence on this question has recently been obtained from lunar laser ranging carried out by Williams, Sinclair and Yoder. Their results provide weak confirmation of (2), but the uncertainties are too large for one to be able to draw any definite conclusions.

The equation (2) can also be tested by radar observations of the planets. Here one sends radar waves to one of the nearer planets and observes the waves that are reflected back to earth. The time taken for the journey to and fro is then measured with an atomic clock. Shapiro and Reasenberg have been working on this method. They obtain results agreeing with equation (2), but the confirmation is only a weak one because the probable errors in the results of the observations are about as large as the effects being sought for.

With the Viking expedition to Mars in 1976 some apparatus was landed on Mars which enables the distance of Mars from earth to be monitored with very great accuracy. This will enable one to get a much better check of equation (2). The results are not yet available, but will probably come soon.

I have discussed a possible way of supplementing the Einstein theory, by adding to it the LNH. There is as yet no direct confirmation of it by observation. But I feel confident in the basic correctness of the idea because of its simplicity and the natural way in which it fills a gap by providing a unique cosmological model.

P. L. Kapitza

The Impact of Modern Scientific Ideas on Society*

The theme of our discussion is interesting in that it concerns the scientific basis of the structure and working of our society. Today, I am attracted most of all by global problems whose practical solution is directly relevant to the social structure of society, and I propose to speak about the role of science in this connection.

Science's leading role in our civilization is now, of course, universally recognized. Science has even been described – and probably rightly so – as a productive force. History has invariably shown that practically every major scientific discovery or theory has an effect on the development of our civilization.

The following examples illustrate this particularly clearly. Although seemingly limited in scope and not leading initially to any major results, the discoveries made over the past two centuries concerning electricity by Franklin, Galvani, Ørsted and Faraday, and the theoretical description of those discoveries accomplished by Maxwell, have led to today's electrical technology, on which the everyday operation and industrial production of our modern society are largely based.

The role of science can be seen no less clearly when we consider radioactivity, discovered by Becquerel in 1896. His discovery was at first regarded as a curious but fairly insignificant phenomenon

* Distributed in printed form owing to the author's absence.

of nature. Research carried out by Curie and Rutherford showed that this phenomenon was of fundamental importance and was connected with the processes that take place in the nuclei of atoms. Less than a hundred years have passed since these discoveries, yet they have already given man his mightiest source of energy – to which we now look for a solution to the universal crisis caused by the depletion of energy resources. Nuclear energy, moreover, has also put into man's hands a weapon of such destructive force that fear of its possible use has compelled States to revise radically their attitude towards armed conflicts.

The link between scientific discoveries and their practical application is rather unpredictable and unexpected, as is well illustrated by a single, remarkable example of Einstein's endeavours. I am referring to his work on induced radiation, published in 1916 [1]. I think I am right in saying that of all Einstein's major works this publication attracted least notice, and yet its practical value is now unquestionable.

The modern laser, which today plays an important part in both science and various practical fields, is based – as we all know – on the phenomenon of stimulated emission; its basic theory was provided by Einstein as early as 1916 in the above-mentioned work. Scientific experimental technique was sufficiently advanced at that time for the laser to have been built then, and yet it was not developed until the 1960s. The examples I have given thus show that science advances practice only when there exists a close interrelationship between theory and experiment. The separation of theory from experience is what causes the time lag in the introduction of a scientific discovery into practical life.

Speaking about the role of science, it occurs to me that perhaps I should clarify more precisely what science really is, for it seems to me that these days matters that in no way constitute science are often called science to improve their image.

The concept of science goes back to ancient Greece, but its modern meaning emerged only in the sixteenth century. I believe that, in broad outline, the meaning of the term 'science' can be clarified as follows.

It is well known that human beings, unlike animals, shape their own well-being, remoulding nature rather than adapting to it as the rest of the animal world does. As this has always been done collectively it has given rise to the State. At the basis of evolution, guided by 'the wisdom of nature', lies the trial-and-error method, in which experiences that prove to be in keeping with the requirements of the species continue to develop. This is what is meant by the law of natural selection. It is how our natural environment was formed and how man was formed – but it took millions of years to form man.

Man also began to use the trial-and-error method in reshaping nature. But the essential factor to ensure the effectiveness of this process consists in not repeating mistakes and in forming generalized theories from empirically discovered knowledge.

Thus the process of social succession for man came into being – a process that was able to operate effectively given the opportunity for wide dissemination and preservation of the experience transmitted from generation to generation. At first, this was accomplished through the establishment of traditions; it was assisted to a significant degree by the rites that were developed by religion. The written word certainly contributed greatly to the preservation of accumulated experience and the wider dissemination of profitable experience. The process of social succession that had been formed by experimental trial-and-error began to exert a stronger influence on the development of civilization once it had acquired the form we now call *science*. Perhaps it is no accident that we trace the origin of modern science to the time when printing was widely introduced.

Religion at first played a progressive role, summing up elements of acquired experience, but – unlike science – it lacked objectivity in its analysis of positive tests and did not evolve due to its dogmatic approach.

With the trial-and-error method, acquired experience becomes scientific when it is interpreted in accordance with the law of causality, i.e. that a given cause always produces a given effect and that every problem therefore admits of only one solution. This is what constitutes the fundamental characteristic of scientific analysis: its objectivity renders it universal, and therein lies the essential difference between it and religion.

Hence the only interpretation of empirical facts that may be considered scientific is one that is objective and universally recognized.

It is a well-known fact that religion is capable of a blithe disregard for the laws of causality and consequently provides answers to problems that can have no scientific solution, such as the creation of the world, free will, the existence of a divine force and so on. This is why it is possible for many different religions to exist, whereas science – like the multiplication table – is unique.

Science began to acquire an influence as an independent field in the organization of society at the time of the Renaissance. The clearest statement of the nature of scientific analysis and of its significance at that time was given by Francis Bacon, who held that empirical data obtained by observation for use in science are analysed by means of the logical methods of induction and deduction. The role of dialectics in the development of science was demonstrated later, beginning with Hegel and Kant. Bacon gave a most picturesque illustration of the importance of scientific cognition of nature as the most effective way of solving practical problems: 'A lame cripple going along the right road can overtake a trotter if the latter is running along the wrong road. Moreover, the faster the trotter runs, once having lost the path, the further he lags behind the cripple'. Bacon prophetically described the social significance of science in his *New Atlantis*, in which he painted a Utopian picture of a State structure organized on a scientific basis.

It was then that differences between religion and science became acutely apparent in the clash between the teachings of the Church and the scientific concepts of Copernicus and Galileo on the question of the structure of the universe.

The reason for these conflicting descriptions is now perfectly clear: it lies in the fact that on one and the same question – for example, the description of the world – science came up with an answer that differed from the mythological picture accepted by religion. The scientific explanation was based exclusively on the objective laws of mechanics as established by Galileo and subjected to theoretical analysis by Newton. The universe as described by Copernicus did not correspond to the picture presented in the Bible and accepted by the Catholic Church. Such defiance undermined the authority of the Church, on which the social structure of the time was based and which ensured the stability of the foundations on which the ruling power rested. This opposition between science and religion not only retarded the development of science but frequently took a tragic turn that cost a scientist his life – as in the case of Giordano Bruno, who perished at the stake.

The opposition between science and religion has continued to this day. Naturally, it does not take such an acute form as it did with Galileo and Copernicus but, as recently as the last century, it reached a heated pitch when Darwin proclaimed his theory of the origins of animal species as having evolved by way of natural selection. Nor did he hesitate to extend this theory to include the origin of man, despite the fact that religion held man to have been created by God. The arguments between science and religion on this matter took on no less a proportion than they had on the question of the universe; the retarding influence of religion cost some scientists their jobs, although this time there were no human sacrifices. In time, these differences began to assume a more peaceful form, leading to the division of world outlook into the materialistic and the idealistic.

Attempts are now being made to resolve these differences, chiefly on the grounds that the social function of religion is today no longer based on the questions around which such arguments arise. The hindrance that religion has imposed on science for over 300 years is now coming to an end.

In addition to the teaching of theology in universities, leading scientists were able to pass on to youth their experience in the realm of the natural sciences. The number of universities increased rapidly, and in almost all the countries of Europe, academies of sciences sprung up and engaged in scientific co-operation. Postal links developed, and printing provided for international collaboration among scientists. The first scientific journal appeared in 1650 and, according to research carried out by the scientific historian D. de Solla Price [2], from that date to the present day the number of scientific journals has been growing exponentially – doubling every ten to fifteen years and now nearing 100,000.

In the development of scientific disciplines a certain progression was discernible: in Bacon's time development was mainly in physics, mathematics, mechanics, chemistry and other natural sciences. Biology began to develop somewhat later.

In the last century, the development of technology and industry gave rise to new directions in science, which today we call its applied aspects. These were particularly necessary for the introduction of electricity to industry and the application of electricity to everyday life. It was also the beginning of the development of applied disciplines such as construction engineering, strength of materials, hydraulics, and many others. The applied sciences, although firmly based on fundamental sciences such as mathematics, physics, chemistry and mechanics, exist in their own right since their content is determined by the branch of industry or technology they serve.

Whereas up to the eighteenth century the higher educational establishments – universities in most cases – developed the fundamental sciences (or pure sciences, as they were then called), at the beginning of the nineteenth century a new type of educational establishment, known as the polytechnic, was set up to train engineers in the applied sciences.

The Germans were the first to introduce, on a wide scale, specialized higher educational establishments for engineering, which of course explains the high level of technology – especially electrical technology – achieved in Germany towards the end of the last century and the beginning of this one. It was an age that produced world-famous scientific engineers such as Siemens, Arnold, Walker, Steinmetz, Stodola, Tesla and Loewi. It is interesting to note that these technical educational establishments were of such a high calibre that many of their graduates went on to become great scientists. Einstein, for instance, graduated from the Federal Polytechnic Institute in Zürich (ETH), while such eminent scientists as Dirac, Langevin, Debye, Ioffe, Lebedev, Poincaré, Cockcroft and many others also studied at technical engineering institutes.

In this century, the scientific method has spread to a new field – that of organizing industrial production and management. In the United States, it has been developed to the highest degree, mainly through the introduction of standardization and through the mass production method devised by Henry Ford. It was also in the United States that Taylor developed his scientific method for studying the actual process of production, thus giving rise to the field of applied science known as management theory. It now relies heavily on the use of computers, which serve to establish a functional relationship between a multitude of factors governing the efficiency of production processes. The scientific approach to production processes that has been developed in the United States no doubt explains the high and as yet unsurpassed level of productivity reached there. This new field of applied sciences is now being widely used in both capitalist and socialist countries.

There is one important sphere, however, in which science still has great difficulty in influencing development – that of the social sciences, which study the laws governing the functioning of the State. The practical role of these sciences is to accomplish the effective organization of a country's national economy. One would think that, if it is possible to establish a science for organizing production at factory level, it should also be possible to do so on a national scale. This area of social science is generally termed political economy. Although it has long been in existence, for a long time it could not, from a scientist's viewpoint, be regarded as a science because it did not possess the necessary objectivity. Economists were like doctors telling a patient, on the strength of their empirical experience, what treatment to follow – but often not understanding the mechanism that had caused the disease. Economists, in like manner, would give advice on how to overcome difficulties usually without any knowledge of the natural scientific laws creating those difficulties.

The first to achieve a scientific approach to economics was Karl Marx. His role may be compared to that of Newton who, as everyone knows, broadened the concept of force in mechanics by introducing the force of inertia and thus discovered, from the condition of equilibrium, the fundamental law governing the motion of bodies possessing a mass. As the basis of economic processes Marx postulated the movement of capital and the manifestation of the social processes that produce such movement. In this connection Marx extended the concept of 'capital', defining its size not in terms of accumulated cash but in terms of everything that constitutes the true wealth of a country or a person.

The rate of growth of capital is determined by laws that are constant under all social structures. These laws, discovered by

Marx, are – like Newton's laws of mechanics – entirely objective and therefore scientific. Marx investigated these natural laws by studying the economics of capitalism. The fundamental law he discovered leads to the conclusion that when production is based on hired labour, capital growth is determined by the profit the owner of production receives. Marx demonstrated that in such a case the dynamics of the capital growth process was unstable because of the spontaneous nature of capitalist economy. One of the principal reasons for the instability of the capitalist economy lies in the fact that the profit goes to the capitalists; there is therefore nothing to prevent capital from accumulating in the hands of the employers, which inevitably leads to the impoverishment of the workers. In the final analysis Marx believed that in the industrialized countries this would result in the impoverishment of the masses and thus in a situation that would be resolved by revolution. The spontaneous economy of capitalism would then be replaced by a planned national economy like those due to come into being under socialism. As history has shown, this did not happen. The reason is that, although Marx's scientific construction was right, it was based on the rate of development in his time – in the last century. As a result of the scientific and technological revolution, this rate began to increase rapidly at the beginning of the present century. It is a known fact that the rate of capital growth is determined by the productivity of labour, which is in turn almost wholly a function of the amount of energy available to the worker. In Marx's time this energy supply was small and consisted almost entirely in the worker's own muscular strength; today the position has altered substantially. In the developed countries, physical labour accounts for less than 1 per cent of the total energy expended on production. The result of this has been that the growth of the total capital of countries – the 'gross national product', as it is now called – has become so great that the impoverishment of the proletariat is not taking place. The 'affluent society' has come into being.

Marx pointed out yet another factor that was bound to produce unsteady economic growth and was also connected with the unplanned nature of capitalism. He demonstrated that, under capitalism, the capital in a country increases unevenly and that from time to time there must be crises that cause industrial depression and unemployment. The mechanism of such crises is explained by the fact that the growth of any branch of industry is determined by capital investment. Under capitalism, the volume of such investments is governed by capital returns, which are in turn determined by demand. When the market becomes saturated in a given branch of industry, profits fall and there has to be a reduction in capital growth in that branch in order to restore the balance. Hence, there exists a reciprocal relationship between profits and capital investment. A time lag naturally occurs before equilibrium is re-established, and the technical term for this is relaxation. The process leads to oscillatory fluctuations that may be used to describe periodic economic crises.

Similar processes in mechanics have been thoroughly studied, and the way in which they can lead to auto-oscillation has been demonstrated. The duration and intensity of such oscillation are determined essentially by the relaxation time, which is in its turn determined by the effectiveness of the feedback. It is possible to dampen these oscillations by increasing the effectiveness of the feedback, this is being done in planned economies and is practised in socialist countries. This is confirmed by the fact that, in the existing socialist countries, where there is planned control of capital investment, counteraction has been greatly improved and, although a certain degree of instability still remains, it is much smaller than in the capitalist countries.

Under the capitalist system, the growth in production brought about at the beginning of this century by the scientific and technological revolution was accompanied by a rapid increase in the amplitude in the processes of oscillation that took place in capital investment; finally, the crisis of 1929 reached such proportions that it turned into economic catastrophe.

It would seem logical that, in order to overcome the crisis, measures should have been taken, in accordance with Marx's scientific analyses, to institute a planned economy – but this was not done.

It is instructive to recall the way in which attempts were made to deal with crises of the dimensions of the one that occurred in 1929. A method of tackling them was proposed, as we know, by the British economist, John Maynard Keynes. An exceptionally talented and widely educated scientist, Keynes began his scientific career as a mathematician, working in the field of probability theory. Later, he worked as a consultant to insurance companies; after World War II, he demonstrated the unsoundness of the Versailles peace treaty and then began to concern himself with economics on a national scale. Keynes knew and valued the work of Marx but, being a realist, he came to the conclusion that so long as capital was in private hands, a direct transition to socialism as a means of fighting the crisis was not a practical proposition. According to Marx, of course, the effort should be directed against the uncontrolled growth of capital investment. It was therefore necessary, as far as was practically possible, to limit freedom of investment and to step up State control over capital. This could be achieved in one or two ways. The first was to increase taxes, thereby placing part of capital growth under the control of the State. Since taxation had always existed in every country, what had to be done was unobtrusively to increase it. The second way proposed by Keynes was bolder and more original. It consisted in running the national budget, contrary to all the accepted rules of financial management, actually in debt, which would naturally lead to inflation. The reasoning behind this proposal was that capital depreciates when it is lying idle – which, it goes without saying, is unprofitable. Inflation, therefore, would tend to stimulate capital investment; the counter-effect would be improved; and that would lead to the development of new lines of industry. And it is indeed a fact that moderate permanent inflation, as suggested by Keynes, has had the effect of mitigating the crises.

This recipe of Keynes was readily applied, and the capitalist economy became considerably more stable for a period of forty years. Crises still occurred, but they were of acceptable dimensions.

Over the last few years that recipe suddenly stopped working. In many capitalist countries inflation began to shoot upwards, until it reached such a pitch that it became almost impossible for the national economy to develop and function normally. Growth of the national product dwindled; unemployment became permanent, the major currency exchange rates became unstable. A series of attempts to battle with the crisis during the past few years have yielded no effective remedy, and the crisis is beginning to take on a chronic character.

And yet it can be asserted with reasonable accuracy that world crises originate according to the laws discovered by Marx as applying to the capitalist economy of a single country. It is certainly not hard to see that great changes have taken place in the world economy over the past forty years. Certain branches of industry – together with the capital invested in them – began to be shared by a few highly developed countries. That community of interests led to a specialization of industry in certain States necessitating the use of the raw materials and manpower resources of other countries. This pooling of capital investments resulted in the formation of multinational companies.

Although, within the framework of a single country, it has proved possible over the past forty years to control the dynamics of capital sufficiently to stabilize the economy by means of taxation and the creation of artificial inflation, on an international scale this method of stabilization becomes useless. The reason is that each State resists interference in its affairs and acts in accordance with its own national interests, which may be contrary to the interests of other countries. Even if the governments of individual States were able to reach agreement on measures for economic development, the free rein given to private capital would normally make it impossible to implement such measures.

The need to coordinate the economies of individual countries on a global scale is now so keenly felt that a certain amount of integration is taking place in developed countries: instances of this are the Common Market and the Council for Mutual Economic Assistance (CMEA). Mention should also be made of the serious research work undertaken by the Club of Rome, which has also begun to study the stability of existing national economic processes on a world scale. Its published studies on these problems [3] bear witness (despite the constant criticism to which they are subjected) to the fact that scientific investigations are undoubtedly being conducted on the right lines and are furnishing valuable material for scientific understanding of the present crises.

In time, of course, a way will be found to achieve economic stability on a global scale. According to the natural laws discovered by Marx, all that is needed is to find a way within each country of placing capital – and the returns on capital – under effective State control. Only then will the governments of individual countries be able to reach agreement and begin to implement a concerted economic policy. That international economic stabilization is a practical possibility where there is full control of capital, as there is under socialism, is demonstrated by the existence of CMEA.

Most leading economists already admit that control over the dynamics of capital investment has become essential in view of the global proportions attained by the present-day economy as a result of the high labour productivity brought about by the scientific and technological revolution. Like Keynes, the economists are seeking appropriate measures, but at the same time they are trying as far as possible to preserve the principle of '*laisser faire, laisser passer*' that forms the basis of the capitalist system. Attempts to find a compromise solution are being started; these have given rise, for example, to the theory of convergence – which states that as the present social systems evolve and develop they will in time merge into a single system that will preserve the best features of each and constitute a compromise between socialism and capitalism.

It is interesting to note the biased reaction inspired by a dread of socialism, that was provoked by Marx's research demonstrating the need to set up a planned economy, despite the fact that his work was purely scientific and therefore objective – so that there was no justification for an emotional attitude to it. The natural laws discovered by Marx would seem to have given rise to a situation similar to that which arose in the last century, when development of the natural sciences was inhibited because they were undermining the authority of the Church. Development of the social sciences is not being similarly inhibited in so far as they frequently lead to conclusions that undermine the authority of the State.

Besides the problem of a stable world economy it is certain that in the next century mankind will have to solve a number of global problems connected with the world-wide depletion of energy and raw materials resources and pollution of the environment. All these problems can be solved only by a strictly scientific approach and on an international scale.

Human beings, like other gregarious animals, live in closed communities, i.e. States. Although today the social structures of the developed States are similar in many respects – each one having organizations such as a police force, an army, a monetary system, a national education system, and so on, that come under the direct management of the State – they, nonetheless, differ in the nature of their social structure and their degree of cultural development. And it is these last which are the indicators that reflect man's evolutionary development.

The question arises of how to define the progressiveness or backwardness of any of the existing social structures. Which of them is following the road leading to the evolutionary progress of mankind? Can this question be answered on a strictly scientific basis, in such a way that the answer will be objective and unambiguous?

Let us attempt to analyse this question.

Human culture can be divided into the material and the spiritual, each of which is capable of evolving on its own. The material culture of a State is made up essentially of the capital at the disposal of the State. It is now generally considered that economically developed countries are those in which the annual gross national product per capita exceeds approximately $2,000. The total number of people in such countries comprises approximately one third of the population of the world, and it is in those countries, by and large, that the scientific activity of mankind is concentrated. The practical role of science, as can be seen from the foregoing analysis and as put forward long ago by Bacon, consists in organizing human labour in such a way as to insure the most effective growth of material culture.

Spiritual culture, on the other hand, corresponds to human mental activity. Although it cannot be measured quantitatively, the evolutionary growth of man is in fact determined by his culture inasmuch as it gives him mastery over nature. Between the material and spiritual cultures there is a link: spiritual culture points out the direction in which the wealth of the State should grow in order to meet the material needs of society. It is therefore customary to regard material culture as the foundation on which spiritual culture develops – like a kind of superstructure.

Such a construction, however, can scarcely be considered accurate. Material wealth is situated outside man, is progressively expanded and has to be renewed. Spiritual wealth such as science and art is handed down from generation to generation; it is preserved and can therefore evolve independently. There is no limitation to its growth, whereas the growth of material culture is limited by the number of food calories a person needs, how many items of clothing there are in his wardrobe, and the amount of living space he requires, etc. In the developed countries these limits are now fully within reach.

Unlimited growth of material consumption by one person inhibits his spiritual development and soon becomes harmful (an excess of food, for instance, leads to overweight). People who are engaged in intensive creative work therefore do not usually waste time consuming large quantities of material resources.

Endeavours to push growth of material resources beyond a certain limit produce a situation in which people often have to work under greater pressure than their nervous system can normally stand. The organization of labour under conditions of high productivity calls for the tightly regulated management of production and, so far as the daily routine of the worker is concerned, it also leads to a lack of freedom of choice in the type of work he does. All this puts pressure on a person's morale, and the price he has to pay for a high level of material well-being is the loss of his spiritual contentment. That this is already happening is borne out by statistical indicators. In the richest countries the number of suicides is increasing – a sure sign that there is a growing number of unhappy people. A similar indicator is the fact that, in those countries, the numbers of drug addicts and alcoholics is going up. It is a known fact that the physiological action of narcotics consists in shielding a person's psyche temporarily from the constraining pressures imposed on him by social life. What all this indicates in the final analysis is that the social structure of society, in its progressive evolution towards the goal of providing people with the happiest possible existence, should monitor both the size and the quality of the gross national product. This is diametrically opposed to the yardstick applied in the developed countries to a country's level of development, which they gauge by the material prosperity of the population – calculated merely from the size of the per capita gross national product.

Insofar as spiritual culture guarantees people the happiest existence, it should serve as the basis, with regard to the evolutionary development of mankind, for evaluating the progressiveness of the social structure of a country.

A person's spiritual life is composed of three elements: his private life, his relations with society (principally the people with whom he lives and works) and his activity as a citizen of the State.

Meeting the needs of a person's private life is a matter that varies with the individual person, depending on his natural abilities and the demands made on him by society through its ethics and traditions. From a scientific viewpoint these processes can be studied by means of psychology, as was done most successfully by Pavlov and Freud – although the practical significance of such research is restricted to its application to curative psychiatry. At the present time, there are still no generally accepted, objective laws governing the development of the spiritual culture of man and society. What is important and well known, however, is that a person's spiritual happiness is associated with the feeling of freedom. People desire freedom in the choice of a husband or wife, friends, religion and occupation, and they want to be free to live peacefully.

The attainment of a high level of material culture in a modern developed society demands such high labour productivity that – as has already been indicated – it creates conditions in the work and life of the individual that are hardly distinguishable from forced labour. This is most clearly evident in the case of assembly-line production, in which freedom of work is totally absent. With the highly organized daily life of people these days, many aspects of life are strictly regimented, and people find themselves constantly under control. They are obliged to obtain an education, to get to work on time and to wear certain clothes – and they cannot even cross the street where they want to.

The State compels a person to abide by its laws, and society compels him to live in accordance with its traditions – and even, in wartime, to kill people. As has been shown, after a certain degree of well-being has been reached, people begin to lose their liberty as their prosperity increases, and already the freedom of the individual in the developed countries is now extremely limited. Modern society strives to organize people's lives in such a way that they will have an *impression* of freedom despite the lack of it. This may be achieved by means of propaganda and by turning people's interest towards sports, sex and entertainment so as to distract them from reality. Such were the principles on which society was organized in Aldous Huxley's anti-Utopian novel *Brave New World.*

The civilization of a State is determined not only by the social and economic processes that take place within its frontiers but also by the international relations that influence the development of culture. We have already spoken about economic relations, but no less a role is played by culture. These latter relations are of an emotional nature and may take different forms. They may, for example, create ideological, national, racial or religious disagreements between countries, leading to conflicts and wars. However, in the fields of science, art, sports and so on, such relations can promote cultural growth.

The processes associated with the development of human culture are studied by history. From a scientist's point of view, history cannot be considered a science, because it is not based on the discovery of objective natural laws. Historical processes, such as the establishment of power, class conflicts, expansion and so forth, are always associated with emotional activity on the part not only of individual men but of entire communities. As J. Piaget rightly showed, objective study of such processes cannot be achieved, because they do not lend themselves to scientific investigation.

It is possible, nevertheless, to exert an influence on man's emotional activity and organize that activity. It can be done through art. Art has played a major organizing role among all peoples and in every age. It has developed and has been transmitted from generation to generation and, like science, it constitutes a national cultural heritage. To this day music is played at funerals; every people has its national anthem; religion makes wide use of music.

Literature and figurative arts have a particularly strong impact on the development of spiritual culture, because they exert an influence on the emotions that are involved in the formation of morals and ethics both in personal interrelationships between individuals and in social interrelationships.

There is a certain similarity between the impact of science and the impact of art on the organization of social life. As indicated earlier, these scientific laws that are a generalization of experience are fixed for all time and are internationally accepted.

Similarly, art is a generalization of processes which take place in the lives of people and of society. A truly great work of art that has an effective impact on the growth of spiritual culture cannot be affected by any specific political situation, for it becomes international and everlasting. In literature, the works of Cervantes, Shakespeare and Tolstoy have for hundreds of years exerted a world-wide impact on man. The same applies to figurative art. We have only to think of the paintings and sculptures of Titian, Michelangelo, Goya, Rembrandt . . . Or, in music, the works of Beethoven, Mozart, Chopin, Mussorgsky. . .

Thus the impact of art on the cultural growth of the whole of mankind is at least as great as the impact of science. It was not without reason that Jean Cocteau said, 'Poetry is indispensable, although why – I know not'.

To try now to answer the question we formulated earlier – which State social structure in the evolutionary development of mankind is the most advanced – I think there is full justification for believing that such an evaluation should be based on the quality of a country's spiritual culture. Since the process of human evolution unfolds by means of competition between different social structures, on the final count the States that survive will be those in which the spiritual culture meets the requirements of mankind's evolutionary development. We may expect, however, that in the process of evolution the law of natural selection will also extend its effects to individual man. The evolutionary development of mankind operates in the selection not only of social structures but also of man himself.

Discovering the natural laws that govern these two processes will probably remain forever beyond the reach of human capability. In this matter, we must place our trust in the 'wisdom of nature', which has unfailingly guided the development of the whole of nature over the course of hundreds of millions of years.

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Jürgen Ehlers

On Einstein's Life and Works

According to the German romantic poet and science-enthusiast Novalis 'theories are nets: only he who casts will catch'. Using this metaphor one can say that no fisherman in this century was more successful than Albert Einstein. In his *annus mirabilis* 1905, comparable in the history of science perhaps only to the memorable year 1666 when Isaac Newton conceived most of the ideas which were to govern science for more than two hundred years, Albert Einstein published in one and the same volume of the *Annalen der Physik* three papers each of which, besides containing important specific results, laid the ground for new extensive areas of fundamental research.

In the first of these papers Einstein considered the interaction of light and matter. He pointed out that in processes during which energy is exchanged between matter and radiation, as it is in thermal equilibrium between gas atoms and the radiation field, or in the case of photoluminescence or photoionization, the energy of monochromatic radiation of frequency ν behaves as if it were composed of discrete, localized, independent 'quanta' of amount $E = h\nu$, a discovery which extended Max Planck's pioneering work of 1900. Einstein emphasized that such a behavior is incompatible with the Maxwell-Hertz theory according to which light is a rapidly oscillating electromagnetic field the energy of which is distributed continuously in space, a theory which was and is very successful in explaining interference, diffraction, dispersion and many other phenomena. The strange fact that in some respects light behaves like a wave, in others like a swarm of particles, now called photons, which was convincingly demonstrated by Einstein in this paper, was recognized about twenty years later to be a special case of a property common to all particles of the atomic and subatomic world. Much work and ingenuity was required until this strange fact was incorporated into a coherent theory, the 'new quantum theory' which was created in 1925 and 1926 by Werner Heisenberg, Max Born, Pascual Jordan, Paul A. M. Dirac, and Erwin Schrödinger.

In the second paper Einstein gave one of the most direct arguments for the existence of atoms and molecules. He demonstrated that the irregular motion of the molecules which measures temperature, according to the kinetic theory of heat initiated already in 1738 by Daniel Bernoulli, should produce microscopically observable movements of small particles suspended in a liquid. Such motions had indeed been observed already in 1828 by the *princeps botanicorum*, Robert Brown, the discoverer of the nucleus of plant cells. The quantitative agreement between Einstein's theory and observations convinced even the most critical opponents of the atomic theory like the physicist Ernst Mach and the chemist Wilhelm Ostwald that matter is really composed of irregularly moving atoms.

In both the first and the second paper Einstein applied statistical thermodynamics in a new way. Instead of considering mean values he studied observable consequences of irregular deviations from the averages. This enabled him in both cases to uncover fine structures of radiation and matter, respectively, which in contrast to mean values cannot also be accounted for by a continuum theory. This manner of reasoning led to a whole new branch of physics, called fluctuation theory.

The title of the third paper, 'On the electrodynamics of moving bodies', seems to indicate that this work is of interest only to scientists working in a rather special branch of physics. The reason why this paper came to be considered as being of general interest not only to physicists but also to other scientists, philosophers and to anybody concerned with the conceptual basis of physics, is that in this work Einstein proposed a radical change of the conceptions of space and time which had been taken either as evident or as firmly established by the successes of Newtonian dynamics of which they form a part. Even the apparently simple statement, 'a body moves with constant speed relative to the earth', acquires an unambiguous meaning only after it has been specified (1) how the distances between points of the orbit of the body are to be measured, (2) whether time is to be measured by a clock attached to the moving body or by several clocks at rest on the earth, and in the latter case a prescription has to be given as to how the various clocks, assumed to be of the same kind, are to be set or 'synchronized'. According to Newton and common sense it does not matter which of the two procedures of measuring time is used, provided the clocks on earth are synchronized by slow transport. Einstein realized that this assumption was neither logically necessary nor experimentally established, and he recognized that several difficulties which had arisen in the application of James Clerk Maxwell's electromagnetic theory to moving bodies – difficulties which had been considered notably by G. F. FitzGerald, Lord Rayleigh, Hendrik Anton Lorentz and Henri Poincaré – do not arise if certain simple statements about the propagation of light in empty space are regarded as part of an implicit definition of time, in a similar way to which, according to Ludwig Lange, the law of inertia partly serves to define 'inertial frames' in mechanics. Starting from the assumption that there are preferred frames of reference relative to which the laws of physics, in particular the laws of mechanics for slowly moving particles and the law that light propagates with one and the same speed c irrespective of the motion of the source, have one and the same form, Einstein obtained a simple, consistent and empirically extremely successful theory which included a new kinematics and an electrodynamics and optics of moving bodies, as indicated in the title of his paper. Einstein's basic assumptions turned out to be a firm foundation not only for kinematics and electrodynamics, but for all those parts of physics including mechanics, thermodynamics and elementary particle physics which are concerned with local phenomena for which inhomogeneities of gravitational fields are negligible.

It appears that very few papers in the whole of scientific literature have excited as much discussion among scientists, philosophers and the general public as this thirty-page article submitted on June 30, 1905, to the *Annalen der Physik*. This seems to be due to the fact that Einstein's theory led to a prediction about the behavior of moving clocks which contradicts common-sense expectations. Although this particular prediction has by now been tested directly and indirectly with considerable precision under various circumstances, the discussion is going on, though not among physicists.

In the same year 1905, in the next volume of *Annalen der Physik*, Einstein deduced in a three-page note the 'very interesting conclusion' that any change ΔE of the energy of a body or a system of bodies is accompanied by the change $\Delta m = \Delta E/c^2$ of its inertial mass. The importance of this relation needs no comment at a time when the pros and cons of nuclear energy generation are discussed with deep concern and frequently with great anxiety by people whose fate it is to live in a world which is largely dominated by technical achievements based on at first sight merely 'intellectually interesting' and apparently practically useless insights into the structure of the material world.

Who was this man Albert Einstein who, as a twenty-six year old technical expert of the third class at the patent office in Berne, invented in his spare time new methods in statistical mechanics, discovered light quanta, gave a proof of the existence of atoms, solved the problem of constructing a correct electrodynamics of moving bodies, a problem tackled without definitive success by leading scientists of the time like Hendrik Anton Lorentz and Henri Poincaré, by setting up a new theory of space and time?

Albert Einstein was born in 1879, in the same year as Max von Laue and Otto Hahn were born and James Clerk Maxwell, the founder of the modern theory of electromagnetic fields, died. The Einsteins were Jews, but did not follow the rituals and laws of the Jewish religion any more. In 1880 the family moved to Munich, where Albert's father Hermann ran a small electrochemical factory with his brother. In the same year Albert's sister Maja, his only sibling, was born. The young Albert has been described as a taciturn, pensive, day-dreaming little boy, slow at learning to speak, not liking physical activities or playing much with other children. When he was four or five years old, Albert Einstein experienced, according to his recollection, what appeared to him as a miracle. A magnetic compass, shown to him by his father, appeared to be drawn steadfastly and by a mysterious, invisible power, always into the same direction, irrespective of how one moved the housing of the compass. Does this deep impression, vividly remembered after many years, indicate a longing for something dependable, something which the young as well as the mature Einstein did not find in the human world surrounding him, but which he did find in the unchanging, impersonal structure of nature?

Albert attended a Catholic elementary school, and at the age of ten entered the Luitpold-Gymnasium. He disliked the strict discipline, the authoritarian spirit, the lack of freedom at the gymnasium, where he had to learn Latin and Greek grammar which interfered with his studies of mathematics and science, the interest in which had been excited in him by his uncle, who was an engineer. Unhappy and depressed, an ill-adapted outsider, considered as having a disruptive influence on his class-mates by his teachers, Albert Einstein soon followed his parents without a school diploma when they moved to Milan in 1894 because of business difficulties. After one year of studies at a school at Aarau in Switzerland where he felt much happier, Albert Einstein was admitted as a student of mathematics and physics to the famous Polytechnic Institute in Zurich. Among his fellow students were Mileva Maric, a Serbian girl who in 1902 became Einstein's first wife and who was to be the mother of his two children, and Marcel Grossmann who eighteen years later became his mathematical collaborator. Among his teachers was the outstanding mathematician Hermann Minkowski, who in 1907 invented the concept of space-time and thus contributed in an essential way to the development of the theory of relativity. After graduation in 1900 Einstein failed to obtain a position at the Polytechnic or as a school teacher, but in 1902, with the help of his friend Marcel Grossmann, he got a post at the Patent Office in Berne. Here he prepared himself for the examination for his doctor's degree which he took in 1905, and found enough time to pursue his research in theoretical physics and to elaborate the ideas which he published in the papers some of which I described earlier.

Einstein kept the position in Berne until the end of 1909 when he accepted his first full-time academic appointment as associate professor at the University of Zurich. His accomplishments had by then been widely recognized. He had extended his researches on Brownian motion, light quanta and relativity; he had created the first quantum theory of specific heats of solids; and he had already in 1907 formed the opinion that a satisfactory theory of gravitation would have to incorporate in a basic and natural way the equality of inertial and gravitational mass, the fact that all test bodies fall with the same acceleration, as noted already by Galileo. Gravity and inertia are essentially the same thing, Einstein decided, and therefore a satisfactory theory of gravity required a generalization of the space-time framework of his theory of relativity, for if gravity is taken into account the concept of a finitely extended, strict inertial frame of reference is no longer adequate.

In 1910 Einstein accepted a full professorship at the German University of Prague. For the reasons just indicated Einstein was searching for a generalization of what he now called the 'special theory of relativity', in order to include gravitation. Gravitation theory was his main concern between 1907 and 1916. Whereas the majority of physicists had by then accepted special relativity as a solid part of the building of physics, Einstein was occupied with finding out the limits of its validity and struggled for a more inclusive and more precise mathematical representation of physical processes. It was in Prague in 1911 that he arrived at the prediction that light waves are bent by gravitational fields, but not before 1914 was an expedition ready to make appropriate observations during a solar eclipse. The First World War stopped this attempt, and the first measurement had to wait until 1919. Precise measurements, now possible with an accuracy of better than 1 percent, have been achieved only in recent years by means of radio telescopes.

In Prague, Einstein discussed the problem of constructing a relativistic theory of gravity with his mathematical colleague Georg Pick who conjectured that the proper tool for developing such a theory would be the absolute differential calculus which had been developed between 1896 and 1900 by the German mathematician Elwin Bruno Christoffel and the Italian mathematicians Gregorio Ricci-Curbastro and Tullio Levi-Civita in order to elaborate analytically the theory of curved spaces of arbitrary dimensions initiated in 1854 by Bernhard Riemann. Pick's conjecture turned out to be correct. In 1912 Einstein recognized the importance of the metric of space-time and became convinced that in the presence of gravitation this metric was a curved, Riemannian one. Pick died at the age of eighty in the Theresienstadt concentration camp.

After 18 months, at the end of 1912, Einstein left Prague and returned to Zurich, this time to become a full professor at the

Polytechnic Institute where he had studied a dozen years ago. At about the time when Einstein went to Zurich, Lenin travelled in the opposite direction from Switzerland. Science and history were to evolve swiftly.

In Zurich, following Pick's suggestion, Einstein studied the absolute differential calculus with his friend Marcel Grossmann who had become a professor of mathematics. Together they published a preliminary version of a new theory of gravity.

At the end of 1913, due to the initiative of Max Planck and Walther Nernst, Einstein was offered a well-paid position as a member of the Royal Prussian Academy of Sciences in Berlin and director of the yet-to-be-founded Kaiser-Wilhelm Institut für Physik. His duty was to organize research. He was not obliged to teach, but could do so if he wished. Einstein had always considered formal teaching as a burden, and he was attracted to the lively scientific atmosphere of Berlin. So he accepted the offer. Soon after his arrival in Berlin he separated from his wife Mileva. Einstein was now thirty-four years old and a star of the first magnitude in the heavens of science.

In Berlin, in spite of many contacts with colleagues, in particular with Max Planck, Max von Laue, Walther Nernst and later Erwin Schrödinger, and many others, Einstein felt somewhat isolated and a foreigner. He did not lecture, but participated actively in the discussions following colloquia. Being a pacifist and opposed to nationalism, he felt even more isolated during the First World War. He now concentrated fully on the theory of gravitation, and after a strenuous effort Einstein succeeded at the end of 1915 in formulating a coherent theory which is still considered as the most admirable part of classical physics. This theory has stood all experimental tests performed up to now with flying colours.

The basic idea of Einstein's general theory of relativity is that the metric of space-time, the structure which determines spatial distances, time intervals and the propagation of light, is not a rigid one, given once and for all, like the metric of the Euclidean-Newtonian space or that of space-time in the special theory of relativity, but a dynamical physical field generated by and acting on matter. The contents of this theory can briefly be described as follows. Matter determines the curvature of space-time, and the system of straightest lines in this curved space-time, corresponding to the set of great circles on a sphere, determines, like a system of rails, the motion of bodies. That is, it represents at the same time inertia and gravity.

Einstein's fame increased, particularly when after the war the British astronomer Arthur Eddington confirmed his theory by measuring the deflection of star light by the gravitational field of the sun.

In 1917, in a paper which is regarded as his most important contribution to quantum theory, Einstein proposed a statistical description of the interaction of atoms and photons and gave a new derivation of Planck's law. Forty years later the process of induced emission – then called negative absorption – whose existence was demonstrated in this paper, was applied in the maser. In the same year Einstein founded modern cosmology, the science of the large-scale structure of the universe, by constructing the first mathematically consistent model of the universe containing gravitating, homogeneously distributed matter.

I mention only in passing the anti-Einstein campaign by Weyland, Gehrke and company around 1920, connected with anti-Semitism in Germany, and the *Deutsche Physik* by Philip Lenard, Johannes Stark and others.

During the years 1921, 1922, and 1923 Einstein travelled in the United States, Europe and Asia. Convinced by Weitzman he engaged himself in the Zionist movement. In 1922 he was awarded the Nobel prize, not for his relativity theory, but 'for the photoelectric law and his works on theoretical physics'.

When Hitler came to power in 1933, Einstein was travelling in the United States. He never again entered Germany. After a short stay in Belgium, during which he resigned from the Prussian Academy and the Bavarian Academy of Sciences in protest against the passive attitude taken by these academies when academic freedom was suppressed in Germany and many scientists and intellectuals were removed from their positions for ideological 'reasons', Einstein accepted a position at the newly founded Institute for Advanced Study in Princeton. He continued research, concentrating mainly on the creation of a unified field theory which would, so he hoped, give a deeper account of both gravity and electromagnetism, and in addition would describe particles as stable regions of high concentration of the field. Einstein did not succeed in these efforts, but in a modified form his idea of using geometry to create such a unified theory has received a strong new impetus and has had considerable success in recent years in the form of unified gauge theories, which use a different type of geometric structure.

Besides these main efforts Einstein occasionally returned to his gravity-theory of 1915 and enriched it by new results. In 1932 he collaborated with Willem de Sitter to construct a model of an expanding universe which is still a possible candidate to represent the large-scale structure of the material world. Joint work with Nathan Rosen in 1937 resulted in solutions of his field equations which describe gravitational waves, and a celebrated paper published in 1938, written with Leopold Infeld and Banesh Hoffmann, was devoted to the derivation of equations of motion of particles from the gravitational field equations. The subject of this 'E-I-H-paper' is still under discussion. For example, research on it is being carried out by my collaborators and myself at the Max-Planck-Institut für Physik und Astrophysik.

Einstein's opposition to quantum theory is a topic which would require another lecture; I shall not describe it in spite of the importance which Einstein attached to it.

Even after his retirement in 1945, Einstein continued to work. After a short illness Albert Einstein died of an aneurysm of the aorta on 18 April 1955, at the age of seventy-six.

One important characteristic of Einstein's approach to basic problems of physics was that he questioned the adequacy of even those concepts and relations which were generally regarded as evident; in this sense he was a philosopher. On several occasions he expressed his views on how scientific concepts and theories are created, connected with experience, and judged. In his autobiographical notes Einstein described what he called his epistemological credo in the following words:

> I see on the one side the totality of sense-experiences and on the other the totality of the concepts and propositions which are laid down in books. The relations between the concepts and the propositions among themselves and each other are of a logical nature, and the business of logical thinking is strictly limited to the achievement of the connection between concepts and propositions among each other according to formally laid down rules, which are the concern of logic. The concepts and propositions get meaning or content, respectively, only through their connection with sense experiences. The connection of the latter with the former is purely intuitive, not itself of a logical nature.

According to Einstein, concepts are free inventions, and the axioms or basic laws of a theory are guesses; they cannot be deduced or inductively inferred from experiences or observations. On the other hand, a theory should permit the derivation of propositions which can be tested experimentally, and therein lies its value. Thus, science requires three human activities: free invention or guessing, logical-mathematical deduction, and observation or experiment. As Einstein – as well as Dirac – remarked, the process of guessing is guided not only by factual experience and experience with previous theories, but also by a sense of structural simplicity and mathematical beauty. There is not much point in classifying Einstein as a positivist, a rationalist, an empiricist or any other 'ist', but if some such label were required, I would propose to call him a logico-empirical artist. It appears that Einstein has strongly influenced natural philosophy not so much through his philosophical statements as such, but because of the manner in which he practised science, constructed new theories and thus contributed to knowledge, often in a surprising way.

Einstein regarded himself as a physicist and not as a philosopher. He was proud of the general theory of relativity which he considered as his greatest intellectual achievement. For this reason I should like to end this lecture with a quotation from Hermann Weyl who wrote:

> Einstein's theory of relativity has advanced our ideas of the structure of the cosmos a step further. It is as if a wall which separated us from Truth has collapsed. Wider expanses and greater depths are now exposed to the searching eye of knowledge, regions of which we had not even a presentiment. It has brought us much nearer to grasping the plan that underlies all physical happening.

PART IV

DISCUSSION PAPERS

Erwin N. Hiebert

Einstein as a Philosopher of Science

Between 1905 and 1906 Einstein published four papers that contributed conspicuously to establishing the direction of twentieth century theoretical physics. As is well known, these papers are models of originality, clarity, and elegance. They deal with quite diverse topics: the light quantum hypothesis, a theory of Brownian motion, an analysis of the electrodynamics of moving bodies that incorporates new views on space and time into a special theory of relativity, and a paper on the relation of the inertia and energy, or the general equivalence of the mass and energy, of a body. In one way or another this early work of Einstein – each paper a landmark in its own right – sets the stage not only for much of his subsequent scientific work but also for the direction of his philosophical reflections.

In his later years Einstein turned his attention more and more towards deliberating about the object, methods, and limits of science. In exercising these rights, that is, to pursue the philosophy of science as a scientist, Einstein was completely in step with the trends that had been set by late nineteenth century investigators, and that were being perpetuated with vigour, if not always logical vigour, by the scientists who belonged to his generation. In his essay on Physics and Reality in 1936, Einstein tells us why it is not right for the physicist to let the philosopher take over the philosophy of science, especially at a time when the very foundations of science are problematic. 'The physicist', he says, 'cannot simply surrender to the philosopher the critical contemplation of the theoretical foundations; for he himself knows best, and feels more surely, where the shoe pinches.' For Einstein, the philosophy of science definitely was not the remote and exotic affair that most professional philosophers practised; rather, it was something that called for an in-depth acquaintance with science as a prerequisite.

On the other hand, Einstein by no means assumed that the narrow scientific specialist was qualified as a philosopher of science. He says:

> The whole of science is nothing more than a refinement of everyday thinking It is for this reason that the critical thinking of the physicist cannot possibly be restricted to the examination of the concepts of his own field. He cannot proceed without considering critically a much more difficult problem, the problem of analyzing the nature of everyday thinking.

What I would like to do here is to offer some brief comments about the self-reflective aspects of Einstein's career that may help to shed light on the conception he had of himself as a philosopher of science. Before doing so, however, may I offer an explanation for approaching the subject in the way I have. First, I want to say that I acknowledge explicitly and candidly that there are some severe limitations imposed upon the investigator who chooses this approach, i.e., to focus on what scientists *say* they are doing when they claim to be engaged in science, rather than analysing more single-mindedly their published scientific contributions in order to discover *what they do* when they claim to be engaged in science.

Einstein once said:

> If you want to find out anything from the theoretical physicists about the methods they use, I advise you to stick closely to one principle: don't listen to their words, fix your attention on their deeds. To him who is a discoverer in this field, the products of his imagination appear so necessary and natural that he regards them, and would like to have them regarded by others, not as creations of thought but as given realities.

If Einstein has suggested here that one should not listen to what scientists *say* they do, but rather look at their works in order to learn *what* they do, he also wrote in his autobiography (or in his obituary as he called it): 'the essential in the being of a man of my type lies precisely in what he thinks and how he thinks, not in what he does or suffers.' I want to suggest that, over the years, Einstein, as so many other scientists, surrendered to the temptation to reify his own methodological preferences into a credo that guided him in all of his work.

The point I mean to stress in advance, with these remarks, is that what a scientist *really* does, if we may speak that way, is not revealed to the historian of science unambiguously, either by an analysis of the retrospective account of what is going on, or by an examination of the finished, formal, published, product. In my opinion, anything that contributes to the clarification of the methodological question about how science advances, or retrogresses, is fair game for the historian.

I mainly want to suggest that it is an extremely difficult task to reconstruct what actually transpires in the mind and work of a scientist engaged in generating, executing, implementing, and reporting scientific activity. I believe, nevertheless, that an examination of what scientists do *qua* scientists is historically and philosophically meaningful and rewarding, and certainly fundamental for analysing the role of science in the contemporary world. And so I think that it is important to approach the problem from as many different ways as will help to illuminate the behavioral patterns and contemplative life of different scientists at work. My feeling about this is that one can profitably ask a great many meaningful and even manageable questions about scientists – their motives, beliefs, prejudices, styles of work, and methodological priorities – but one cannot ask them all at the same time.

Suffice it to say that one way to search out the self-image of Einstein as a philosopher of science, and to discover the way in which he conceives of his own work and thought within the context of the scientific currents of his times, is to listen seriously to what he has to say as he reflects on these matters in so many of his essays and lectures. Besides, the historians can take advantage of Einstein, so to speak, by invading his more unbuttoned, private, and internal life, to examine the uninhibited outpourings of his soul as revealed in the correspondence and informal interchanges with his most intimate friends and invisible opponents. While this invasion may not be quite fair to a man like Einstein, since he undoubtedly never intended to add these documents to the historical record, they, in fact, do help substantially to answer the questions that I have posed here.

I want to assert at the outset that Einstein had two images of himself and his work. The self-image that dominated his early career may be characterized roughly in reference to his attraction to critical positivism and the empirical status of theories advocated by Ernst Mach. The other more mature, more consciously worked out self-image of Einstein, and the one I want to talk about here, was one in which Mach's sensationalism and pluralism were abandoned and replaced by a realistic, unitary and deterministic world view that lays claim to the intuitive recognition, or near-recognition, of rock bottom truths about nature. Concerning this position he wrote, 'My epistemological credo . . . actually evolved only much later [in life], and very slowly, and does not correspond with the point of view I held in younger years'.

To analyse with psychological insight and historical credibility the many reflective accounts of Einstein that reveal something about his self-image as a philosopher of science is an undertaking that would be far too ambitous on this occasion. Therefore I have set for myself the more modest objective of examining the way in which Einstein was prodded into explaining his philosophical position by two of his closest colleagues and critics – Arnold Sommerfeld and Max Born. In both cases we have at our disposal a very substantial portion of correspondence and intellectual interchange that covers a period of almost forty years.

Both Sommerfeld and Einstein were enthusiastically committed to the technical mastery and critical evaluation of everything that transpired in the intellectual realm of relativity and quantum mechanics during the revolutionary era of physics from 1900 to 1930. However, no two persons could have followed the shifting scientific scenario from more diverse perspectives. We learn that Einstein, the philosopher, with cool detachment, was attracted to general, far-reaching unitary principles, and over the years became increasingly more impatient with, and even hostile toward, quantum mechanics with all of its outlandish baggage of indeterminacy, statistical and probability functions and discontinuity. He simply felt that the future of physics lay more in geometry than in particles. Intellectually independent, he continued, for decades, to puzzle deeply about scientific questions that most physicists had accepted as self-evident.

By constrast, Sommerfeld, the unphilosophically disposed master of broad domains in theoretical physics, ten years older than Einstein, surrounded by an energetic and productive school of disciples in Munich, became a staunch supporter of the revolutionary quantum trends. He managed, with his unique mathematical dexterity, and his facility with intuitively clever mechanical models, to squeeze out and exploit subtle implications that lie hidden beneath the basic principles that had been laid down by other investigators. We may add that, in the process of doing so, he formulated new problems eminently worthy of being explored on their own merits. Sommerfeld was an early enthusiast for both relativity and quantum theory. I want to concentrate on the Sommerfeld/Einstein discussions about quantum theory, because they demonstrate most convincingly the distinctive philosophy that Einstein generated over the years. He became increasingly confident that the failure to provide a unitary field theory, that would encompass both macro- and micro-phenomena, provided proof positive that the quantum theorists were on the wrong track.

It was one of Einstein's early papers, the revolutionary 1905 hypotheses on light quanta, that brought him in contact with Sommerfeld. They first met in Salzburg in 1909 at the *Naturforscher Versammlung*, where Einstein lectured on the new quantum ideas. The next year Sommerfeld travelled to Zürich to spend a week in discussions with Einstein. At the first Solvay conference in 1911, Sommerfeld explored the theoretically exciting idea that the existence of the molecule was to be taken as a function and result of the elementary quantum of action h, and not vice versa, as Haas had argued.

Sommerfeld, early on, was stirred to action by Einstein's deduction from quantum principles about vanishing heat capacities at absolute zero temperature. He was also encouraged by the experimental support for the quantum theory being provided by the low temperature heat capacity measurements conducted by Nernst and his colleagues in Berlin. Sommerfeld did his best to get into the act in 1912 by requesting from Einstein an in-principle clarification of quantum ideas. Unfortunately for Sommerfeld, Einstein was largely preoccupied with gravitational theory; and, we may note, he did not manage to attract much attention to this work from his colleagues in Berlin at this time. It was not relativity, but rather quantum mechanics, which was the topic of lusty debates.

In 1916, Einstein wrote to Sommerfeld:

> You must not be angry with me that I have not answered your interesting and friendly letter until now. During the last month I have experienced one of the most exciting and trying, and certainly one of the most successful times of my life.

What follows, in the letter, of course, is a discussion of some of the germinal ideas and consequences of his general theory of relativity. Somewhat late, in 1916, while commenting favourably on Sommerfeld's spectral investigations and successful extension of Bohr's theory of the atom, Einstein remarked, 'If only I knew which little screws the Lord God is using here' – which remark I interpret to mean something like: it is rather inconceivable that the real world is like that, i.e., quantized; but if it should turn out that it *is* so constructed, then I must ask, Is it not a bit undignified for God to have to use little screws to run the world that way?

Disturbed neither by Einstein's cavalier disregard of what was going on among quantum theorists, nor overly sensitive about the fundamental theoretical rationale behind it all, Sommerfeld continued courageously to work out the mathematical formalism of the modified Bohr theory with great finesse and virtuosity. Einstein responded in 1918: 'If only it were possible to clarify the principles about quanta! But my hope in being able to experience that is steadily diminishing'. What Einstein had been trying to show, but unsuccessfully, was that particles can be treated as stable regions of high concentration of the field.

Dubious about the direction in which quantum theory was moving, by contrast, Einstein believed, by 1918, that general relativity was an accomplished theory. Thus he wrote:

> Behind general relativity henceforth there is nothing new to be found. In principle all has been said: identity of inertia and mass; the metrical proportion of matter (geometry and kinematics) determined by the mutual action of bodies; and the non-existence of independent properties of space. In principle, thereby, all has been said. I also am convinced that a consistent theory without the hypothesis of spatial closure is impossible.

In this domain, Einstein was very certain that he had uncovered the real physical truth about nature. In a letter to Sommerfeld in 1921, concerning a small supplementary addition to relativity theory that both he and Hermann Weyl had published he wrote: 'I have my doubts about whether this thing has any physical worth. God makes it as he wills, and does not allow something to be put over on him.' When asked to lecture on relativity, he remarked that he had nothing new of interest to say, and added, 'the old stuff is already whistled by all the younger sparrows from the roof tops better than I can do it.'

In 1920 Sommerfeld succeeded in explaining the multiplicity of many of the spectral lines by introducing an inner quantum number that had no physical meaning for him. 'I can only further the technique of quanta', he wrote to Einstein, 'you must construct their philosophy'. Beginning with the work of Sommerfeld's pupil Heisenberg, in the summer of 1925, and promoted by the dramatic and ingenious contribution of Born, Jordan, Dirac, Schrödinger, Bohr and Pauli, the elaboration of quantum theory was approached from quite different directions, and given a formalism and mathematical structure that represents one of the most magnificent theoretical and practical accomplishments in the history of science. Much has been written about this subject and I only want to mention here that in the outcome two opposing camps were created that divorced the enthusiasts for the Heisenberg/Bohr matrix mechanics – Born, Jordan, Dirac, Hund, and Pauli – from the supporters of the Schrödinger wave mechanics, e.g., de Broglie, Planck, and Einstein.

Actually, Einstein essentially alienated himself from the whole quantum business except for irregular pot shots against the whole enterprise. Sommerfeld, typically engrossed in anything that would result in a practically useful and theoretically sound outcome, and philosophically uncommitted, stood outside the debate but continued to elicit reactions from Einstein that at times revealed more about his native intuitions than can be learned from studying his scientific papers.

In 1926 Einstein wrote to Sommerfeld:

I have worried a great deal about searching out the relationship between gravitation and electromagnetism, but now am convinced that everything that has been done in this direction by me and others has been sterile . . . The theories of Heisenberg and Dirac, in fact, force me to admiration, but they do not smell of reality.

Or again, in another letter,

The results of Schrödinger's theory make a great impression, and yet I do not know whether it deals with anything more than the old quantum rule, i.e. about something with an aspect of real phenomena.

Concerning Sommerfeld's monograph of 1930 on wave mechanics, Einstein said, in the same vein, that it was very nice, but that in spite of the tremendous successes accomplished, the whole development and the prevailing trends did not satisfy him.

After 1930, as we well know, scientific communications suffered miserably in Germany. Research and discussion groups were splintered so severely that Sommerfeld in a reminiscent mood in 1937, wrote to Einstein (by then in Princeton) that he was consoling himself for having been able to experience personally the golden age of physics from 1905 to 1930. A decade later Sommerfeld was curious to know whether Einstein had changed his views about quantum theory. 'Perhaps you will tell me what you now think about continua and discontinua. Or do you take the situation to be hopeless?' Einstein replied,

I still believe in all earnesty that the clarification of the basis of physics will come forth from the continuum, because the discontinuum provides no possibility for a relativistic representation of action at a distance.

In 1951 Sommerfeld died at the age of eighty-three thus terminating the discussions between the philosopher-physicist Einstein and the no-nonsense master of physics, Sommerfeld, who claimed no expertise in the philosophy of science but who had been anxious to exchange ideas with one whose philosophy he respected.

In contrast to the picture that we have sketched of Sommerfeld in Munich, as the philosophically neutral correspondent of Einstein, we have at our disposal the life-long scientific interchange of ideas between Einstein and another physicist who was himself passionately disposed to philosophizing about relativity theory and quantum mechanics at the slightest provocation. This was Max Born, in Göttingen, the physicist whose completion of Einstein's statistical interpretation of quantum theory earned him the Nobel Prize twenty-eight years after it was presented.

Einstein's and Born's philosophical views were invariably 180 degrees out of phase on the subject of quantum mechanics. Accordingly, an examination of their intellectual debates is all the more important because of Born's relentless efforts to entice Einstein, the independent and relatively isolated thinker, to explain and defend his position as he moved around the world and took up new positions in Prague, Zurich, Berlin and Princeton.

As in the case of Sommerfeld, the two men first met in Salzburg in 1909. Born characterizes the young Einstein, up through the early 1920s, as an empiricist and enthusiast for the philosophy of Hume, Mach and Schlick. But, already in 1919, when Einstein was first ruminating about a unitary field theory that would bring gravitation and electromagnetic theory together, he was expressing a degree of discomfort about the developments in quantum mechanics. The theorists operate, he wrote, as though 'the one hand is not allowed to know what the other does'.

Basically at odds with the upsurge of the idea of discontinuity in physics, Einstein wrote to Born in 1920:

> I do not believe that the quantum can be detached from the continuum. By analogy one could have supposed that general relativity should be forced to abandon its coordinate system.

Einstein was also unhappy about what seemed to him the failure of the strict law of causality in quantum mechanics, and the simultaneous encroachment of statistical arguments. There is no doubt about the fact that by 1920, Einstein sought to hold tenaciously to continuum theory – in the hope that quantum phenomena would be absorbed somehow into the differential equations.

In the 1920s and 30s, Einstein was preoccupied mostly with general relativity. He was clarifying and perfecting its theoretical exposition, and pursuing its practical consequences with great determination. But he wrote to Born that in his spare time he was 'brooding . . . over the quantum problem from the point of view of relativity' because, as he said, 'I do not believe that [quantum] theory will be able to dispense with the continuum.'

From that time on, Einstein was compelled, periodically, to admit that he was getting nowhere with his *Lieblingsidee*, that is, the continuum, in spite of all attempts to analyse the issues. Now and again over the years, he felt – and announced – that he had achieved at least the glimpse of a reconciliation between relativity and quantum theory under the umbrella of continuum ideas, but these hopes were shattered one after another either by himself or others. In his letters to Born we come to see how often and how deeply Einstein was distressed about the conception of a wave-particle duality for radiation – a view he could not embrace except as a temporary crutch devoid of physical reality. In 1924 Einstein confided to Born:

> My attempts to give the quantum a tangible form . . . have been wrecked time and again, but I am nowhere close to giving up hope. And if nothing works, there still remains the consolation that the failure is my fault.

In truth, the state of quantum theory in the early 1920s was one of considerable confusion. For example there were the negative correlations with the Bohr-Sommerfeld rules. Attempts to connect quantum theory with classical mechanics were not successful. Qualitatively things worked out tolerably well, but the quantitative predictions were not impressive. Many technical difficulties simply escaped resolution. It was Born who spoke of the quantum puzzle (*das Quantenrätzel*), and in 1921 wrote to Einstein, 'The quanta are a hopeless *Schweinerei*' – as he expressed himself. As already mentioned above, from 1925 to 1930 we witness a series of dramatic and bold moves which reveal that the negative results of current quantum theory pushed investigators in the direction of making a sharper break with classical mechanics that simultaneously provided a new quantum mechanics.

After 1925, Einstein and Born carried on a running commentary characterized by hard arguments in which neither could convince the other. Commenting about this interchange some forty years later, Born wrote:

> Einstein was fairly convinced that physics provides knowledge about the objective existence of the external world. But I, along with many other physicists, was gradually converted by experience in the domain of atomic quantum phenomena, to realize that it is not so – but rather that at every point in time we have no more than a rough approximate knowledge of the external world and that from this, according to specified rules of the probability laws of quantum mechanics, we can draw some conclusions about the unknown future world.

In response to the accomplishments on quantum mechanics by Born's Göttingen group (Heisenberg, Jordan, and Hund) Einstein could only respond:

> Your quantum mechanics commands much attention, but an inner voice tells me that it is not yet the true Jacob. The theory offers much, but it brings us no closer to the secrets of the ancients. In any case I am convinced that He does not play dice.

When Einstein spelled out most of the details of his attempts to establish a quantum field theory, Born wrote back politely that it was very interesting but not convincing.

In a letter of 1944 to Born we have a compelling illustration of Einstein's mature image of his own philosophy of science. It demonstrates convincingly how two talented scientists can be worlds apart in their interpretations of the same cognitive subject matter. Einstein writes:

> In our scientific expectations you and I have reached antipodal positions. You believe in a God who throws dice, and I believe in complete lawfulness, *viz*. in a world of something that exists objectively and that I have attempted to snatch in a wild speculative way. I believe firmly, but I hope that a more realistic way, and especially that a more tangible evidence will be found than I was able to discover. The great initial success of the quantum theory cannot bring me to believe in the fundamental nature of a dice-throwing God, even if I know that my younger colleagues interpret this position of mine as the result of calcification. Someday it will be known which instinctive conception was the right one.

Born responded by saying that Einstein's expression about a dice-throwing God was totally inadequate:

> In your determined world, you must throw dice too – that is not the difference [between us] . . . First of all you underestimate the empirical basis of quantum theory . . . and second, you have a philosophy that somehow brings the automaton of dead things in accord with the existence of responsibility and conscience.

Einstein at this point could do no better than say (1947) that he was sorry to discover that, 'I just cannot manage to express my position so that you will find it to be intelligible'; and then he adds the comment that the mathematical difficulties involved in trying to reach his objective are so severe that,

> I will bite the grass before I get there . . . But concerning this I am convinced that eventually we shall land a theory in which law-like things will not be probabilities but facts -- facts such as formerly were just taken for granted. But to prove this conclusion I have no logical reasons.

And so the debate wore on and on. Einstein called Born a positivist. Born said that that was the last thing he wanted to be called by anyone. Einstein to Born: Don't you believe in the reality of the external world? Born to Einstein: Do you really believe that all of quantum mechanics is a fraudulent affair?

Einstein to Born: Your remarks in essence are not philosophy at all but the manipulation of a hidden machinery of reasoning. Born to Einstein: Your position is one of metaphysics and not philosophy. That was the tone of the intellectual interchange.

We see that Einstein had formulated his own image of what the philosophy of science should be and what it should accomplish; and so had Born. But neither Einstein or Born felt that they were being successful in communicating what that image was. At one point Pauli entered the debate and managed to convince Born that they had not so much disagreed, as argued from basically different premises. Pauli, in fact, had constructed his own image of the philosophical positions that Einstein and Born represented.

I will suggest that it can be argued that when Einstein died in 1955 he was holding in firm grasp essentially the same world view that he had formulated in the 1920s and 30s. In his lecture on the theory of relativity at King's College London in 1921, Einstein said:

> The theory of relativity may indeed be said to have put a sort of finishing touch to the mighty intellectual edifice of Maxwell and Lorentz, inasmuch as it seems to extend field physics to all phenomena, gravitation included .... I am anxious to draw attention to the fact that ... [the theory of relativity] is not speculative in origin; it owes its invention entirely to the desire to make physical theory fit observed fact as well as possible. We have here no revolutionary act but the natural continuation of a line that can be traced through centuries. The abandonment of certain notions connected with space, time, and motion hitherto treated as fundamentals must not be regarded as arbitrary, but only as conditioned by observed facts.

A decade later, in an essay on the problems of space, ether, and fields Einstein wrote:

> The theory of relativity is a fine example of the fundamental character of the modern development of theoretical science. The initial hypothesis becomes steadily more abstract and more remote from experience. On the other hand, it gets nearer to the grand aim of science, which is to cover the greatest possible number of empirical facts by logical deduction from the smallest

number of hypotheses or axioms. Meanwhile the train of thought leading from the axioms to the empirical facts or verifiable consequences gets steadily longer and more subtle. The theoretical scientist is compelled in an increasing degree to be guided by purely mathematical, formal considerations in his search for a theory, because the physical experience of the experimenter cannot lead him up to the regions of highest abstraction . . .

Or again, at about the same time, in his essay on the methods of theoretical physics, Einstein raises the question whether we can ever hope to find the *right* way – seeing as he believes, that the axiomatic basis of theoretical physics cannot be extracted from experience but must be freely invented. In other words: Has this *right* way any existence outside our illusions? Einstein's position is unequivocal:

I answer without hesitation that there is in my opinion, a *right* way, and that we are capable of finding it . . . . [It is one which furnishes] the key to the understanding of natural phenomena. Experience may suggest the appropriate mathematical concepts, but they most certainly cannot be deduced from it. Experience remains, of course, the sole criterion of the physical utility of a mathematical construction. But the creative principle resides in mathematics. In a certain sense, therefore, I hold it true that pure thought can grasp reality, as the ancients dreamed.

Let me pull some of Einstein's view together by saying that the philosophical, or rather epistemological credo that comes through clearly and with remarkable consistency over a period of some thirty to thirty-five years includes at least the following four elements:

(1) God is a mathematician; or rather Einstein's position might be expressed by saying that natural phenomena can only be understood in depth, and natural laws can only be formulated successfully, in the language of mathematics.

(2) According to Einstein, a correct or right unitary theory of natural phenomena is conceivable and feasible, and scientists are making steady progress in achieving that right unitary theory. Imbedded in this conception of a right theory is the belief that

unambiguous progress can be and has been achieved in moving forward the goal of constructing (discovering) a real picture, or physical representation of phenomena, that corresponds with the way things really are in nature. The right theory is equated with existence. Implied, of course, is also the conviction that the right theory is unique and not merely one of a plurality of alternative theories that might be constructed to do the job equally well.

(3) The right, potentially unitary theory, upon which Einstein places all of his stakes, is seen to rest on a mathematical foundation that deals with fields (continua), and *not* quanta, i.e., *not* discontinua. The overall aim is a unified field theory that will encompass macro- and micro-mechanics, or gravitation, electromagnetism, radiation, and atomistics including all aspects of science that pertain to the ultimate constituents of matter and their interactions at all levels.

(4) Finally, Einstein believed that however abstract and remote from experience the mathematical formalism of theory turned out to be, the investigation could nevertheless use experience to suggest appropriate concepts. While the concepts themselves could not be deduced from experience, experience was still acknowledged as the sole criterion of the physical utility of the theory. That is, in the end, it was absolutely crucial that the physical theory fit the empirical facts.

To the above four landmarks of Einstein's image of what he considered to be a correct philosophy of science, namely his own, we might want to add that he obviously held in high regard the importance of the foundational analysis, critique and reformation of the basic concepts that lie at the heart of a right and realistic scientific world view. How close Einstein's physics borders on philosophy may be seen in the way that philosophers of science have continued to discuss his philosophy perhaps even more than physicists. I therefore would not hesitate for one moment to assert that Einstein was a truly important modern philosopher, and that his highly individualistic philosophical ideas have exerted an influence which, as Professor Dirac stated so beautifully earlier, has changed the course of history. But let us remember that Einstein's philosophy, although thoroughly saturated with scientific ideas, was one that reaches very far into all of the nooks and crannies of our material and spiritual lives. He was a fantastic scientist. He also was a genuine humanist whose intellectual integrity has been and will continue to be a model for all of us.

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Olaf Pedersen

The Introduction of Relativity into Denmark: A Case Study

INTRODUCTION

The centenary of the birth of Albert Einstein presents a natural occasion for recalling the days when the theory of relativity had to fight for its very existence against a sea of opposition. The debate following Einstein's seminal paper of 1905 and Minkowski's four-dimensional formulation of the special theory of relativity in 1907 provoked a controversy which was in many ways similar to the discussion following in the wake of the theory of evolution half a century earlier. Thus not only scientists but also philosophers were involved and the battle was eagerly watched by the general public to which the name of Einstein became a household word to the same degree as that of Darwin. The literary evidence of the battle is extremely comprehensive and – as far as I know – nobody has ever tried to survey the whole range of papers, books or lectures to which it gave rise. In the absence of any detailed historical analysis we have only a very approximate picture of what really happened and one of the major revolutions of modern science is still to some extent in the dark. This rather disappointing situation will not easily be overcome; but until some historian of science of no mean assiduity devotes himself to remedy our general ignorance it might be of some use of examine how relativity was introduced into a single country where the scene was small and the actors were few. Although of a limited scope, such a case study may well reveal at least some of the principal issues of the debate and point to areas where further research might yield more firmly established results. The choice of Denmark as the scene is more or less arbitrary although it may perhaps be of some advantage to select an area where theoretical physics had a good standing at the same time as none of its adepts had any personal or original contributions to make to the theory of relativity as such.

Around the turn of the century physics in Denmark was still marked by the tradition stemming from L. V. Lorenz (1829–1891) who had been equally brilliant in both the experimental and the theoretical field. Thus he was a leading figure in the international efforts of defining standard electromagnetic units just as his highly original electromagnetic theory of light was a remarkable achievement comparable to that of Maxwell [1]. In the next generation of physicists there were two outstanding names. K. Prytz (1851–1929) continued the experimental tradition from Lorenz and is still remembered for a beautiful lecture experiment demonstrating the principle of equivalence (Prytz's lantern experiment). His contemporary C. Christiansen (1843–1917) was the discoverer of anomalous dispersion and had done valuable experimental work on black body radiation at the same time as he was the author of a brilliant text book in mathematical physics. Finally there was an emerging group of younger physicists, one of whom was destined to play a major role in twentieth century science. They were P. O. Pedersen (1874–1941) who later became famous for his work on the propagation of radio waves, Niels Bohr (1885–1962) who after a brilliant study of the classical theory of electrons turned to the quantum theory of the atom, and H. M. Hansen (1886–1956) who became a distinguished spectroscopist; it was he who at a critical stage drew Bohr's attention to the importance of studying line spectra in connection with the Rutherford atom, thus preparing the way for Bohr's seminal paper on the quantum theory of the hydrogen atom in 1913. Also

M. Knudsen (1871–1949) should be remembered for his work on the kinetic theory of gases.

It is a curious fact that no member of this highly qualified school of Danish physicists seems to have paid any attention to the theory of relativity when it was first introduced by Einstein in 1905. In fact, the first hint that something new was in the offing came from the least theoretically minded among them in the form of a short obituary on A. A. Michelson published in 1907 by K. Prytz [2]. Here Michelson was praised for his work in interferometry which kept the interest in optics alive during a period when most physicists were engaged in research on electricity. The notice concluded: 'Finally his researches into the relative motion of the earth through the ether of space must be mentioned. It was to this purpose that he constructed his interferometer.' This is presumably the first reference in Denmark to anything connected with relativity although the author failed to mention the fundamental importance of the Michelson experiment.

THE FIRST PRESENTATION OF THE THEORY OF RELATIVITY

The next step was not taken until 1912 when, after his return from a stay at Göttingen, H. M. Hansen gave a lecture on the 'Principle of relativity' to a joint meeting of the Physical and the Mathematical Society of Copenhagen. It was printed in the *Fysisk Tidsskrift* (*Journal of Physics*) which also opened its pages to the following debate [3]. Being the official publication of the Danish Society for the Propagation of Science, founded in 1924 by the discoverer of electromagnetism, H. C. Ørsted, this journal was primarily devoted to the general diffusion of scientific knowledge and did not publish research papers. In spite of its limited purpose it played a significant role in Danish science, and it is perhaps worth noting that the first battle of relativity was fought upon its pages at a time when the more scholarly journals of the various scientific societies were silent about Einstein's ideas. Dr. Hansen's paper begins with the blunt statement that 'the principle of relativity means a revolution of our inherited opinions on space and time, and a break with Newtonian mechanics.' The author then states as the most general feature of classical mechanics that all mechanical laws are invariant under transformations belonging to the Galileo group. This is called the principle of relativity of classical physics. It has the corollary that it has no meaning to speak of absolute motion or absolute rest as separate and opposite states of mechanical bodies; all motion is relative and all systems of reference interconnected by Galileo transformations are equivalent.

The author then refers to the prevalent view that all physical phenomena might be subject to a mechanical explanation. If this be the case it follows that any phenomenon must be described in similar terms in all systems of reference belonging to the Galileo group, and that absolute motion must escape detection by any physical means whatsoever. The problem is whether this far-reaching conclusion – here clearly drawn from the general assumptions of a mechanistic philosophy – can be supported by non-mechanical experiments. The central question is said to be the following: Does the ether move together with the earth or does the earth move through the ether? This reveals that the author has optical experiments in mind. Accordingly the following part of his lecture is devoted to a long and careful discussion of optical aberration, the Doppler effect of light, Fizeau's experiment on the velocity of light in moving water, and finally the Michelson-Morley experiment.

The general conclusion of this part of the paper is that there is a more and more common opinion that it is impossible to prove absolute motion, and that it is the essential properties of nature which make it impossible. If our theories lead to such a possibility they must be founded upon false assumptions.

After these preliminaries the author is now able to introduce his principal theme – the fact that Einstein has been able to remove the difficulties of interpreting the Michelson experiment in another way than that proposed by Lorentz. From a formal point of view they both arrive at the same result, but Lorentz's solution is without the audacity and simplicity which makes Einstein's theory so attractive. This theory rests upon the fundamental postulate that the laws of nature (not only of mechanical phenomena) are independent of the state of motion of the observer if the latter is devoid of acceleration, in connection with a new and more profound notion of time. From this principle of relativity Einstein has drawn a number of startling consequences by means of simple thought experiments. Thus he has shown how clocks in different frames of reference may be adjusted by means of optical signals which are the fastest signals we have at our disposal; the result is that two events may be simultaneous for one observer without being so for another. Similarly, if we agree to measure the length of a rod by placing markings simultaneously at its end points, two observers will disagree upon this length if the rod is at rest relative to one of them, but moving relative to the other. However, this situation is completely symmetrical: A will conclude that everything set in motion relative to himself will contract in the direction of motion. Another observer B in motion with respect to A is unaware of this and assumes on the contrary that it is A and his rods which are contracting; they are both right to precisely the same degree.

These qualitative arguments have their mathematical counterpart in the Lorentz transformation which is now derived from the following clearly stated presuppositions,

(1) that the principle of relativity is valid for all physical phenomena;

(2) that the velocity of light is independent of the motion of the observer; this is the outcome of the Michelson experiment and

equivalent to assuming that the equation of a spherical wave of light

$$x^2 + y^2 + z^2 - c^2 t^2 = 0$$

must be invariant under the transformation;

(3) that the transformation is linear; and

(4) that there exists an inverse transformation.

A fifth assumption is used without being explicitly stated, viz.

(5) that the transformation must lead to the classical Galileo transformation in the limit where $v/c \to 0$.

It is then shown how these assumptions lead to the well-known formulae of the Lorentz transformation connecting two systems of reference moving with the constant velocity v relative to each other in the direction of their x-axes. The transformation is then used to derive the Lorentz contraction, the time dilatation, the formula for the composition of parallel velocities, and the constant velocity of light. Furthermore, the author touches upon the problem of causality, showing that the order of cause and effect is preserved if the velocity of light is greater than any other possible velocity in nature. Finally the Maxwell equations are stated to be invariant under the Lorentz transformation with the important corollary that the magnetic force can be regarded as a relativistic effect due to the relative motion of the observer and an electric charge. Also the formula for the mass of a moving electron is quoted and the equivalence of mass and energy mentioned.

At this stage the author is left with only one important question: Do we have any reasons to believe that the theory of relativity is true, and to which extent is it or can it be expected to be verified by experience? The starting point for his discussion of this question is again the Michelson-Morley experiment which is now said to have found no other explanation. This rather bold statement makes it necessary to reconsider the solution proposed by Lorentz on which the author now seems to have made up his mind. The two theories lead to the same conclusions and no experiment will be able to distinguish between them. Accordingly, it is a matter of opinion which of them is to be preferred. Here Dr. Hansen points to the fact that the principle of relativity is incompatible with Lorentz's assumption of an ether at rest since the latter could be used to define absolute time and absolute motion. Furthermore, it is not very satisfactory to assume the existence of a medium which we shall never be able to discover experimentally. But in the last resort the theory of relativity must be preferred for more general reasons. It is simpler than Lorentz's theory, more audacious, and also more satisfactory to the mind of a physicist, particularly in the elegant geometrical formulation given to it by Minkowski. The last words of the author is that the very essence of the theory of relativity is the notion of time as a parameter which undergoes transformation from one system of reference to another. Minkowski had wondered that nobody had come upon this idea from purely logical reasons; but only the force of experiment was able to make it worthy of serious consideration – an illustration of Michelson's famous dictum that the physical discoveries of the future are a matter of the sixth decimal.

THE CAMPAIGN FOR RELATIVITY

To the great majority of Danish scientists, Dr. H. M. Hansen's paper must have been the very first introduction to the theory of relativity. From one point of view it has to be admitted that it was not very original. There is nothing in it which is not found in earlier expositions by Einstein, Minkowski or v. Laue whose works are acknowledged in the concluding bibliography. Also the calculations are somewhat pedestrian, and several approximative expressions are derived in cases where the exact formulae could have been found without greater effort. On the other hand the paper had the great advantage of being both thorough and clear.

The author deals with almost all the questions still mentioned in any elementary text-book on relativity. His style is brief and unambiguous, and he is obviously devoted to his subject. Everything considered, it would be difficult to imagine a better introduction to the subject. From now on there could be no doubt of what it was all about.

The immediate reaction to Dr. Hansen's paper is hard to discover. If physicists in Copenhagen discussed it there are no published records of their opinions on the new theory. But there is some evidence that Dr. Hansen mounted, as it were, a deliberate campaign to further the study of relativity, particularly by reviewing a number of publications on the subject.

The upshot of this campaign is obvious. Dr. Hansen felt in a way responsible for the theory which he had himself introduced to his colleagues and tried to stimulate any growing interest in it by calling attention to reliable, but not too difficult presentations.

The following year Dr. Hansen became one of the editors of the *Fysisk Tidsskrift*. This provided new opportunities of furthering the cause of relativity with the immediate result that the journal published a Danish translation of the inaugural lecture on the 'Crisis of the ether hypothesis' given by P. Ehrenfest on his assumption of the chair of theoretical physics at Leiden [4]. As the title suggests this lecture deals with a crisis which threatened one of the fundamental hypotheses of physics – the ether hypothesis – and gives a good picture of the curious revolutionary feelings which dominated theoretical physics.

The crisis of the other hypothesis is described by Ehrenfest on the basis of a historical analysis of the theories of light from Newton to Maxwell. This period in the history of optics was marked by a series of efforts to decide experimentally between emission theories and wave theories of light. The result was that Maxwell's conception of light as an electromagnetic wave moving through an ether at rest in space had won the field. In consequence one would expect an 'ether wind' to blow through any laboratory moving through space together with the earth. Therefore, the crisis appeared as soon as Michelson's experiment showed that no trace of this ether wind could be discovered – and yet it should blow through our laboratories with a speed a thousand times greater than that of an express locomotive!

Ehrenfest then continues by describing how physicists reacted to the crisis. Lorentz stuck to the idea of an ether at rest but assumed that both the forces between charged particles, and the geometrical shape of the electrons were affected by their motion through the ether. These assumptions completely removed the difficulty and explained why the ether wind will be forever hidden to the experimental physicist. Ehrenfest notes, however, that not all physicists were able to declare themselves satisfied with this solution. Among them were Einstein in 1905 and Ritz in 1908. Their solution rests upon the assumption that *there is no ether at all*, and consequently no ether wind to be discovered. This entailed further consequences for our conception of the nature of light. Ritz had compared light to the splinters emitted from an exploding bomb and adding their velocity to that of the bomb with the result that the velocity of light cannot be the same to two observers moving in opposite directions relative to the bomb. Einstein, on the other hand, had based his theory on the postulate that the velocity of light is independent of the motion of the observer relative to the source. Ehrenfest is aware of the fact that so far no *experimentum crucis* has been able to decide between the two theories, although in a footnote he refers to de Sitter's interpretation of the observations of light emitted from double stars; they would seem to exclude Ritz's conception although this is denied by E. Freundlich. Until we have an unambiguous *experimentum crucis* we are left with the choice between Lorentz and Einstein. This is not an easy one since their theories are in complete formal agreement. However, in order to accept Einstein's solution we should be prepared to admit, (1) that rays of light moving away from a source through empty space are self-contained, spatially limited entities; (2) that we shall measure the same velocity of light regardless of whether the source is moving or at rest relative to us, and finally (3) that the combination of these two propositions is satisfactory.

It is now clear that Ehrenfest does not wish to take any definite stand on this issue. He will consciously refrain from expressing any opinion concerning the future solution of the ether crisis, his only purpose being to analyse this crisis, and through this analysis make room for the conviction that we still have no completely satisfactory solution. One can only hope that it may be possible to construct a theory which is able to avoid all the contractions and other functional disturbances inherent in the theories by Lorentz and Einstein. His own hope is that this may be possible along the lines already laid out by Ritz.

Thus Ehrenfest's lecture appeared as a word of caution from a physicist who seems to have felt that Lorentz's theory was unacceptable because it introduced 'functional disturbances' of the measuring instruments, and that Einstein's theory was even more unacceptable because it was based on a postulate which Ehrenfest clearly regards as absurd. That Dr. Hansen included the paper in the first volume he edited of the *Fysisk Tidsskrift* could be so construed that he himself had become doubtful of the theory of relativity. This interpretation is contradicted by the firm stand he was going to take during the following debate. It is more reasonable to assume that he simply wanted to draw attention to the difficulties of interpreting the Michelson experiment on the basis of any of the classical assumptions regarding the properties of light, difficulties which make some kind of new approach unavoidable.

THE INTERVENTION OF THE PHILOSOPHERS

Although there are no explicit references to Ehrenfest's paper during the following period it seems to have made some impression on people who remained skeptical towards the drastic modification of traditional physical concepts proposed by Einstein and advocated in Copenhagen by a young scientist who had not yet acquired any firm scientific reputation either abroad or at home. The fact that a well-established physicist of international standing like Ehrenfest still nourished grave doubts with respect to both Einstein and Lorentz seemed to indicate that things were not as simple and definite as they appeared in Dr. Hansen's paper. Perhaps this is the reason why the next phase of the debate begins with a counter-attack on relativity from philosophical quarters.

At this point in time the only Danish philosopher interested in science was K. Kroman (1846–1925) whose genuine sympathy with scientific questions was attested by a charming little book on Newton, but also by a major work on *Our Comprehension of Nature* which still commands respect as an informed and competent survey of a wide range of problems connected with classical physics [5]. Therefore, Kroman was in many ways a competent critic whose intervention had to be taken seriously. It appeared in the *Fysisk Tidsskrift* in the form of a paper with the title 'The principle of relativity' and was clearly meant as a reply to Dr. Hansen's lecture with the same title [6].

From his introduction it can be inferred that if Professor Kroman was against the theory of relativity it was certainly not because he was unable to handle the necessary mathematical formalism. On the other hand, he is clearly of the opinion that this formalism is empty: all this is only mathematical fantasy; we must now try to connect it with reality.

What this means is explained in very unambiguous terms. Consider two observers A and B moving relative to each other and comparing their measuring rods. It follows from the Lorentz transformation that *A* must consider *B*'s rods as contracted, while *B* must have the same opinion of *A*'s rods. The important thing is that they cannot both be right. Their starting points are incompatible. Their results are contradictory. Furthermore, the author concludes that *A* (or *B*) can never be sure that his system of reference is at [absolute] rest if only he is without acceleration. And according to the principle of relativity *A* commits no error in supposing himself to be at rest. Thus we have here two truths. *A* is right for he has no acceleration, and *B* is also right for he too has no acceleration. But this will not do! There is a fundamental principle in logic stating that *A* is not non-*A*. Contradictions in the realm of things do not exist, and contradictions in the realm of thought are not tolerated. There is no double truth. Truth is one. This statement does not need any defence. Every science is founded upon it. But Einstein's theory is opposed to it. Therefore, it must be rejected.

This passage reveals Kroman's fundamental attitude. Logic is superior to physics and a physical theory is false if it violates only one logical principle. Now one could suppose that another logical principle would speak in favour of Einstein, i.e. *Diversi respectus tollunt omnem contradictionem* – there is no contradiction in viewing a thing from different points of view. But according to Kroman this principle does not apply to the case of our two observers *A* and *B*. Their disagreement is real because they are speaking of the same thing, for example, the lengths of identical rods, or the simultaneity of two events, in which case there is no place for different points of view. *A* and *B* are not in the same case as a man on Bornhold and a tourist from London who disagree on the time of the day but are able to overcome their disagreement by taking the difference of geographical longitude into account. It seems that Einstein assumes that the physicist is either *A* or *B*. But unfortunately the physicist is a third person who must produce agreement between them, and this agreement is possible. Lorentz has hit the weak point of the theory on the head when he hinted that it would be bad if *A* and *B* ever came to speak together. This is the heart of the matter as far as Kroman is concerned. A physicist is not simply an observer who tries to describe what he observes. A physicist is an impartial judge of what others pretend to observe, and his task is to decide who of them is right. In other words, a physicist enjoys a privilege denied to mere observers.

Kroman then attacks those who speak of a restricted principle of relativity in classical physics. There was no such principle, and in the *Principia* Newton himself sharply distinguished absolute motion from absolute rest as truly different states. This, he meant, was a necessity for our thinking. In rational mechanics we have also been able to distinguish between rest, relative motion, and absolute motion in a clear and non-contradictory way. This fact is by no means contradicted by the other fact that it is difficult to define an absolute frame of reference; this is a practical difficulty only – to our thought everything is clear. Therefore, the preliminary conclusion must be that Einstein has not solved the riddle behind the Michelson phenomenon. He has only hidden it away behind a couple of formulae which he offers to us as a kind of charm, overlooking the fact that the cure is worse than the disease – and that a well-known adage says that although the patient died, the fever left him.

In order really to drive the absurdity of the theory of relativity home, Kroman tries to substantiate his conclusion by considering some of the consequences of the Lorentz transformation. He deals in a mathematically correct manner with the motion of a spherical wave of light, with aberration and the Doppler effect, the motion of light in moving water, the composition of parallel velocities, the Lorentz contraction and the time dilatation, and ends with proving that the order of cause and effect is conserved if any velocity is smaller than the velocity of light. In each of these cases he proceeds in the same way. If the theory of relativity leads to the same result or approximately the same result as the classical treatment of the problem, it is declared to be superfluous. If, on the other hand, it leads to new and unexpected effects, these are taken as proofs of the utter absurdity of the new theory. And let no one say that the difference between a classical and a relativistic result is small, for this difference is at the same time a difference between the conceivable and the inconceivable. No one will be satisfied with a theory declaring that $2 + 2 = 4 + \epsilon$, even if ϵ be ever so small! Kroman is not impressed by the fact that Lorentz and Einstein arrive at the same formalistic expressions. To this it must be answered that mathematics is not yet physics. The same mathematical expression may have quite different meanings and values in two different theories.

There is but little doubt that Kroman had succeeded in expressing what numerous physicists and philosophers of science must have thought – motion and rest must be different states of a body; a scientist must be a privileged observer able to judge between conflicting experimental results; two equal and parallel velocities added together must give twice the velocity – any other idea is inconceivable; and contractions must be real, physical effects produced by known forces – not something drawn out of the hat of a mathematical magician for no physical reason at all.

THE IMPARTIAL ARBITER

At this stage the debate has arrived at a characteristic situation. The same phenomenon (the theory of relativity) is studied by two different observers *A* (Dr. Hansen) and *B* (Professor Kroman) who profoundly disagree. According to Kroman such a situation calls for an impartial judge who can tell the two parties where the truth of the matter is to be found. As it happened the next participant in the debate assumed this very role. He was Helge Holst (1871–

1944) who was educated as a physicist, but was best known as the author of an impressive and well-informed survey in four massive volumes of the history and present state of technology. His contribution to the discussion on relativity was a paper in the *Fysisk Tidsskrift* with the title 'The problem of time' [7]. He begins by confessing that many physicists will agree with Professor Kroman in his rejection of Einstein's theory; nevertheless, they will make use of the formulae derived from it; this is no grave fault since these formulae are approximately true – although deduced from false presuppositions – and may serve until the difficulties leading to Einstein's theory have been removed in another way. As his personal contribution to this removal Holst then offers his thoughts on one particular aspect of the debate, viz. the problem of time.

Holst realizes that the core of the matter is the notion of simultaneity which necessarily implies some kind of signal to be exchanged between two observers. But he is not content with Einstein's exclusive use of light signals. After the coming of relativity, says Holst, it has been stressed as some merit of Einstein's that he has realized the necessity of giving a precise definition of the simultaneity of events taking place at different points in space, and that he has made the curious discovery that it is impossible to make such a definition unambiguous. But the truth is rather that that notion of simultaneity which follows from the very nature of our mind was formerly correctly assimilated by the minds of physicists without definition, whereas Einstein's definition has caused confusion by elevating our limited means of observing simultaneity into something fundamental to our knowledge as a whole.

In consequence, Holst has to propose a definition of simultaneity different from that of Einstein. He considers an event taking place at the point A and another at B. At the moment when A occurs a signal is emitted to B and immediately reflected back to A where the observer notes that the signal was emitted at the time t_1 and returned at the time t_2. If we now suppose that the event at B occurs at the same time as the signal from A is reflected, it must have happened some time within the time interval between t_1 and t_2 measured on the clock at A. If the velocity of the signal is increased, this time interval will diminish and tend towards zero as the velocity of the signal approaches infinity. In other words, if we are possessed of a signal moving with infinite velocity we can say precisely whether two events are simultaneous or not, and it is of no importance whether A and B are moving or at rest relative to one another.

The difficulty inherent in this definition does not escape the author. One could object that we are unable to emit a signal with infinite velocity (. . . .) our fastest signal – that of light – taking years to travel from the nearest fixed star to the earth. But this objection does not hit the point. What we consider here is not to which degree of precision we are able to measure simultaneity by the means we have at our disposal but, on the contrary, what the notion of simultaneity implies, and as to that there has been no disagreement between physicists until now. In other words, simultaneity is an *a priori* notion, inherent in the minds of physicists and possessed of a meaning quite independently of the practical operations employed in ascertaining it.

Starting from this assumption it is no wonder that the author feels unable to agree with Einstein. He is, of course, aware that his own definition is equivalent to Einstein's if we assume that A and B are without relative motion, and also that the velocity of light is the same in both directions. But the latter assumption is characterized as dogmatic, and when it proved incompatible with the usual notion of simultaneity, Einstein did not hesitate to discard this notion for the benefit of the dogma, with the now well-known *revolution of our concepts of space and time* as a consequence. This is a bad procedure for a physicist. Furthermore, the author is not convinced that the velocity of light is greater than any other velocity in the physical universe. But even if this were the case we could still imagine velocities 1000, 10 000, 100 000, or an arbitrary number of times faster than that of light.

Accordingly, Einstein's revolution of our concept of time is not so much a revolution as a destruction. If we tamper with that we shake the very foundation upon which we had to build the picture of the physical universe. We have arrived at a situation in which it is possible to create a mathematical system, but where natural control breaks down and absurdities are given a free play if only they fit into the system. The essential Kantian point of view of the author is summarized in the phrase '*We perceive existence in the form of space and time*'.

This is not to say that Holst is prepared to go all the way with Kroman. He is not sure that all problems of absolute motion or absolute rest have been solved within the framework of rational mechanics. He is not even sure that these concepts have a precise meaning. Only the notion of simultaneity is clear, and to say that we can never produce a signal with infinite velocity and, accordingly, not speak of events as simultaneous, is a sophism of the same kind as the statement that Achilles can never reach the tortoise. The relativity connected with our notion of time is – contrary to that of Einstein – not in disagreement with our traditional concept of time. It does not lead us into a mystical universe where space has four dimensions [sic!]. It does not forbid us to stay in the good, old three-dimensional space (. . . .) where simultaneous events are simultaneous, where every physical change has a physical cause, and where two trains moving in opposite directions at 100 kms per hour have a relative velocity of precisely twice this value, whether we be passengers on board one train or the other, or stand looking at them at the side of the railway.

THE FINAL ROUND

In the absence of other participants the scene was now clear for the final skirmish between the principal actors, in which Dr. Hansen replied to Kroman and Holst in another paper with the now well-known title 'The principle of relativity' [8]. Here he clearly characterizes Lorentz's explanation of the contraction of moving rods as an *ad hoc* hypothesis. Furthermore, even if Lorentz talks about a frame of reference fixed to an ether at rest, enabling him to define absolute motion and absolute simultaneity, these concepts are purely theoretical or ideal, without any practical importance. He also mentions some of the research performed since the publication of his first paper, for example, Einstein's explanation of the movement of the perihelion of Mercury, based on an extension of the principle of relativity. The conclusion is that Einstein's theory has in no case proved incompatible with experience, and that it has been verified in the few cases where verification was possible.

Hansen then addresses some courteous remarks to Kroman for the mathematical ability shown by the philosopher, but only to continue with a blunt denial of a number of Kroman's statements. Thus he denies any logical contradiction between what two different observers describe. It is not necessary to give one of them any preference over the other – A knows what B does, and vice versa, so there is nothing to argue about and no need for any privileged observer or any impartial, ideal physicist as umpire. Also it is wrong that there is no principle of relativity in classical mechanics. Rest and uniform motion are equivalent concepts: what one observer describes as rest may be uniform motion to another, and no decision is possible.

To H. Holst, Dr. Hansen has not much to say. He admits that the Lorentz-Holst conception of simultaneity might be maintained, but that Holst has misunderstood the essential point. The crux of the matter is not that we have no signals travelling faster than light, but that the velocity of light in empty space is the same in all directions, as proved by the Michelson experiment. Whether Holst's concept of the nature of simultaneity as absolute is interesting is to physicists a matter of opinion. One of the last phrases of the paper summarizes Hansen's final position: The cause of changes sought by Lorentz in the ether wind is sought by Einstein in the very nature of space and time without the assistance of any mechanism at all, in accordance with his phenomenological point of view.

This clearly was too much for Kroman whose reply 'Some further remarks on the principle of relativity' is more vehement and personal than any previous intervention in the discussion [9]. Kroman first expresses his complete agreement with Holst and also has some kind words to Walsøe who is right in calling Einstein's theory an unscientific hypothesis. On the other hand he is rather impatient with Hansen whom he attacks on a number of points, mainly from epistemological considerations. First he is angry with the alleged simplicity of Einstein's theory. This simplicity must be of a rather superficial nature as seen from the unusually artificial results concerning space and time to which it leads, and courage is no unmixed scientific virtue. The courage of Einstein is mostly the courage to exaggerate and be vague, to go against all reasonable probability, and to disregard fundamental epistemological principles.

In this reply Kroman refrains from going into details, concentrating the counter-attack upon the point raised by Hansen's final remarks on Einstein's phenomenological point of view. This is not a reassuring defence, for it is anything else than fortunate for a scientist to be a phenomenist [sic!]. A phenomenist is a scientist who has formed the opinion that it is most scientific to stick to the phenomena, to that which appears, disregarding causes, forces, et cetera. This means that sensation is placed upon a throne while reason is relegated into a corner as an unreliable counsellor. But of course such an epistemology is as impossible as it is false.

Next Kroman repeats his denial that there is a principle of relativity in classical mechanics. This branch of physics has only three principles, viz. Newton's three laws. Among these the second law has the following logical consequence: if a body has a certain motion, and another body has the same motion plus a uniform velocity, the law of force for the two bodies must, of course, be the same, for unaltered motion demands no force. It is clear that Kroman has not realized that this statement implies the classical principle of relativity. That he is unable to change his original positions is even more apparent when he continues with some further remarks on the velocity of light and Einstein's derivation of the Lorentz transformation from the assumption that the velocity of light is the same in all directions. But, of course, he is no allowed to do that. He commits a *petitio principii* and proves nothing, or – not to say too much – he proves that rest and motion are one and the same from the supposition that they are the same. The error lies in the fact that he takes something for a principle when it is no more than a hypothesis. If according to his assumption light has a constant velocity in space, and thus in a system at rest, then it is, without further ado, unthinkable that it should also have a constant speed, i.e. the same speed in all directions, in a moving system. If Einstein had been a student of Professor Kroman he would have had to answer the following two questions: Is it possible and not contrary to common sense that (1) phenomena always are the same in absolute rest and in uniform motion, and (2) light always has the same constant velocity c in space (and in air)?

In both cases the answer must be no. For if the phenomena should be the same in absolute rest as in uniform motion, the light must have the apparent velocity c in all directions in a uniformly moving system. But this is unthinkable unless the system and its contents are contracted according to certain laws when it is moving. But if this be the case the phenomena are not the same in absolute rest as in uniform motion (. . . .) But Einstein is unaware of all this. He sticks to his assumptions without any suspicion of their contradictory nature. Kroman's final words are therefore,

> Thus is the outcome of Einstein's doctrine. Its contradictions are moved further and further away, like criminals who were once deported to Botany Bay. In the end the fundamental notions of space and time are attacked. It is impossible to proceed any longer, unless one takes the final step and postulates that contradictions and non-contradiction are, fundamentally, one and the same thing.

Fortunately Lorentz is innocent of these crimes and proceeds in a scientifically impeccable way. He has no dogma that there is no velocity greater than that of light. He is also to derive the same formulae as Einstein, but with a different inner meaning. He is no relativist and believes in the unity of truth, although we are sometimes unable to find it. Lorentz rejects neither the demands of thought, nor its results, and always clearly distinguishes between rational truth and that which can be achieved by experiments.

With this final exchange of arms the discussion died away.

CONCLUSION

Looking back at this controversy one is impressed by the rather high quality of the various papers. They were all written by people who mastered the necessary mathematics and also had a good physical background, except that Kroman seems to be fairly ignorant of the electromagnetic theory of light.

The controversy on the theory of relativity was – at least in Denmark – not a purely scientific discussion. From the very beginning it had philosophical overtones which made themselves heard more and more clearly as the debate progressed. Perhaps this feature represents one of the major effects of the coming of relativity upon the general attitude of scientists. The debate deprived physicists of their philosophical innocence. It forced them to show their hands and disclose to each other their innermost assumptions on how physical nature and human thought are related. From this point of view relativity did more than evolution to sharpen the awareness of scientists to those philosophical presuppositions which lie at the bottom of any scientific activity. For whereas the battle of evolution was fought at the frontier between science and religion, the battle of relativity took place within the pale of science itself. In consequence no scientist, or at least no physicist, was allowed to sit on the fence without taking a stand on a number of fundamental questions. The fact that a single scientist was able to bring this about is one of the good reasons for celebrating his first centenary.

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Theo F. Nonnenmacher

Size Effect on Surface Tension and Vapour Pressure: Applications of the Capillarity Approximation

My contribution to this symposium will be concerned with the impact of Einstein's first scientific activities on the development of surface thermodynamics and its application in different areas of modern science. Before Albert Einstein presented his theory of special relativity in 1905, his scientific interest was focused on a thermodynamical problem, which I would like to bring to your attention. The content of Einstein's first paper is not so spectacular as his beautiful theory of relativity, which plays a central part in most of the other contributions to this symposium, and is less known than the influence of his ideas on the development of quantum mechanics or other branches of physics.

In his first paper (1901) entitled 'Folgerungen aus den Capillaritätserscheinungen', Albert Einstein [1] discussed the influence of surface tension γ on the total energy of a thermodynamical system with a flat surface. From experimental observations he conjectured that γ should be a linear function of temperature and concluded that the surface energy, i.e. the energy needed for the creation of the surface, is not a thermal but a mechanical (potential) energy. In his calculation of this surface contribution to the total energy he assumed that the density in the interior of the liquid should be constant up to the surface. This is precisely the Gibbsian point of view for treating thermodynamic systems, and this model has since commonly been used in the theory of capillarity. A generalization of Einstein's formula to a many component system is given by Defay et al. [2].

But during the first decades of this century scientific interest was focused primarily on the theory of relativity and the development of quantum mechanics. Although the starting point for Planck's success in discovering his famous constant was initiated by a thermodynamic problem (black body radiation), thermodynamics was of interest – at that time – only in connection with the new statistical description of quantum systems (Bose-Einstein and Fermi-Dirac). Insofar as thermodynamics had not been forgotten totally, its application was concentrated mainly on the study of pure bulk behaviour. However, at the beginning of the second part of this century, problems of surface thermodynamics came to be discussed with increasing interest and its development was initiated into scientific areas like physics, chemistry and biology.

A crucial role in surface thermodynamics is played by the surface energy. Its knowledge allows one to solve many problems in different branches of science: adsorption phenomena, nucleation phenomena in a phase transition, determination of the nucleation rate, formation of clouds, condensation of primordial vapour in the solar system to form meteorites, domain structure in biological membranes etc. Many of these effects are caused by the finite size of the system, i.e. by the influence of the size of the system on its thermodynamic behaviour. In this case one has to calculate the surface tension γ as a function of the size of the system, while Albert Einstein [3] has assumed in his treatment that γ does not depend on the size of the system, an assumption which is only true for a system with a flat surface or interface. A fresh approach for calculating the interfacial free energy of a system with a flat interface has been developed by Cahn and Hilliard [4]. But the value of the surface tension for a small system with a curved interface may be significantly different from that for a bulk system with a flat surface.

In discussing the size effect on the surface tension we study as a prototype example the problem of a phase transition via nucleation as an important application of a size-dependent behaviour of a thermodynamic system. Our model system consists of a homogeneous liquid droplet of radius r surrounded by its homogeneous vapour phase. This model for treating systems in heterogeneous equilibrium with curved interfaces has been advanced by several authors [5] and is routinely used in classical nucleation theory (drop model).

Before I go on to discuss some relevant size-dependent problems within the frame of equilibrium thermodynamics let me give some comments on non-equilibrium problems. There exists today a great interest in non-equilibrium surface processes arising in different disciplines such as physical chemistry, cell biology, chemical genetics, enzyme regulation, morphogenesis, immunology and biology [6]. It is a great success of the methods of mathematical physics that such complex problems can be formulated in terms of mathematical models. Of course, a complete understanding of all these phenomena including non-linear problems requires further investigation. But an increasing number of publications indicate a growing interest in these modern scientific ideas, which influence not only natural sciences but also medical research.

The main problem arising in equilibrium surface thermodynamics is the calculation of excess quantities like the Helmholtz free energy $\Delta F = F(r) - F_0$, where $F(r)$ means the free energy of the finite system (for instance, a droplet of water in equilibrium with its surrounding vapour phase) and F_0 is the reference energy of the corresponding bulk system. Having in hand $F(r)$, the size effects of several thermodynamical equilibrium quantities can be calculated. Let me give some examples: the knowledge of the excess free energy $\Delta F(r)$ for a photon gas in a finite box leads to size-dependent corrections of the Stefan-Boltzmann Law [7]. The knowledge of the density of photon modes in a boundary limited system gives us corrections to Planck's radiation law [8]. Calculating the excess free phonon energy of a finite solid we shall be led to size-dependent corrections of Debye's specific heat formula [9]. Modern experimental technologies have been developed to observe such types of size effects [10].

Another type of size-dependent problem, where the surface tension γ comes into play, is related to first-order phase transitions in finite systems. Formation of clouds, adsorption and nucleation phenomena and the problem of domain structure in biological membranes are prominent examples of this branch of surface thermodynamics. The crucial role in dealing with such problems is played by the formation energy (excess free energy) for a droplet: $\Delta F = F(r) - F_0 = A\gamma - V_l n_l kT \ln y$, where $y = p/p_0$ is a measure for supersaturation, p is pressure, $A = 4\pi r^2$ is the droplet surface, $V_l = 4\pi r^3/3$ its volume and n_l number density of the condensed phase. Knowing this free energy expression, which follows from the classical drop model, the size effect on phase transitions can be discussed. The decrease of transition temperature T with decreasing droplet size r is a well-known and experimentally observed consequence of a size-dependent phase transition [11]. Plotting the excess free energy as a function of the droplet radius r (see Figure 1) but keeping the surface tension γ constant (independent of r) we observe the expected maximum of ΔF at the critical droplet size $r = r_c$, but with increasing r, ΔF decreases without bound as $r \to \infty$ (curve (a) of Figure 1). This behaviour is typical for the commonly used drop model which assumes that (i) the formation of a liquid cluster does not reduce the number N_g of vapour particles, (ii) the surface tension γ is independent of r and (iii) the vapour phase shows ideal gas behaviour. Within these restrictions the drop model does not work very well. But giving up restriction (ii) and taking into account a size-dependent surface tension $\gamma = \gamma(r)$, (Tolman's result), the surface energy $A\gamma(r)$, which represents the work required to

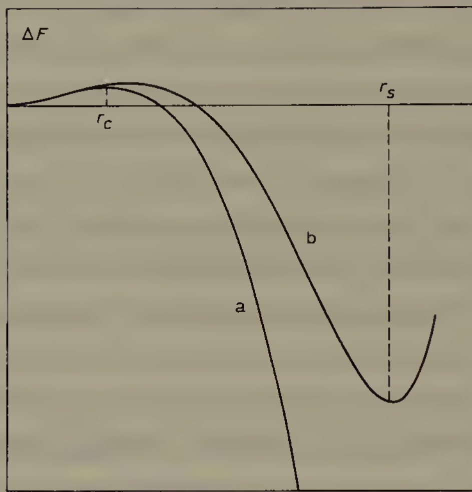

Fig. 1. Qualitative plot of the excess free energy $\Delta F(r)$ as a function of droplet size. Curve (a) shows the result of the standard drop model based on an infinite vapour phase. Curve (b) results from the verified drop model and has a minimum at $r = r_s$ indicating a stable droplet size as a consequence of a finite vapour phase.

create a spherical surface of area $A = 4\pi r^2$, now shows agreement with experimental observation [12]. But this verified drop model is still incorrect for large droplet sizes ($r >> r_c$) due to the fact that ΔF is still decreasing without bound for $r \to \infty$. Giving up, additionally, restriction (i) and keeping $V_g + V_l = V =$ constant and $N_g + N_l = N =$ constant with variable V_g, V_l, N_g and N_l, where l stands for liquid and g for gas, one shall be led to a modified drop model with a corresponding formation free energy ΔF, which shows for certain fixed supersaturations y, two extrema indicating a maximum at the critical droplet size $r = r_c$ (as before) and in addition a minimum (for $r_s > r_c$) marking a stable droplet of radius $r = r_s$ (curve (b) of Figure 1). This existence of stable droplets are in agreement – at least qualitatively – with observations, with molecular dynamical calculations and with Monte Carlo simulations. Giving up, additionally, restriction (iii) and taking into account that the vapour is not an ideal but a real gas, no new characteristic features will occur but the model becomes now more quantitative [13]. I wanted to draw attention to these developments in surface thermodynamics as a supplement to the drop model, which can be used in this verified version for the determination of the size of a stable cluster under fixed thermodynamical conditions.

The effect of size and curvature in liquid bilayers and biological membranes opens an interesting field of applications of such thermodynamical methods for treating some relevant biophysical problems. In biological membranes, for instance, stable circular domains have been observed. These domains have a size of $r_s \approx$ some 100 Å, which is of the order predicted by the verified drop model discussed above. This domain structure has been very recently investigated experimentally and compared with theoretical models [14].

The size range of some 100 Å or less is relevant in most nucleation phenomena. For larger clusters or domains of some 1000 Å or even more the surface tension γ can be regarded as independent of the size of the system and curvature effects can be neglected. But for sizes of the order of some 100 Å or less, γ depends on r. In this case Tolman's expression for $\gamma(r)$ can be used [15]. Einstein, obviously, considered a large system or a system with a flat interface in his first paper. But it stimulated the development of surface thermodynamics, which influenced – at least partially – present-day science in such widely different branches as those pointed out above.

ACKNOWLEDGEMENT

I am grateful to Dr. F. Gleisberg for plotting the Figure 1.

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Charles W. Misner

The Immaterial Constituents of Physical Objects*

Some of Einstein's ideas were so forceful and clear that it was quickly evident they would have a permanent cultural impact. For instance, special relativity reconstituted space and time. Minkowski proclaimed its impact in elegant phrases, 'Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality' [1].

Einstein's influences as clear and dramatic as this I do not need to review. And I lack the historical skills to seriously assess the impact of Einstein's ideas on modern culture, even if that would fit the title of this conference nicely. But I would like to inquire about Einstein's impact by pointing out some nebulous but pervasive ingredients of our present culture in which I seem to see the spirit of Einstein.

In addition to overturning our ideas of space and time, special relativity also constituted an assault upon the mechanical view of the physical world and upon the materialistic view of nature. After special relativity was accepted, one no longer searched for insight into what really lies at the base of electromagnetic phenomena by conceptually building mechanical models full of gears and idler wheels, or by imagining an ether as a superpenetrable material with peculiar elastic properties. Instead, Einstein's concept of a

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field, as refined from the ideas of Faraday and Maxwell, is frequently taken as fundamental. Today the search for insight into what really lies at the base of elementary particle phenomena often leads to building conceptual models of interacting fields. (Of course, the model builders of both Maxwell's generation and our own, although often motivated by a desire to know 'what things really are', proceed with a very large dose of skepticism as to whether the models they create actually seize much of that goal.) The question I present then, as defining an area in which the impact of modern scientific ideas on society should be studied, runs: 'Is the world made up of material objects?'

An aspect of this question was forcefully presented by Sir Arthur Eddington (who, as we know, led the eclipse expedition in 1919 that seems to have triggered the elevation of Einstein to his unique status as a hero in the popular culture). Writing the introduction to his popular book, *The Nature of the Physical World* [2], he says (and I condense):

> I have settled down to the task of writing these lectures and have drawn up my chairs to my two tables . . . .
>
> One [table] has been familiar to me from earliest years. It is a commonplace object of that environment which I call the world . . . . Table No. 2 is my scientific table . . . . [It] is mostly emptiness. Sparsely scattered in that emptiness are numerous electric charges rushing about with great speed . . . . Modern physics has by delicate test and remorseless logic assured me that my second scientific table is the only one which is really there – wherever 'there' may be.

Eddington does not say that his scientific table contains no material substance (although he questions it), nor can we now. The idea that everything is to be explained as a construct built from some replacement for Newton's 'hard, massy' material atoms is a theme [3] still capable of motivating scientists. If elementary particles have failed to be elementary, no matter, a search for the 'ur-atom' still proceeds.

But it is not the 'ur-atom' but a contrary theme that I want to explore. Eddington's captivating review of modern science shows that the material substance of the universe is on the defensive in this century, reduced at most to scattered specks in the emptiness, its garrisons pulled together in isolated posts. Of course, it does not necessarily follow that by conceding ground in the spatial arena, matter has lost sovereignty in the sphere of understanding. But, in fact, matter's position is not good there either. For the scientist who can see Eddington's second table, the locus of understanding is not in the matter, the particles, but in the interactions among them. We do not say what an electron is, but we do write laws for how it interacts with photons and other electrons. Thus, even for the action-at-a-distance atomic theorist, the locus of understanding is not in the specks of matter, but in the intervening space through which the particles communicate in order to interact, and in the patterns of higher symmetry in the laws describing their interactions.

Part of Einstein's genius was his ability to see real if invisible things inhabiting the emptiness in Eddington's table, where so many others had seen nothing. Attempting to explain how we grasp external realities, Bronowski tells a delightful tale [4] of a Sherpa mountaineering guide who had for a lifetime known two mountains, seen from two different valleys, and called by their own proper names in the different local languages. The guide reacted with the pleasure of scientific insight when a European climber suggested that they were the same mountain, seen from different viewpoints. And the guide could then even verify this to his greater satisfaction by recognizing features visible in both views. In some such way an infant must correlate his varying retinal images as he turns a toy over in his hand and achieves the conception of independently existing external objects that we all share in common discourse. This was Einstein's approach, also, in special relativity. He had no need for the Michelson-Morley experiment. He had instead played with a simple electromagnetic induction experiment in his mind. Viewing this experiment one scientist could see electric forces at work, another magnetic forces. These E_i and B_i forces were, to infant scientist Einstein, mere retinal images. But he soon saw, and taught others to see, the really existing thing, the invariable object in the external world (indeed in empty space), that gave rise to them, namely the electromagnetic field F_{ab}. Notice how different my emphasis is from the usual statement that Einstein unified the two vectors E and B in the tensor F. It is not the unification I stress, but the grounds he found for conviction in the existence of some external reality (here F). By this insight Einstein discovered fields in nature as surely as Galileo discovered the solar system by showing it to us (actually a model of it) from a new viewpoint in turning his telescope on the moons of Jupiter.

We must now skip rapidly on. Einstein showed us that immaterial entities are fundamental constituents of the universe. He discovered (in the sense described above) not only the electromagnetic field, but also the gravitational or metric field. He also introduced into physics the first conscious use of what is called 'higher symmetries', which is the use of mathematical structures as co-authors in writing the laws of physics, and not merely as the pen and paper that communicate and embody the laws when written. (Perhaps in these higher symmetries we will find those further embodiments of geometry in physics for which Einstein had long searched, as Dirac has reminded us.) The extent to which these generative structures will be seen as fundamental constituents of ordinary matter is not yet known. Most theories of this type (general relativity, Yang-Mills, harmonic maps) are only beginning to be explored, and we cannot have a sound philosophical reaction to vague hints of insights speculated for achievement in the future.

But beyond Einstein and modern physics we find many other examples in modern culture of the expanding conquest of immaterial entities while material objects decrease relatively in value, although apparently overwhelming us. Russell Baker in a humorous column for the New York Times about a decade ago made the point. 'What do you do all day, Daddy?' asks a young school child studying his first books, which have stories of colonial villages filled with blacksmiths, carpenters, farmers, and other materialists. 'I go to New York and sit at a desk.' 'Yes, but what do you do at your desk?' 'I read papers people give me, sometimes I write something on them, then the papers go on to other people, or into a box.' 'What do the other people do with the papers?' 'The same thing.' 'And is that how automobiles get made then, Daddy?'

To an increasing extent it appears that this, in fact, is the way automobiles do get made, and computers even more so. The computer field provides also the best language for succinctly summarizing the theme I am trying to explore. There it reads: 'Hardware is software.'

We know that software in the form of labour, design, advertising, management, finance, insurance, etc., is a significant part of any product. For nuclear power, for instance, fuel is a relatively small part of the cost, with the major parts being development, design and labour costs, and interest on the invested capital. The theme 'hardware is software' suggests that in any object whatsoever there is nothing except design and environmental impact (or ecological participation) and other such 'software' constituents. While we are normally prepared to accept that material objects embody significant 'software' in the form of design and craftsmanship, we customarily assume that the coal and steel or other material used in the construction process are something entirely different. Eddington's table reminds us, however, that all we have so far found by the scientific study of such materials is more design, more software. The theme 'hardware is software', whose origins (including the field concept as clarified by Einstein) I would like to see traced, proposes that 'software' is not only all that we will ever find, but even that in some sense it is all there actually is underlying the material world of everyday experience.

Chemistry, and particularly biochemistry, is a field where the 'hardware is software' theme seems quite apt. Chemical theory discusses how some basic 'material' units combine and interact to produce a variety of substances. The units may be atoms or molecules, or other groupings, but are rarely anything as small as an electron or a nucleus. Thus the chemical unit is not normally Eddington's 'speck of matter' but rather a conceptual or software unit corresponding to logical and geometrical relationships among other smaller units that include the 'speck of matter' that only gets resolved into software by the elementary particle physicist. The DNA molecule is an excellent example of this hierarchy, with its arrangement in terms of phosphates, sugars, and nucleic acid bases seldom resolved into atoms in any discussion. And above this level of organization it also shows more software, with bases grouped into triplets as characters in a twenty letter alphabet, and these into longer messages coding complete proteins, and these again into still larger structures whose significance for the processes of cell development are only beginning to be worked out. But even greater levels of software are required before a simple piece of biological 'material' such as a simple cell is explained. One is also curious why some DNA strings have come to exist, among all those physically possible, and other DNA strings not. This, we find, is governed largely by history, through the process of evolution.

I hope I have now sketched enough so that you can provide yourself with many more examples illustrating how the modern scientific viewpoint can be considered radically anti-materialistic, since all its explanatory power resides in the immaterial constituents – the design relationships – in the objects it analyses. This 'hardware is software' theme is rarely explicitly stated (Einstein's hopes for a unified field theory and some successors in that tradition being exceptions), but it is so close to the surface in the work being done in many fields that I presume it must be having some quiet impact on society at large. I cannot imagine that one important and pervasive myth – Newtonian atomism – can be jettisoned in favour of another – Einstein field theory – at all levels of culture and society without consequences of great moment. The nature of these changing presuppositions can be stated, in conclusion, in the language of another myth:

> The world is made of earth
> water air and fire.
> Earth and water are, we see,
> just knots of air and fire –
> what then can air and fire be
> but skeins of hope and history?

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E. R. Caianiello

Some Remarks on Organization and Structure

I. INTRODUCTION

1. The view is here taken that the search for general principles governing the formation and change of structures in systems of the most varied sorts (biological, social, economical, linguistic, military, physical . . .) may be, at this time, a legitimate object of scientific enquiry; that such principles, if any, should be very few indeed, because of their assumed universal character; that the major difficulty in the task proposed may be expected to lie in the discrimination between the obvious (as any such principle is wont to be *a posteriori*) and the evident, which is readily seen but not as readily recognized to be most often of a specific rather than general nature.

Any such endeavour can only be a study of models (stemming from motivations that need interest only the author), the cruder at the inception the better; also, overly general definitions turn out to be, more often than not, wishful thinking or mathematical traps. The discussion that follows adheres strictly to these premises, by being a discourse on models rather than on things, narrowed by definitions as strict as possible. This constraint will not be maintained in the last Part, where some comparisons with known facts are made and others are proposed as objects of theoretical and experimental research.

2. The concept of 'system' is taken as primitive. Although

'large' systems with 'complex interactions' among their elements ('element' is also of course a primitive concept) are our main interest, these added qualifications, easily confusing, are not needed and better kept away at this stage.

Two examples will be useful to fix ideas and render most of the following intuitive:

(a) given an alphabet A of M letters, consider all possible strings of letters, of any length (up to a maximum, if so desired): they form the *semigroup* generated by A. Again, consider all possible sequences of such strings: this is the *monoid* A^* generated by A;

(b) given a number system (e.g. decimal) consider the semigroup obtained as in (a) with $A \equiv (0, 1, \ldots, 9)$, $M = 10$: this contains all integer numbers (up to a maximum, if so desired). A^* will be formed by all possible sequences of numbers (no connection with the operations of arithmetic is implied).

We restrict from now on, *by definition*, our attention only to systems composed of a *discrete*, however large, number of elements. The rounding off of a number into the nearest integer will be *understood without further mention*, as a necessary approximation in the application of theory: e.g. $\sqrt{10} \equiv 3$, if it denotes number of cells, coins or people.

Each string of (a) or number of (b) is, by our definition, a system; so are the corresponding semigroups, or the closely allied monoids. The relation is that of 'system' to 'ensemble' in statistical physics; both concepts will be necessary for us, but the word 'system' will be used indiscriminately to cover *both* instances; the context will make it clear when the discussion applies to both, or only to one situation.

3. A definition of 'structure' will not be attempted in general (it would have no less traps than that of 'randomness', and would be useless for our purposes); we shall rather confine our attention to a particular class of systems (*hierarchical systems*, HS) and more in detail to a subclass of them (*hierarchical modular systems*,

HMS), to be defined in Part II. We shall say that an HS or an HMS (or whatever other system we may have decided to define unambiguously at any time) *have structure* or *are structured*; whenever the word 'structure' is used, it must be so understood.

An HMS will be seen to behave much like Example (b) in the previous section, the 'module' corresponding to the arithmetical base $M(= 10)$.

4. A structured system may be subject to change in the course of time. We distinguish two types of behaviour in this respect, which are best described first by an example. Suppose the system is isomorphic with a set of numbers; the first type of change has to do with changes of these numbers, we may call it 'evolution'; the second with a change of the structure itself, which in this example corresponds to a change of the base of the number system (to provide isomorphism with the new situation of the system): we call this a 'revolution' (we are not considering the 'wrecking' of the system, which one is of course at freedom to call 'revolution' as well).

A change of structure is therefore a 'revolution'. We shall be concerned mostly with this type of change and shall restrict (arbitrarily) the use of the appellative 'self-organizing' to systems which can spontaneously change their structure (besides evolving) so as to meet new situations. We emphasize that our use of words is merely technical, and that a literal reading might prove as misleading as it might appeal as suggestive. (To resort to facile analogies, the warming up of water is for us an 'evolution', its boiling a 'revolution'; the clustering of spins into domains, and again the alignment of the latter into a magnet, and generally all phase transitions of physics, are revolutions; likewise the depolarization of a neuronal membrane, or the sudden transition from the all-white to the all-black state in some U.S. neighborhood once a critical black/white ratio is reached.)

Structure emerges as a quantification into the discrete of the continuum or indefinite; a change of structure must be a change among integer values, so that a criterion of stability is thereby provided to self-organizing systems against arbitrarily small perturbations.

5. Part II contains the necessary preliminary postulations and definitions, as well as a description of what a non-structured system may be expected to gain by acquiring a hierarchical structure.

Emphasis is then placed on how one may best characterize structures (assumed as *given*, the mechanism of their formation is *not* the object of investigation), and parameters pertaining to them, so as to judge their efficiency in performing specific tasks. This is done in Part III, on the particular case of HMS's, which are amenable to a complete mathematical treatment; they are expected to play a relevant role in further analyses of this nature, both as conceptual tools and as approximating devices.

In Part IV it is shown that a full thermodynamics (not only an 'entropy', but also a 'temperature', an 'energy', etc.) can be developed for HMS's.

Part V is devoted to a first, by necessity preliminary, comparison with some realistic situations. HMS's are seen to have a distribution law which coincides strikingly with that empirically determined by experts from available data on the monetary circulation in the world's countries; the agreement of it with the standard military chain of command is also intriguing. A brief discussion of further possibilities, as well as limitations, of the present approach is finally given.

II. DEFINITIONS AND REMARKS

1. *Bose-Einstein and Boltzmann Counting*

Elements will be regarded as *identical*, non distinguishable, when in a collection of them their identity is *irrelevant for the purpose at hand*. Thus, any two groupings into a same 'state' of the same number n of infantrymen to form a squad, or of 100-dollar bills to form a same total (if one is not interested in forgery and serial numbers), etc., are indistinguishable for the general officer, or the tax collector, conceived here as physical 'Observers'.

We pose no *a priori* restriction on the values that n, the number of identical elements of some sort, may assume; given n, the number W of *different* states that can be formed with them is clearly $W = n + 1$ ($n = 0$ is included). This is the counting of Bose-Einstein statistics (we do not treat here, though we do not exclude, situations in which Gentile or Fermi counting may be appropriate).

Whenever non-identical elements are involved, e.g. coins of different denominations when this is important, Boltzmann counting will apply.

2. *Information and Level Formation*

Since we are going to utilize quantities that are familiar in Thermodynamics, our notation and symbols will conform to physical usage and terminology. This is of course only a matter of conceptual convenience, the reader need not feel so constrained.

We need first to get some notion of the function of hierarchical levels in a system. This is best seen by an example; of the host that might be quoted, the simplest is perhaps that of a monetary system. We ask whether any reason can be found for the fact that all such systems (in less than primitive societies) are always quantified into discrete units of different denominations and values, rather than being 'continuous' (as would be the use, say, of gold by weight, any weight; 'evident' reasons, such as the certification of exact weight imprinted by the royal mint of ancient Lydia, or many others to be found in history, would be misleading for our purposes). We assume to have at the start only an indefinite amount of coins, or tokens, of a same unit value (we are restricted to discrete systems: this is here no limitation, only a simplification).

Plot (Figure 1) on the horizontal axis the number of different

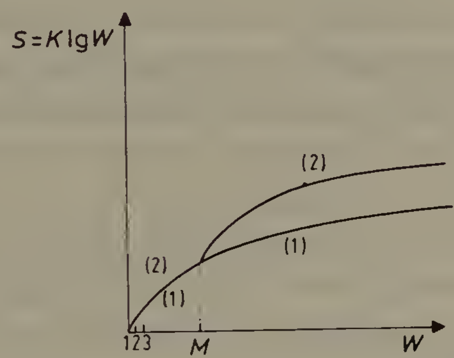

Fig. 1. Information growth with clustering.

possible states (sums of money) $W = n + 1$, on the vertical the corresponding entropy (or information: no distinction is here necessary)

$$S = K \lg W = K \lg (1 + n).$$

The logarithmic growth of S (nearly linear for small n, increasingly slower for higher n), well typifies our correspondingly increasing awkwardness in handling the system when n grows, whatever we may want to do or know about it (Von Neumann, 1958): doubling n nearly doubles S for small n, while for large n an enormous increase is necessary to double the information S.

Suppose that, at this point, the system is restructured into a new one, in which identical 'clusters' of unit coins, each containing M elements, are formed; a cluster is a bag of unit coins, or, equivalently, a second type of coin. We can now form a definite total in more ways, if it exceeds $M - 1$; suppose we use n_1 unit coins and n_2 coins of the second type, and put them down one at a time, starting with the unit coins. The latter being distinguishable from the former, we have

$$W = (1 + n_1)(1 + n_2)$$
$$S = K\lg(1 + n_1) + K\lg(1 + n_2).$$

Curve 1 of Figure 1 changes into Curve 2, which has a kink, and separates from 1 to form a new logarithmic arc *which is again nearly linear for small* n_2, as soon as the new coins start being used. *The introduction of a new value, or level, keeps the information nearly linear within a broader range* (n_1, n_2). Another way of looking at Curve 2 is to imagine its second arc as deriving from a contraction by a scaling factor $1/M$ of the subjacent portion of the horizontal axis. We may then want, associating information with value, the following:

$$S = K\lg[(1 + n_1)(1 + n_2)] = K\lg(1 + n_1 + Mn_2).$$

This occurs only if $n_1 = M - 1$, that is, we must not use unit coins unless necessary.

The latter remark is not trivial, it is rather typical of questions that arise once one starts in this field. We need not comment upon it here, as the issue will become evident from the sequel. We have thus seen that, informationwise, we can cope with the same ease with any system of identical elements (that is, staying always nearly linear) provided these systems are organized into levels, the elements of which are identical clusters of those of the level below, and that such clusters be treated as, or replaced by, new elements, identical among themselves but not with those of levels below or above.

3. Clustering

We have thus a cue for regarding clustering, and then the identification of a cluster as a new element of a different nature than its components, as a typical process of level and structure formation; also, a hierarchical arrangement of elements, clusters, clusters of clusters, etc., appears as a rather natural mechanism to achieve this effect.

We note that an element, by becoming a part of a cluster of the next higher level, *loses* many of its features and *acquires* the new function of member of the cluster. All examples we can draw, from collective motions to biology to army life, substantiate this view.

4. Definition of Hierarchical System

We are now ready for a definition which will suffice for our present purposes. Greater generality would be only detrimental at this stage.

Consider a system composed of elements of levels 0, 1, 2, . . . , L ($\leqq \infty$). The elements at each level are indistinguishable among themselves, distinguishable from those at other levels. Let there be n_h elements in the level h ($h = 0, 1, \ldots, L$).

The *total number of elements* is

$$(1) \qquad N = \sum_{h=1}^{L} n_h.$$

Such arrangement we call a *partition* of the elements of the system.

Attach now to each level h an (integer) *value* v_h; the *total value of the system* (we assume for simplicity that there is only one value function) is:

$$(2) \qquad V = \sum_{h=0}^{L} n_h v_h;$$

the *average value of an element* of the system is then:

$$(3) \qquad \langle \nu \rangle = \frac{\sum_{h=0}^{L} n_h \nu_h}{\sum_{h=0}^{L} n_h}.$$

We recall that we have convened to term 'self-organizing' a system which can organize itself by the partitioning process into one or another hierarchical structure. This definition may be readily generalized to any other given specification of structure.

We further require that the value function be such that:

$$(4) \qquad \frac{\nu_h}{\nu_{h-1}} = \text{integer} > 1, \text{ any } h;\ \nu_0 = 1 \text{ (in suitable units).}$$

If, in particular, (4) reduces to:

$$(5) \qquad \frac{\nu_h}{\nu_{h-1}} = \frac{\nu_{h-1}}{\nu_{h-2}} = \ldots = \frac{\nu_1}{1} = M,$$

we call the system *modular* (HMS), and M the *module* or *base* of the HMS and of the corresponding partition.

5. Hierarchical Partitions

We are now concerned with relations among different partitions of a same self-organizing system. We call a partition π_b a *refinement* of a partition π_a if it has more levels than π_a and retains *all* the levels of π_a (which stay invariant under π_b).

A *hierarchical modular partition* $\pi_b^{(\mathrm{mod})}$ is therefore a refinement of a previous $\pi_a^{(\mathrm{mod})}$ if, and only if:

$$(6) \qquad M_b = M_a^{1/p}, \quad p \text{ integer} > 1.$$

From now on our interest will be confined to HMS's. After (6), we shall call for short any $\pi_b^{(\mathrm{mod})}$ a *p-refinement* of $\pi_a^{(\mathrm{mod})}$.

6. Hierarchical Modular Systems

They have many interesting properties, which the reader may easily consider by himself. We notice here only the following: provided the number of elements employed at each level is always $\nu_h < M$, any (integer) value ν (not exceeding the total value of the system) can be expressed *in a unique way* in terms of elements of the system:

$$(7) \qquad \nu = \nu_H M^H + \ldots + \nu_0 M^0.$$

This property is far from trivial; it can be elaborated upon in several ways to lead again to a definition, or to other properties, of HMS's. The proof is immediate, if we choose M as the basis of a number system (decimal, binary, or whatever) so as to write $M = 10$; then (7) becomes

$$(8) \qquad \nu = \nu_H \nu_{H-1} \ldots \nu_0$$

and uniqueness becomes evident because all possible values ν can be expressed, provided $\nu_h < M$ (which is a minimal requirement) by means of *strings* (8), which are *isomorphic with the numbers of ordinary arithmetics in base M*; the figures ν_h retain their arithmetic meaning, level corresponds to position.

III. HIERARCHICAL MODULAR SYSTEMS

1. It is important to make a clear-cut distinction between two orders of questions:

(a) those pertaining to specific assignments of values to the levels of a HS or of a HMS (in the latter case to M^h); these, as well as the number $L + 1$ of levels, are in the present work assumed to be given *a priori* (their discussion is expected to be specific for each system, and therefore beyond our scope; we shall return to this point in Part V);

(b) those which relate to the distribution n_h of the N elements of the system among its levels, $h = 0, 1, 2, \ldots, L$, once their number and values are known; this distribution will reflect the way the system *adapts* to an *external* requirement.

We expect that general properties may be derived from a study of (b) in typical instances, i.e. models. As an example of the method, we shall give a complete discussion of HMS's.

2. As long as a self-organizing HS stays 'isolated', it has no reason (from what was said thus far) to prefer any particular choice of n_h. If, however, it is in 'interaction with the universe' this cannot be expected to be the case any more. We shall adopt for handling this problem the following principle: to assume that the system, which is in a given situation as assigned under (a), is however at freedom to change it by any *refinement* of its original hierarchical partition. This principle assumes, in other words, that the 'universe' is not interested into what partition the system chooses to organize itself; its interaction with the system is of a *global* nature, to be expressed therefore by requiring that the value of some *mean* quantity of the system be imposed from its outside (the universe).

We have here a requirement of invariance under a class of transformations (the refining partitions); this is important also because additional requirements (see Part V) may impose refinements of structure. We note, however, that (on purpose) we have said very little about HS's in general, as it carries more conviction in a first work to discuss completely a single, though restricted instance, than only to touch upon a variety of cases. We shall therefore from now on concentrate on HMS's, for which our definitions are complete; pleasingly enough, remarkable computational simplifications will be seen then to occur.

3. The principle just stated requires that the average value of an element of a HMS stay invariant under any p-refinement of the HMS

(9) $\quad M \to M^{1/p}$;

then

(10) $\quad L \to pL$

and it is wanted that ($n_h \equiv n_h^{(1)}$):

$$(11) \quad \langle v \rangle = \frac{\sum_{h=0}^{L} n_h^{(1)} M^h}{\sum_{h=0}^{L} n_h^{(1)}} = \frac{\sum_{h=0}^{pL} n_h^{(p)} M^{h/p}}{\sum_{h=0}^{pL} n_h^{(p)}}.$$

We also note that a HMS possesses a natural *invariant* under (9): the ratio of the maximum number of states to the module:

$$(12) \quad w = \frac{M^{L+1}}{M} = \frac{(M^{1/p})^{pL+1}}{M^{1/p}} = M^L.$$

We want to determine $n_h^{(p)}$ so that, for given L, M, (11) stays valid for any p. This task, otherwise formidable, turns out to be surprisingly simple for modular systems.

Take first $L = 1$ and set

(13) $\quad n_h^{(p)} = n_0^{(p)} f(M^{h/p})$, with $f(1) = 1$;

write (11) for $p = 1$ and 2:

$$(14) \quad \frac{1 + f(M) \cdot M}{1 + f(M)} = \frac{1 + f(\sqrt{M}) \cdot \sqrt{M} + f(M) \cdot M}{1 + f(\sqrt{M}) + f(M)}$$

whence

(15) $\quad f(M) = M^{-1/2}$

and

(16) $\quad n_1^{(2)} = n_0^{(2)} M^{-1/4}, \; n_2^{(2)} = n_0^{(2)} M^{-1/2}$.

Try now to generalize (16) into

$$(17) \qquad n_h^{(p)} = n_0^{(p)} M^{-h/2p}.$$

Substitution into (11) leads, after (12), to:

$$(18) \qquad \langle\nu\rangle = \frac{\sum_{h=0}^{pL} M^{h/2p}}{\sum_{h=0}^{pL} M^{-h/2p}} \equiv \sqrt{w} \equiv M^{L/2},$$

independent of p. The modular nature of the system is of course crucial in determining the simplification which leads to (18), and proves (17) to be indeed the correct solution of our problem.

We add from now on the further restriction that our HMS be such that:

$$N = n_0^{(p)} \sum_{h=0}^{pL} M^{-h/2p};$$

this is not in anyway necessary, may be easily removed and is made only to shorten the discussion to barest essentials. Then, in conclusion:

$$(19) \qquad n_h^{(p)} = N \frac{1 - M^{-\frac{1}{2}p}}{1 - M^{-\frac{1}{2}p - L/2}} \cdot M^{-h/2p}$$

is the distribution law that secures the wanted invariance of $\langle\nu\rangle$ under p-refinements.

In the following we need not consider values of p other than 1; in a HMS there is no way of knowing a 'past history' of levels. Note that, in particular:

$$(20) \qquad n_h = \frac{n_{h-1}}{\sqrt{M}}.$$

IV. THERMODYNAMICS OF HMS'S

1. Given an *HMS* with distribution law (we remind the reader that N has been assumed, for short, to be a constant)

$$(21) \quad p_h = \frac{n_h}{N} = \frac{1 - M^{-1/2}}{1 - M^{-1/2 - L/2}} \cdot M^{-h/2} \quad (h = 0, 1, \ldots, L)$$

we can regard p_h as expressing a frequency, or a probability scheme, to which we may associate an information, or entropy, in the familiar way:

$$(22) \quad S = -K \sum_{h=0}^{L} p_h \lg p_h .$$

A change of variables will clarify the form without altering the content. Write:

$$(23) \quad \beta = \frac{1}{KT},$$

$$(24) \quad \frac{E_0}{L} = \epsilon_0,$$

$$(25) \quad \epsilon_h = \epsilon_0 h,$$

$$(26) \quad M = e^{2\beta\epsilon_0},$$

and set then

$$(27) \quad Z = \sum_{h=0}^{L} e^{-\beta\epsilon_h} = \frac{1-M^{-\frac{L+1}{2}}}{1-M^{-1/2}},$$

$$(28) \quad \psi = \lg Z.$$

Then (21) is rewritten in the well familiar form

$$(29) \qquad p_h = \frac{1}{Z} e^{-\beta \epsilon_h}$$

and (22) becomes

$$(30) \qquad S = K\psi + \frac{1}{T} \langle \epsilon \rangle ,$$

where

$$(31) \qquad \langle \epsilon \rangle = \sum_{h=0}^{L} p_h \epsilon_h = \epsilon_0 \sum_{h=0}^{L} h p_h = -\frac{\partial \psi}{\partial \beta},$$

corresponds clearly to the average energy of Thermodynamics and means here, to within a factor ϵ_0, the *average order*, or *length*, of a level. For instance, should we attribute to each word, conceived as a string of h code letters, an 'energy ϵ_h', this energy would come proportional to h. We recover thus, from our premises, a concept which has been used sometimes by mathematical linguists (see Part V). The *variance* is given by

$$(32) \qquad \sigma^2 (\epsilon) = \frac{\partial^2 \psi}{\partial \beta^2} .$$

We note finally, from (18) and (23)–(26), that

$$(33) \qquad \lg \langle \nu \rangle = \frac{E_0}{KT} .$$

2. Our principle of invariance under p-refinements of the average value of a HMS leads thus (N = const) to the Boltzmann statistics (29). The quantities (25) $\epsilon_h = \epsilon_0 h$ that correspond to the usual energies are *not*, however, connected with the value, but only with the order of the levels. To have found a formal definition of energy, however remote our starting point, is significant, because we can then develop for any such HMS the full formalism of Thermodynamics.

We choose to do so with the 'subjective' interpretation of probability by means of which Jaynes (1957) has connected Information Theory and Statistical Mechanics (Rothstein, 1951). Although this is not necessary (we could just call $N\langle\epsilon\rangle$ = total energy), it may allow a freer transition between Information Theory and Physics, according to opportunity and without formal changes. To do so, we have only to remark that the average energy per element of the system is given by (31) and that (Tribus, 1961) we can regard

$$(34) \qquad dQ_r = \sum_{h=0}^{L} dp_h \cdot \epsilon_h$$

and

$$(35) \qquad dW_r = \sum_{h=0}^{L} p_h d\epsilon_h$$

as the (reversible) heat and work, so that

$$(36) \qquad d\langle\epsilon\rangle = dQ_r - dW_r$$

is (one way of formulating) the first principle of Thermodynamics for our HMS. Next, if ϵ_h (through ϵ_0, h or both) is dependent on some external parameters X_k [which act upon the system: $\langle\epsilon\rangle = \epsilon(\beta, X_k)$], then one can define forces

$$(37) \qquad (F_k)_h = -\frac{\partial \epsilon_h}{\partial X_k}$$

so that, for a change dX_k

$$(38) \qquad dW_r = -\Sigma\, p_h d\epsilon_h$$
$$= -\sum_{h,k}\left(p_h \frac{\partial \epsilon_h}{\partial X_k}\right) dX_k = \sum_k \langle F_k\rangle\, dX_k$$

and from (27) and (28):

$$\langle F_k \rangle = \frac{1}{\beta} \frac{\partial \psi}{\partial X_k} .$$

Also:

$$(39) \quad \begin{aligned} dS &= K d\psi + K\beta d\langle \epsilon \rangle + K \langle \epsilon \rangle d\beta \\ &= K\beta d \langle \epsilon \rangle + K\beta \sum_k \langle F_k \rangle dX_k . \end{aligned}$$

and, for reversible processes:

$$(40) \quad dS = K\beta dQ_r + K\beta \Big(\sum_k \langle F_k \rangle dX_k - dW_r \Big) = K\beta dQ_r ,$$

or

$$(41) \quad dS = \frac{dQ_r}{T} .$$

The discussion is omitted, because it is amply done in the references cited in this Section, and otherwise, if things are done in the traditional way, it is standard.

By analogy with physics, two different HMS's 1 and 2 will be said to be *in equilibrium* (0^{th} law) if they have the same 'temperature' T, or β (23), *to which we must now add the further requirement that* $\langle v \rangle$ *be the same for both*; from (33):

$$(42) \quad T^{(1)} = T^{(2)} ,$$

$$(43) \quad E_0^{(1)} = \epsilon_0^{(1)} L^{(1)} = E_0^{(2)} = \epsilon_0^{(2)} L^{(2)} .$$

If $\epsilon_0^{(1)} = \epsilon_0^{(2)}$, then (43) imposes that, besides having the same 'temperature', the two systems have also the same number of levels; if $\epsilon_0^{(1)}$, $\epsilon_0^{(2)}$ are some integers, there will be obvious connections with refinements.

V. CONCLUDING REMARKS

1. Invariance within an Equivalence Class

We may now try to give a general formulation to the method which has been here applied *in extenso* only to a sub-class (N = const) of HMS's. Asking no questions as to 'why', but only as to 'how', we take as initial data a description of the levels; and of the value functions attached to them, of the system (these define its 'structure'). In so doing, one is naturally led to consider transformations, such as the p-refinements for HMS's, which change the system into an 'equivalent' one, both as regards its interaction with, i.e. response to, its 'universe' (as measured by average values) and the type of its structure (e.g. modularity must be retained). The specification of such transformations can be regarded as part of the initial data: what one defines is really an *equivalence class*, within which a self-organizing system can freely move. (A mathematical study linking structures with structure-preserving transformations is of course called for.)

Such transformations within its equivalence class will actually take place and change the structure of the system during its development (e.g., because forced by external influences, or by the growth of the number of individuals in a population model, or of the volume of trade in an economical model . . .); this fact is *not* considered here, because it is to some extent *specific* of each system.

All our attention was focused in this work on finding a general criterion that might allow the determination of the population of each level, once the initial data are given. As such we have proposed, and applied to HMS's, a 'principle of invariance of response under allowed structural transformations': 'response' or 'interaction' is measured through mean values, 'allowed transformations' are in our example the p-refinements. That is, the 'universe' does not know nor care about which class a self-organizing system chooses to settle in, within equivalence.

2. Mathematical Linguistics

The present research stems from work done in mathematical linguistics (Caianiello and Capocelli, 1971), aiming at an *inductive* study of the hierarchical organization of a language; the Example I-1a) is carried over from it. We take, in this respect, HMS's only as a very first step, meant for formulating questions more than answering them.

It is however significant to find, even so, a natural connection between 'energy' and 'word length', such as was postulated by Mandelbrot (1954) in his attempt to find an explanation of the so called 'Zipf's law' (1949); proceeding further as he does, we would immediately obtain the same result, for any HMS and not only for somewhat idealized languages. This we refrain from doing, as we feel that Herdan's criticism (Herdan, 1962) is not to be taken lightly.

3. Monetary Systems

HMS's should be regarded as the crudest possible models of self-organizing systems, especially with the (unnecessary) restriction that the number of elements stay constant under refinements. It was therefore rather surprising to find a realistic situation which is described by them quite satisfactorily. The evidence is provided by an interesting study made by Hentsch (1973) (former president of the 'Association suisse des analystes financiers'), in which a penetrating analysis is made of monetary circulation in the various countries of the world, in the attempt to find some regularities; data are reported by this author for the 1969 circulation in Switzerland, and the 1971 circulation in Switzerland, France, Holland, Germany, and USA; the results he discovers are said to hold for all countries. They all reduce, in our notation, to the law

$$(44) \quad n_h \nu_h \propto \sqrt{\nu_h}\,,$$

which exactly coincides with (17), when $p = 1$ and $\nu_h = M^h$. Various fractional powers of 10 are studied, notably

$$(45) \quad 10^{1/3} \to 1, 2.15, 4.64, 10, 21.5, 46.4, 100, \ldots$$

which, after rounding off to nearest integer, should be well familiar to the reader.

Even more interesting, perhaps, is the fact that the law (44) (which is generally followed within one, at most two, variances) is occasionally not respected; Hentsch shows that this happens either because some country lacks some value of the sequence (45) [and computes that everything would go back to (44) otherwise], or because of external causes [the graph for Swiss circulation in 1969 deviates in excess from (44) for the values 0.5, 1, 2, and 5 francs, which were coined in silver; in 1971 silver was no longer in circulation, and the corresponding graph follows (44)]. The simplification in formula (18) was also noted by this author.

The explanation of this behavior, once it is ascertained empirically that a monetary system is a HMS (M need not of course be necessarily $10^{1/3}$), becomes quite obvious in our perspective. A monetary system is not just a game, it interacts with the 'universe' of all that can be exchanged with money; the requirement (18) and the principle of invariance under p-refinements mean here simply that the average value of the monetary token must equal the average value, or cost, of anything that may be bought or sold, from needle to skyscraper: this 'universe', we repeat, 'does not know nor care' about what module a country may choose for her monetary system.

4. Human Society and Military Structures

Some considerations on human societies cannot be avoided in discussing this subject; we shall do so in the crudest possible manner, by considering as the only basic factor common to any form of society the necessity that its members have of *communicating* among themselves in order to undertake any activity that may be termed social. Of communication we observe that it takes *time*, in amounts which increase with the complexity of the task to be agreed upon or commanded; and that *rational* communication becomes the less efficient, the larger the group with which an individual has to communicate. Aside from one-level societies, which may be termed anarchic and are found only in very small groupings, all others are hierarchical (which does *not* mean authoritarian).

The crudest model one may make is then, again, a HMS where, treating all individuals and tasks as equal, the module M denotes the (assumedly constant) number of individuals who are communicating with, or controlled by, an element of the next higher level.

This model may be compared with the chain of command typical of military organizations. Within this writer's experience (not altogether negligible, thanks to the Second World War!), $M \cong 10$ can be very nearly taken as the module (unless otherwise required for technical reasons). But then one is immediately struck by the systematic appearance of the number 3 (3 leaders: 1 sergeant and 2 corporals, for a squad of 10 soldiers; 3 squads to a platoon, 3 platoons plus one squad to a company; and so on). If we now look at (20), we find that $\sqrt{10} \cong 3$ is just what a HMS would require in this case.

This can only be an argument proposed for discussion: it would be interesting to know from experts how things stand, in case there are armies or similarly schematizable societies where M is significantly $\neq 10$; as well as to know how levels were developed in the course of history.

Another such modular society was that of the Incas – except that, at the highest *échelon*, one finds 4 instead of 10 (higher decisional responsibilities, or something to do with the cardinal points?).

Of the myriads of questions that come to mind only two will be formulated here as examples; both are based upon the crude assumptions that M is a *biological* constant and that no other factors are involved. When the number of individuals increases, M cannot change, so there is the need for p-refinements, or 'revolutions' (no blood is meant!); the dynamics of this phenomenon requires the intervention of splitting forces, or 'social tensions', which it should not be difficult to estimate in models using the Thermodynamics of HMS's: can this be an acceptable explication, in lieu of more 'evident' others? Next: a computer is not bound by so small a value of M; can we make models to evaluate, albeit crudely, a reasonable if not optimal structure for a society based on man-machine symbiosis?

VI. CONCLUSION

The reader will have noticed that several things have *not* been stated in this work, although seemingly 'evident': such as that level formation is a consequence of entropy maximization (the argument in II-2 can be readily construed to this effect); or that it is due to the increased working efficiency of structured systems (army vs. crowd); or that it comes from a balance between 'organizing' and 'disorganizing' agents, as it happens with all equilibria (these statements are not contradictory). We have avoided the issue altogether as a matter of methodology, it not being yet clear to us to what extent they are 'specific' and to what 'general'.

The dynamical development of a system, i.e. of a model, through phases of evolution and revolution as defined here, will have to be studied, as a consequence of intrinsic or extrinsic changes (e.g. in a HMS of N and/or V), and the corresponding dynamical concepts clarified. The work of Part IV should help in this task.

There may be questions for the biologist: e.g., can biological hierarchies be connected with the requirement that the total, or average, mass of food (or of particular substances) used up in a hierarchy be dependent only on the 'universe of supply'? Not to mention physics, where yet another outlook on phase transitions would not cause much surprise.

Another issue that comes to mind is the following: a hierarchical system interacting with another *acts as a template* for it: *structure forces structure* upon the environment. Formula (43) is only one among a host of cases that can be thus studied.

In conclusion, we feel that our attempt is 'exposed to destruction', in Mendeleev's sense, in so many ways, that we find it stimulating to present it for this very reason.

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H. Hörz

Physics and Education

Knowledge of physics, when applied to technological practice, exercises an essential influence upon the material and cultural standard of man. A certain degree of education is a prerequisite for the utilization of scientific knowledge. However, education limited to just one special field is insufficient to stimulate creativeness and to develop a spirit of responsibility. It is only with new scientific ideas of education entering the general consciousness that a social atmosphere of creative activity will arise to bring about new theories. In history, quite a number of examples, such as the struggle for the acknowledgement of the Copernican system and the theory of relativity, show the impact of ideological obstruction upon education. But considerations on the interaction between physics and education would go beyond the intended coverage of this presentation. As the objectives, organization, utilization and ideological interpretation of research work in the field of natural sciences are essentially determined by the social circumstances under which scientific activities are carried out, it would mean investigating the interrelation between physics, society and education. We shall rather try to answer the question, Can physics contribute more to education than just providing knowledge of physical laws and theories?

1. WHAT CAN PHYSICS CONTRIBUTE TO EDUCATION?

Considering the thoughts of Albert Einstein on education, one meets with some ever-returning essential insights [1]. One of them refers to the recognized interrelation between individuals and society. Society needs for its development creative personalities acting and making their judgements independently and promoting social progress. Therefore, man must not be taught just one special subject, which would make him a mere tool for utilization, not a real personality. He must know social needs, take into consideration social motivation and have the right attitude to both his fellow men and community. Einstein requested making the freed nuclear energy serve culture and the welfare of mankind. He set up the plan of a world government. Arguing with the criticism of Soviet colleagues who indicated the illusionism of his plan, he nevertheless emphasized the advantages of socialist economy.

Doesn't this go far beyond mere physics education? If asked whether the knowledge of physics can explain social processes and solve ethical problems, one may answer that this goes far beyond what is comprehended as understanding physics. But physics is not just an agglomeration of insights into the laws underlying physical processes. It is live experimental and theoretical activity. Philosophical and ethical questions emerge out of this working process. These are three essential aspects of physics education:

First of all, physics involves both the theory and methodology of man's interpretation of his inorganic environment. Physics means theoretically comprehending the everyday activities of each human being. Dealing with levers, electricity, friction, heat, etc. is learned empirically and should be theoretically understood as a result of education. But such will only be the case if, as Einstein put it, the education offered is felt to be a precious gift rather than a painful duty. Theories are solutions to problems. Those who wish to comprehend them must know the problem. If education teaches mere results of cognition, the way leading to the results will not be understood. Therefore, physics education should above all provide theoretical and methodological insights into everyday empirical activities, show ways to cognition and, thus, bring about preconditions for personal creative achievement. The term 'creativeness' in this case is characterized by the faculty of mastering in a new way processes and objects, under certain conditions and concrete space-time relations, together with practical and theoretical access to knowledge of social and natural reality.

Secondly, physics education essentially contributes to scientific comprehension of the world. It opposes both irrationalism and mysticism. It is interesting to note the way Helmholtz got down to the vitalistic conception of life, as it was in direct contradiction to the law of the conservation of energy. The investigations of the formation of structures by irreversible processes show possibilities of abrogating the old contradiction between the second principle of thermodynamics and Darwin's evolutionary conception, which gave rise to speculations on thermal death on the one hand, and on immaterial ordering forces within living organisms on the other. Certainly, the theory of dissipative structures does not supply a theory of biological evolution, which comprehends physical possibilities of biological evolution. Thus, a contribution to the scientific comprehension of the material unity of both lesser and highly developed processes is made.

Thirdly, physics education influences development of personalities, if research in physics is understood to be the social activity of physicists performed under given social conditions. This gives us the right to ask them for the motivation of research, for the sense of scientific work and for the responsibility of scientists. Knowledge of physics led to the creation of weapons of mass annihilation. How could that happen? Should we stop research work? What can be done to meet the responsibility with regard to peaceful and humane utilization of scientific knowledge? Such questions essential for the development of personalities must be asked and, as far as possible, answered by taking the behaviour of humanistic physicists as an example. Physics education should help to produce humanism and love for peace.

2. PHYSICS RESEARCH AND EDUCATION IN OUR CENTURY

Our century is approaching its end. In its first half, physics research provided contributions to the development of theories large enough to induce vast thinking about the modification of physics education. Both relativity and quantum physics achieved the collapse of mechanistic thinking, which had been subject to physical and philosophical criticism since the nineteenth century. In the second half of our century, the exploration of space yielded the confirmation of well-known insights, as well as a great deal of new knowledge. Apart from a great number of substantial redeterminations, the boundlessness of physical knowledge, the philosophical and ideological impact of the achievements of physics research, and the growing importance of the social responsibility of physicists are the most essential results to be considered in physics education.

When the mechanistic conception which Kant presented as being a scientific approach collapsed, some physicists who did not understand the dialectics of relative and objective truth arrived at relativism. So, Lorentz in a talk with Joffe declared in 1924 that quantum physics had shocked his faith in physics as a vehicle for perceiving truth. On the one hand, Lorentz argued, the electron moving on a circular orbit emits energy, but according to quantum physics it does not lose energy. He concluded by saying: 'I lost the conviction that my scientific work leads to objective truth, and I do not know what I am living for. I just regret not having died five years ago, when everything still was clear to me' [2]. Meanwhile, quantum physics has asserted itself without refuting Newtonian physics. Classical physics covers fields, in which v is small compared with c, and h is negligeable. Thus, the conditions for the validity of perceived truth were discovered, but truth was not abolished.

This leads to two considerations with regard to physics education. On the one hand, the boundlessness of physical knowledge must not be interpreted as though the basic stock of previously obtained physical knowledge were out of date. The laws recognized to underlie the interaction of man and his inorganic nature are true. They must be taught and learned in order to make man understand modern physics. So far, physics research cannot be represented in education in such a way as to reduce previously obtained knowledge in favour of knowledge gained later on. This would mean failing in theoretical interpretation of empirical knowledge. On the other hand, new perceptions induce thinking over previously obtained knowledge. Both relativity and quantum physics do not abrogate classical physics, but they show its dependency, its relative validity in the same way as the anatomy of today's man helps us to know better the anatomy of his predecessors, the prism of modern physics makes us better understand classical physics. The discussion of the philosophical and ideological impact of modern physics showed the possibility of constructing an ideology involving nature, society and conscience, based on the philosophical conception of statistical laws, to overcome the long-lasting separation between stochastic distributions in both society and morality, as well as clear dependencies between present and future states in physics [3]. On the other hand, classical physics as a mathematically expressed theory of objective processes was the scientific ideal up to the nineteenth century. However, it was illusory to try to reduce all of the complex system of elementary reactions between finally indivisible particles answering the laws of classical physics. Systems laws cannot be reduced to the behaviour of elements. Physical states are more intricate than those determined by position and state of motion. But physics had arrived at a high level of theoretical development, which other sciences were just trying to approach. Therefore, it is essential that philosophical analyses of the structure of laws in nature, society and conscience were performed in order to perceive better the interrelations between necessity and contingency, between possibility and reality, and between cause and purpose. Knowledge of physics should be taught together with its philosophical interpretation.

The social impact of physics research, which became obvious to everybody when the atom bomb was dropped, caused many scientists to raise the question of the value of scientific knowledge and of today's responsibility. Responsibility is a challenge to everybody to be aware of the consequences of his possible activities, to promote beneficial results and to prevent harmful ones, to carry out and evaluate his activities on the basis of expert decisions in order to draw conclusions for further behaviour. Responsibility is determined by one's own ideology, to be measured by social standards and practical results of the activities. Thus, physics education can only raise the question of responsibility, but cannot answer it. Responsibility is a multivalent relation, which makes individual considerations and actions match with social demands and practice.

3. CONSEQUENCES

On the basis of these considerations some consequences can be drawn as to physics education.

First of all, the efficiency of physics education with regard to the development of personalities in Einstein's sense can only be given by an education system which provides both teaching of sociological knowledge and answers ideological and ethical questions. In our country (the German Democratic Republic), we are ever trying to improve the use of the ideological potentials of physics education [4]. Secondly, the increase of knowledge cannot be measured only in a quantitative way. New theories join together partial knowledge. Basic theories are conserved. Their limitations are recognized. Therefore, education should be oriented towards basic laws [5]. Thirdly, education should give an insight into the way science develops and the difficulties involved. This stimulates curiosity and other motivations for personal creative behaviour [6]. In the fourth place, ideological obstacles preventing the development of theories and causing theoretical prejudice should be removed [7]. Finally, the spirit of responsibility for humane and peaceful utilization of physics should be developed.

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Anthony R. Michaelis

The Interdisciplinary Impact

Separately, neither cabinet ministers nor Nobel Prize winners can any longer solve the world's problems. Unless they join again their efforts in interdisciplinary thinking, research and collaboration, the world's greatest threat, nuclear warfare, will solve the second most important problem, the population explosion.

The first modern interdisciplinary impact came during World War II. By the middle of 1939, Albert Einstein had become deeply concerned with the political and military consequences arising from the first experiments of splitting the uranium atom and he was persuaded by Leo Szilard and Edward Teller to write his famous letter to President Roosevelt. It was dated 2 August 1939 and contained the following passage: 'I believe therefore that it is my duty to bring to your attention [that] it is conceivable that extremely powerful bombs of a new type may . . . be constructed.'

Much less well known is another letter, dated 24 April 1939, three months earlier, which was sent by Professor Paul Harteck and Dr. Wilhelm Groth, both of Hamburg, to the German War Ministry. It contained the passage: 'The newest development in nuclear physics, in our opinion, will probably make it possible to produce an explosive many orders of magnitude more powerful than the conventional ones' [1]. Scientists on both sides had taken the same step, but the results were totally different.

Whereas in 1939 scientific knowledge about uranium was available in the open literature, by 1942 secrecy had enshrouded all. That Fermi was able to produce the world's first critical uranium reactor in December 1942 in the famous Chicago Squash Court, was only revealed years later. It was the first brilliant result of America's Manhattan Project, that giant interdisciplinary collaboration between science, the U.S. Army and industry. It was estimated to cost $ 2000 million and it produced the first plutonium bomb in 1945. It led directly to the end of World War II. In hindsight, an independent observer in 1942 could have foretold the subsequent failure of the German research effort to produce an atom bomb. To discuss the future of this project, Professors Werner Heisenberg, C. F. von Weizsäcker, Otto Hahn and Paul Harteck met the German Munitions Minister Albert Speer and high officials from his Ministry, including Professor Ferdinand Porsche, together with Field-Marshal Milch of the Luftwaffe, in Harnack House, the headquarters of the Kaiser-Wilhelm-Society in Dahlem on 4 June 1942. It was a momentous and decisive meeting.

Although Heisenberg [2] correctly guessed American progress and told the meeting that 'America might have a uranium pile very soon and a uranium bomb in two years at the very least', the German theoretical physicists failed completely to appreciate the magnitude of the technological effort required to produce an atomic bomb. They asked for additional building quotas of 40 000 Reichsmark. Both Speer and Milch were amazed about this ridiculously low figure and did not bother any further about the nuclear project. On 23 June 1942, Speer reported this briefly to Hitler.

The German atomic project continued, directed by theoretical physicists without any military co-operation as was arranged in America. By the end of the war, a number of small German research reactors had been constructed; none of them reached criticality. David Irving [3], the great historian of the German atomic project concluded in 1967: 'Germany's nuclear scientists failed to win the confidence of their government'. Fortunately, no interdisciplinary impact resulted.

THE FUTURE INTERDISCIPLINARY IMPACT OF SCIENCE ON SOCIETY

These well-known historical events have here been retold at some length to underline the essential need for interdisciplinary co-operation to solve the great problems facing mankind at present, like the safe disposal of radio-active waste, misuse of raw materials, efficient rescue after natural disasters, and tropical diseases. To all these, science and technology have suggested solutions, but they have not yet found universal social, economic and political acceptance. The population explosion could be halted through mass-education from satellites broadcasting television to villages as was tried in India. Y. Pal [4] has reported the singular success of the first experiments along these lines.

The great problems are too complex to be tackled by any single group of experts. They all have multiple facets from pure science through engineering to technology, from psychology through sociology to politics. Cabinet ministers must learn again to work with Nobel Prize winners, as they did during World War II. Then the end justified the means – and today this must again be our first priority. Society has always paid for its science, be it the mediaeval farmer tilling the land belonging to the College, thus providing for its Fellows' sustenance, or the modern income tax contribution paying for research into quarks and black holes. Until very recent years, society never questioned the use of its money for scientific research: the sums involved were minute, and the eminence of the scientific practitioner went unchallenged. Now, when ever louder questions are being raised about the subjects of pure and applied scientific research, it is only right that scientists should point to the answers.

Here is a brief list of great problems and their possible solutions, necessarily incomplete and in no order of priority:

Safe disposal of radioactive waste: possibly by glass or ceramic encapsulation.

Population explosion: possibly controlled by satellite television education [5].

Food for all: possible by nuclear desalination and irrigation, by new genetic varieties, and with single cell proteins.

More clean energy: possibly from geothermy, fusion, wind, tides, the sun, on earth and from space.

Pollution: reduction possible by industrial action, legislation and biodegradable products.

Urban renewal: possibly by television communication instead of commuting, removing megalopolis.

Open university worldwide: possible by satellite television broadcast.

Misuse of raw materials: possibly minimized by recycling and substitutes.

Health services worldwide: possible by medical, economic and political action.

Tropical diseases: possible expansion of non-industrial research for new drugs.

Drug addiction: possibly limited by research for SOMA (*Brave New World*).

Earthquake prediction: Soon possible, but bringing with it grave social upheavals when warnings are given.

Speedy and efficient natural disaster relief: possible through a new international rescue organization.

Space exploration: as an alternative to warfare, giving similar benefits to the military-industrial complex, yet avoiding mega-death.

Whatever possible solution might be considered appropriate for research for any of these great problems, it will need close inter-disciplinary co-operation between pure scientists, engineers, technologists, psychologists, sociologists and politicians to find an answer socially, economically and politically acceptable to society.

To take but the most difficult of all problems: the avoidance of nuclear warfare and the well-known suggestion that space exploration might replace it as a challenge to human society. The technological feasibility of space exploration has been amply demonstrated, and so has the possibility of close international co-operation, even between the USA and USSR. Yet how many politicians would argue that the thousands of millions of currency units now spent on armaments by every country, could be better spent on joint international space activities?

Apparently only Governor Brown [6] of the State of California has given space exploration more than a passing thought. In a recent speech he urged not only Californians, but all the peoples of the world together, to keep the thrust into space going. He fully realized the interdisciplinary effort required, of the political will, the ability of the private sector, of Government, the universities, all working together.

Is the interdisciplinary concept a modern scientific idea? What precisely is its definition, and how did it arise? Let us now consider these basic aspects.

THE INTERDISCIPLINARY CONCEPT

Creativity is a gift of absolute value which knows no borders of time and space. Beauty can be perceived in the Australian aborigine's bark paintings, in X-ray figures, in the voluptuous sculpture of Indian temples and in the radio charts of the galaxy. Creativity is small and limited in most of us, larger in the works of great artists and of scientific geniuses, and creativity was once sublime in Leonardo da Vinci (1452–1519). His creativity encompassed all disciplines, artistic, medical, scientific and technological. He has been called the last interdisciplinary genius who could embrace all human knowledge of his time, make significant contributions to all disciplines and add prodigiously to the greatest works of art of all times. In the 500 years since Leonardo, our detailed knowledge has increased immensely, but so has the complexity of the problems and the dangers that face all mankind. A deliberate attempt has therefore to be made to recombine the knowledge and experience from many different disciplines – the interdisciplinary concept.

Interdisciplinary work results from the joint and continuously integrated effort of two or more specialists having a different disciplinary background; on rare occasions a single person may have mastered more than one discipline in his life. In multidisciplinary work the individual efforts run along parallel lines and are not integrated. There is an increasing need for interdisciplinary studies to solve difficult research problems, to find solutions for the dangers facing mankind, and to enrich our understanding of each other.

An extension of interdisciplinary thought and philosophy will enhance both art and science in their ever-increasing specialization. Science as part of human culture pursues its single-minded search for knowledge, often neglecting the ingredients which should link knowledge and human needs. Artists without an understanding of science and technology can only superficially enter the *zeitgeist* of the present century, and it is therefore not surprising that their work is often confused and meaningless to the beholder.

Most scientists work today in teams organized in a hierarchical or interdisciplinary system. Their work lies within a framework of rigidly defined constraints. The modern artist has no rules of any kind and can as an individual produce whatever he pleases. However, in order to survive and obtain his materials, he must find a minimum of approval, be it from a government committee, a wealthy Maecenas, or simply from his family. The starving artist is certainly a common image – a starving scientist is practically unknown. Conversely, successful and fashionable artists have died rich, but millionaire-scientists are rare.

INTERDISCIPLINARY INTERACTION BETWEEN THE SCIENCES

Whatever name is given to the intercourse between two or more sciences, operational research, systems analysis or interdisciplinary research, the concept is by no means a novelty. Take as the classical example iatrochemistry, alchemy in the service of medicine. Due to his genius, Paracelsus (1493–1541) liberated alchemy from its useless search for the philosopher's stone and turned it towards the chemistry of the human body, an eminently respectable interdisciplinary subject for modern research.

One might consider the origins of radioastronomy equally classical today. This science goes back to 1932, when the American engineer Karl Jansky investigated disturbances of transatlantic radio telephone conversations and found the source of cosmic static in interstellar space. Only a few decades later, the new science of radioastronomy, using the accumulated knowledge of optical astronomy in interdisciplinary conjunction with the more recently perfected techniques of electronics, could produce astonishing increases in our knowledge of the universe.

A further recent example of a new interdisciplinary science is dendrochronology, tree ring dating. Although the Russian Shvedov, as long ago as 1892, related variation in tree ring width to annual rainfall, it was the German scientist Huber who since 1940, worked out the modern methodology. Today in Europe [7], as well as in North America, there exist a series of accurate chronologies, invaluable in dating natural wooden specimen and artifacts.

Perhaps it is typical that the above three interdisciplinary sciences can trace their origins in each case to the work of a single scientist whose breadth of vision ranged beyond the confines of a single discipline. Two further examples must be given: the Hon. Robert Boyle (1627–1691) who among many other attributes may well deserve to be called the first interdisciplinary physical chemist. Also the name of Alexander von Humboldt (1769–1859) must here be recorded. His mind ranged over most scientific disciplines, he founded modern geography and in his crowning work *Kosmos* (1845–1861) he attempted to show the underlying unity of all nature.

Interdisciplinary research is so common in many laboratories today that it is not even given a passing thought. Wherever an electronic engineer collaborates with a biologist to develop a new technique, or a computing mathematician writes a new machine language for a population census questionnaire, or when a civil engineer studies the ecology of an area before and after his dams are built, always two or more scientific disciplines meet and mutually enrich each other. What is still extremely rare today, and needs the greatest possible development, is the meeting of the two minds of scientist and politician in interdisciplinary intercourse to solve the great problems facing mankind.

CREATIVITY AND THE IMPACT OF THE SCIENCES ON THE ARTS

Creativity is manifest in both artistic and scientific activities and great masters can achieve beauty and perfection, be it in a symphony, a new synthetic organic chemical, a sculpture or a mathematical formula. In fact, beauty can be defined as an asymptotic approach to perfection, perceived by the senses and recognized by the mind as such. It applies to both the arts and the sciences.

Whilst almost anyone can see beauty in a painting or hear it in an opera, it needs the trained mind of a scientist to see beauty in the work of his scientific associates. This fundamental difference presents perhaps the greatest difficulty to the builders of the interdisciplinary bridge between the two cultures.

Naturally opinions will differ among organic chemists, just as they do among art historians, of what is true beauty and what is second-rate. This subjective appreciation of beauty depends of course on the widely different past experiences of the beholder. There is however some considerable agreement that neither the artist's struggle, nor the many false starts of the scientist, must be apparent in the final achievement if it strives for perfection. Techniques must always be subservient to creativity.

Let me quote here three simple examples where geometric beauty was the end result of scientific discovery: the triangle, the hexagon and the helix. Pythagoras (580–497 BC) discovered that in a right-angled triangle $a^2 + b^2 = c^2$; that is the square of the longest side is equal to the sum of the squares of the other two sides. F. A. Kekulé (1829–1896) found in 1865 that a hexagon could best represent the chemical structure of the benzene molecule, C_6H_6, and Francis Crick and James Watson assigned in 1953 to the structure of DNA, the basic unit of the genetic code, the shape of the double helix. In two-and-a-half millenia, the world has certainly changed, but absolute beauty, when created by man, is timeless.

As artistic and scientific activities are but two different aspects of human creativity, one would expect that since Leonardo da Vinci there had appeared at least a small number of similar interdisciplinary geniuses. But this has not been the case. Certainly Einstein could play the violin and Joseph Wright (1734–1797), Wright of Derby, painted scientific pictures of the Air Pump and The Orrery. Yet in these and similar cases, either the artistic or the scientific activity was predominant.

One might well wonder why this was so, and why so few painters and sculptors have been inspired by the great works of science and technology, the 'temples of science' as Maury [8], the American oceanographer, called them in 1855. More than a hundred years later, it needed a special commission from NASA and the National Gallery of Art in Washington to induce forty-seven American artists to record America's historic Space Program [9].

If the fine arts have a poor record in this respect, at least some modern musical composers have been inspired by man's exploration of the universe and a fair number of modern musical works have been graced by astronomic titles, as Ronan [10] has recently shown. In the field of literature, there are a large number of works, including some science fiction, linking science and the *belles lettres*. Aldous Huxley [11] in 1963 first drew attention to this subject and Woodcock [12] of Indiana University has now brought it up-to-date.

What might be called the interdisciplinary techniques of the arts are of course nowadays fully developed. It would exceed the scope of this paper to discuss the purity of artists' colours, the highly developed chemical and physical analyses of ancient paintings, carbon-14 dating of archaeological treasures, or the scientific detection of forgeries in art, which Fleming]13] has reviewed. Much more profound, and very much older, is the theory and practice of perspective which has exercised both artists and scientists alike. Joseph Priestley [14] wrote a charming little work on this subject in 1770 and dedicated it to Sir Joshua Reynolds, then President of the Royal Academy of Paintings, London, and like Priestley, a Fellow of the Royal Society. This would hardly be possible today.

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Maurice Goldsmith

Einstein and Social Challenge

One of the first persons to understand and to lecture on the new theories of relativity was the Frenchman, Paul Langevin. He did so at a time when Einstein's special and general theories were greeted with some derision. But Langevin saw how Einstein had transformed the basic conceptions of the universe: how his theories superseded the older Newtonian framework of physical science (of absolute space and absolute time), and made possible the mathematical investigation of subatomic particles and the development of wave mechanics. Why do I choose Langevin? Because he was a pioneer in the propagation of relativity, but also because he had a view of the responsibility of the scientist which linked him in a social sense with Einstein. When Langevin was asked by his admiring student, Joliot-Curie, why he took so much time off from the laboratory for general political activity, Langevin replied, 'I do not wish to, but I do so so there will be laboratories for young scientists to continue to work in.' Einstein understood that.

The practical application, in the atom and hydrogen bombs, of his conception of the equivalence of mass and energy was a tragedy not only for Einstein, but also for science. It was the beginning of the great disillusionment. We have the task still, in which Einstein began to share, of fighting for the practical application to be used for the liberation of mankind from material needs.

Einstein felt deeply the whole problem of our times, and, like a Hebrew prophet of old, he sought to help us develop new perceptions of human understanding, of responsibility, and of love.

The Science Policy Foundation, in commemoration of Einstein's centenary, is publishing a book tracing the impact of Einstein on the Social Sciences, the Arts, Literature, and the Humanities. The theme is 'Einstein Lived Here'.

This is no easy task, for we have to face up to the understanding that we are at a period of the convergence of a number of the great 'S-curves' of transition from one state of society to another. This is the period of the *problèmatique*. But we are not just at a technical point of change. There is something more basic. We are, also, at operational and ethical points of change, in which we face disaster if our values and policies are not remodelled to ensure the development of the new institutions, international and national, to deal with the transition.

I know little about Einstein and his relationship with other physicists. I do not mean in a purely personal sense, although I do recollect Leo Infeld telling me some years ago of how kindly Einstein treated him. And I recollect two occasions when seated with Niels Bohr in his room in Copenhagen he talked to me for hours of his ongoing polemic with Einstein. I dared not interrupt to say I did not understand.

But it was Bohr who once described the history of quantum physics as involving 'a unique co-operation of a whole generation of physicists from many countries.' I ask, was this co-operation brought about largely through Einstein's efforts, or did it happen, as it does so often in science, because it just had to?

The American historian of science, William Blanpied, has drawn my attention to the fact that Einstein never had a real collaborator, yet there is the Bose-Einstein Statistics theory. This has led many to assume that Einstein and Satvendranath Bose worked closely together. On the contrary, they never met. But Bose provided Einstein with the key clue he needed to formulate the first quantum mechanical theory of the ideal gas. This was in 1924.

I mention this because I believe the work of Einstein acted similarly in other fields of human endeavour; that is, causing us to look at ourselves in a radically new way. Let me put it simply (and, obviously, too simply). There is but one overall culture in societies with the same background and tradition. In Europe, for example, it is broadly the Judeo-Christian culture. A perturbance in one field (e.g. relativity) will not only cause a perturbance in other fields, but there will already be perturbances occurring independently in those fields, which link up in time to provide a changed philosophical outlook. It would take too long to develop this, but the poets and artists, for example, probably 'warned' us well ahead of the perturbance that was to hit us in the natural sciences. A person with sufficient knowledge and insight in the sciences could probably see some future developments in science and technology in the verse being written today.

One example: Cézanne said late in his life, 'Things and creatures alike, we are only a little bit of solar heat. The diffuse moral energies of the world may be the effort it is making to become one again. We are an iridescent chaos.' It appears as if Einstein and Cézanne mark some threshold of profoundly different ways of seeing and experiencing the world than existed previously. What kind of synchronicity is this?

They shared an aesthetic sense of the unity of existence that arose from their intuitive grasp of the world, that is their way of making sense of the world. It is no coincidence that the Age of Einstein is the Age of the dynamic interplay of forms in movement. It is the Age of Cubism, Futurism, Constructivism, Suprematism, Vorticism, and Abstraction. It is, also, the Age of Dada and Surrealism, and all aspects of Symbolism. It is this 'unity of existence' that is the essence of the models of experience for the modern scientist and the modern artist, following Einstein and Cézanne.

It is also the model of experience for the science policy decision-maker. Einstein died without having been able to verify 'the equation in which the secret of the world was enclosed.' That is a task which still continues. And Professor Dirac exposed this beautifully to us.

But the task of the science policy maker is also concerned with another 'secret of the world', but one that has a social dimension. Can we continue to accept the existing system of inequality and the manner of utilization of resources, and find a solution within the existing framework? Einstein would have agreed we need a new model of international co-operation. He was a humanist, an anti-fascist, and a supporter of peace.

Aryeh Dvoretzky

On Some of Einstein's Non-Scientific Opinions

The accelerating pace of scientific discovery and attendant technological development is rapidly transforming our lives. Man literally soars to the heavens and delves ever deeper into the mysteries of his own being. Dazzling vistas of spiritual wealth and material abundance seem to be within reach, but abysmal pitfalls lie ahead. Will man become the master of the awesome powers which science put within his grasp, or will he persist in his puny disputes and be destroyed by these powers?

Ideas generated in the crucible of scientific investigation constantly permeate our thinking, affect our outlook, and eventually have an impact on all aspects of our behaviour. Is this process rapid enough and can it contribute to the solution of the problems raised by technological development?

The papers presented in this symposium are described as 'in commemoration of Einstein and on the impact of modern scientific ideas on society'. Since I feel rather unequal to the task of saying succinctly something novel and interesting on the major questions raised above, I propose to present instead some of Einstein's relevant thoughts. Due to the constraint of time I shall confine myself to a couple of topics connected with nationalism.

The pursuit of Einstein's ideas about non-scientific matters may be more interesting than in the case of most scientists. This is due not only to his great eminence as a scientist and a humanist but, also, to the fact that he had a remarkably integrated world outlook. It seems that the soul that craved for unity and harmony in physics had a similar need for the totality of its activities. His collection of Essays published in 1934 is appropriately named '*Mein Weltbild*'. Though the essays range over a wide variety of topics – philosophy, science, ethics, politics, pacifism, nationalism, Jewish problems etc. – there is throughout a coherent basic outlook fully justifying the use of 'world-view' in the title.

Einstein insisted that people should form their own opinions and would have resented very much an uncritical acceptance of ideas on the strength of his authority. However, though one may accept or reject Einstein's views, they certainly deserve consideration.

Einstein was convinced that it is imperative to have some form of world government and that national sovereignty must be curbed.

> The release of atomic energy has not created a new problem. It has merely made more urgent the necessity of solving an existing one. One could say that it has affected us quantitatively, not qualitatively. So long as there are sovereign nations possessing great power, war is inevitable. That is not an attempt to say when it will come, but only that it is sure to come. That was true before the atomic bomb was made. What has been changed is the destructiveness of war [1].

Not that he was oblivious to the dangers inherent in world government.

> Do I fear the tyranny of a world government? Of course I do. But I fear still more the coming of another war or wars. Any government is certain to be evil to some extent. But a world government is preferable to the far greater evil of wars, particularly with their intensified destructiveness [2].

There is no hope for mankind without insistence on moral values.

> In these great matters success is not a matter of cleverness, still less of cunning, but of honesty and confidence. The moral element cannot be displaced by reason, thank heaven, I am inclined to say.
>
> The individual must not merely wait and criticize. He must serve the cause as best he can. The fate of the world will be such as the world deserves [3].

Basically Einstein was an optimist whose optimism was predicated on activism.

Times such as ours have always bred defeatism and despair . . . . We scientists have ample evidence that the time of decision has come, and that what we do, or fail to do, within the next few years, will determine the fate of our civilization. Man must come to recognize that his fate is linked with that of his fellow men throughout the world. Great ideas have often been expressed in very simple words. In the shadow of the atomic bomb it has become even more apparent that all men are, indeed, brothers [4].

Excessive nationalism may become a threat everywhere, even in the United States, Einstein's adopted country.

As a citizen of Germany, I saw how excessive nationalism can spread like a disease, bringing tragedy to millions. Now, as a citizen of the United States, while appreciating the blessings of a free association of states and peoples in America, I must add in frankness and humility that I recognize indications of the disease of nationalism also in this country. The confidence I have in American democracy compels me to voice this honest warning [5].

The prime, horrible, example of rampant nationalism is, of course, that of Nazi Germany. His spirit was forever tormented by this malignant cancerous regime. Embarrassing as it may be, one cannot avoid recording this in the town where Einstein was born.

In a letter to his friend Arnold Sommerfeld who wanted to reinstate him in the Bavarian Academy, from which Einstein resigned in 1933, he wrote on 14 December 1946:

. . . the Germans slaughtered my Jewish brethren; I will have nothing further to do with them, not even with a relatively harmless academy. I feel differently about the few people who, insofar as it was possible, remained steadfast against Nazism. I am happy to learn that you were among them . . . [6].

Similarly he rejected in 1948 an invitation, transmitted by Otto Hahn, that he become a Foreign Associate of the *Max Planck Gesellschaft*:

It pains me that I must say no to you, one of the few men who remained decent and did what they could during those evil years; but I cannot do otherwise. The crime of the Germans is truly the most abominable ever to be recorded in the history of the so-called civilized nations. The conduct of the German intellectuals – seen as a group – was no better than that of the mob [7].

And in 1951 when he was offered the order *Pour le mérite* by Theodor Heuss, President of the Federal Republic of Germany, he replied:

I thank you for your letter of January 10, 1951, and the material enclosed. Because of the mass murder which the Germans inflicted upon the Jewish people, it is evident that a self-respecting Jew could not possibly wish to be associated in any way with any official German institution. The renewal of my membership in the *Pour le mérite* order is therefore out of the question [8].

Notwithstanding his feelings of outrage towards the Germans he saw the objective necessity of incorporating Germany in the community of nations, establishing diplomatic relations with it and rebuilding its shattered economy. One would like to entertain the thought that consistent eradication of all vestiges of the nefarious past and strict adherence to democratic and humane ideals would have gradually assuaged Einstein's feelings towards his country of birth.

States have, however, their proper functions:

May I begin with an article of political faith? It runs as follows: the State is made for man, not man for the State. The same may be said of science. These are old sayings, coined by men for whom human personality has the highest human value. I should shrink from repeating them, were it not that they are forever threatening to fall into oblivion, particularly in these days of organization and stereotypes. I regard it as the chief duty of the state to protect the individual and give him the opportunity to develop into a creative personality [9].

Nowhere is this more clear than in the case of the Jews. Einstein did not think of the Jews as the chosen people, but he had an immense pride in his Jewish heritage.

The pursuit of knowledge for its own sake, an almost fanatical love of justice and the desire for personal independence – these are the features of the Jewish tradition which make me thank my stars that I belong to it.

Those who are raging today against the ideals of reason and individual liberty and are trying to establish a spiritless state-slavery by brute force rightly see in us their irreconcilable foes. History has given us a difficult row to hoe; but so long as we remain devoted servants of truth, justice, and liberty, we shall continue not merely to survive as the oldest of living peoples, but by creative work to bring forth fruits which contribute to the ennoblement of the human race, as heretofore [10].

Einstein was a convinced and active Zionist. In an early essay 'The Jewish Homeland', Einstein writes:

I believe in the actuality of Jewish nationality, and I believe that every Jew has duties toward his coreligionists. The meaning of Zionism is thus many-sided. It opens out to Jews who are despairing in the Ukrainian hell or in Poland, hope for a more human existence. Through the return of Jews to Palestine, and thus back to normal and healthy economic life, Zionism means, too, a productive function, which should enrich mankind at large. But the chief point is that Zionism must tend to strengthen the dignity and self-respect of Jews in Diaspora. I have always been annoyed by the undignified assimilationist cravings and strivings which I have observed in so many of my friends [11].

His dedication to Zionism continued to the end of his life. In January 1955 he writes Zvi Lurie:

We [the State of Israel] must adopt a policy of neutrality concerning the international antagonism between East and West. By adopting a neutral position, we would not only make a modest contribution to the curtailment of the conflict in the world as a whole, but would, at the same time, also facilitate the development of sound, neighborly relations with the various governments in the Arab world.

The most important aspect of our policy must be our ever-present, manifest desire to institute complete equality for the Arab citizens living in our midst, and to appreciate the inherent difficulties of their present situation . . . . The attitude we adopt toward the Arab minority will provide the real test of our moral standards as a people [12].

And in March 1955, he writes to an Indian friend:

Of course, I regret the constant state of tension existing between Israel and the Arab states. Such tension could hardly have been avoided in view of the nationalistic attitude of both sides, which has only been intensified by the war and its implications.[13].

In preparation for the 1955 Independence Day he was asked to contribute an article on scientific developments in Israel. Einstein decided that he would be of more help to Israel by delivering an address on the political situation. He started working on his notes on April 13; that same day he was fatally stricken. During the four remaining days of his life he frequently expressed concern over his delay in writing the address.

The above ideas of Einstein contain important guidelines for all of us. I should have, to paraphrase a previous quotation, shrunk from stating the obvious, were it not that, unfortunately, we are constantly witnessing many instances where these ideas fall into oblivion.

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Mohammed Said

A Good World

In the holy books of various religions, man has been commanded to search for the unknown on the earth and in the skies, to harness the forces of nature for the benefit of himself and for mankind, and to pass on his knowledge and experience to posterity.

All those who search and re-search in this world are consciously or unconsciously following the divine mandate. It may not be far from the truth to say that those who search consciously, largely follow the path of peace and goodwill, and those who strive unconsciously may not themselves be certain of the results of their search.

No society can be great without great individuals. And one of the greatest individuals of the twentieth century society is Albert Einstein, scientist and humanitarian, searcher and researcher, whose approach was based purely on humanistic instincts and motivations, and whose objective was the security and welfare of the world.

If this were not his basic aim he would certainly not have earned universal acclaim, and there would not have been the commemoration and celebration of his birth centenary to which illustrious men of science have come from all over the world, under the auspices of Unesco, to honour his memory. It is no less an honour given to me by the organizers to be one of those to salute him.

We have gathered together, men of all nations and creeds, to pay tribute to Einstein's unusual search into the universe, his depth of observation and his creative imagination and evolution. At a time like this, while recounting his greatness, we are reminded of the littleness of ourselves by using science for destruction. What is the impact of science on society? Will science and technology ensure man's survival or man's extinction? To be or not to be? That is the question to which scientists and statesmen, militarists and warmongers have the answer.

My discovery of Einstein was when, as a boy of fifteen, I listened to a discourse in the Anglo-Arabic College at Delhi in 1935, given by a great mathematician of the subcontinent of India and Pakistan, Sir Shah M. Sulaiman, who expressed his disagreement with Einstein's theory of relativity and gravitation. This led to further inquiry and appreciation of the work done later on Einstein by Dr Raziuddin Siddiqui, another famous physicist-mathematician of Pakistan. But I am not speaking here as a physicist. I come as a humanitarian on behalf of the universal man, with a fervent appeal for peace. I belong to a developing country and am therefore competent to convey the heart's desire of all the people of the Afro-Asian world to the men of science and thinkers that the only right use of science should be for peaceful co-existence, in which life is measured in terms of progress and not in national victories or defeats, in contests with other nations.

We live in a world of fear. Emphasis upon dangers leads to apathetic despair. What our world needs is peace and the hope of something positive to live for. Science is perfecting the deadly methods of destruction and while mankind is subject to the threat of war, nothing good can be secure.

Einstein himself realized this danger. Although he always maintained that scientific truth must be conceived as a valid truth that is independent of humanity, he readily joined those scientists who sought ways to prevent the spread of war and destruction by scientific devices. His particular and urgent plea was the establishment of a world government under a constitution drafted by the United States, Britain and Russia. He stressed that we must not be merely willing, but actively eager to submit ourselves to the binding authority necessary for world security. He believed that it lies within man's power to create edifices of shining splendour and to turn the inventions and artifacts of science to uses of peace. He exhorted man to discover himself as a being, who by a long and arduous road, has discovered how to make intelligence master natural obstacles, how to live in freedom and joy, at peace with himself and therefore with all mankind. He taught that science has a great responsibility and that the scientist is also a citizen and a humanitarian with a moral duty to suggest and develop those branches of science of which the important practical uses are beneficial for the betterment of mankind. To echo Lord Bertrand Russell's words on the power and duty of the scientist: 'Everybody knows that the modern world depends upon scientists, and if they are insistent, they must be listened to. We have it in our power to make a good world; and therefore with whatever labour and risk, we must make it.'

There can be no more fitting memorial to Einstein, the scientist and humanist, than our efforts to make a 'good world'.

J. B. Donnet

Measures for the Reduction of the Science and Technology Gap between Developed and Developing Countries

The appearance of man and his social system may be recent on a geological scale, but his evolution on the earth's surface has nevertheless been shaped by a slow succession of challenges and struggles, by his adaptation to the local environment and his gradual mastery of the environment through science and technology.

However, the most striking phenomenon of our generation is the acceleration of technological progress and its increasingly determinant influence, a phenomenon that we suggest naming 'technological emergence'.

The phenomenon is well known; it has been eloquently described by numerous authors. We shall limit ourselves to one quotation:

> . . . if the last 50,000 years of man's existence were divided into lifetimes of approximately sixty-two years each, there have been about 800 such lifetimes. Of these 800, fully 650 were spent in caves.
>
> Only during the last seventy lifetimes has it been possible to communicate effectively from one lifetime to another – as writing made it possible to do. Only during the last six lifetimes did masses of men ever see a printed word. Only during the last four has it been possible to measure time with any precision. Only in the last two has anyone anywhere used an electric motor. And the overwhelming majority of all the material goods we use in daily life today have been developed within the present, the 800th, lifetime [1].

This multifaceted explosion of techniques has, on the one hand, both accompanied and brought about a considerable development in the standard of living in the so-called developed countries – at once creators and beneficiaries of the technological evolution. On the other hand, it has produced a true 'future shock' as well as numerous 'civilization sicknesses' which constitute one of the problems of developed countries.

However, a group of nations, wrongly called the 'third' and the 'fourth world', generally in Africa, Asia and Latin America, has benefitted little, very little, or not at all from this technological explosion of the last fifty years.

The consequences of this constantly widening 'technology gap' are increasingly intolerable, especially as they are being suffered at a time when the world, as a whole, is faced with new and also multifaceted challenges, in particular:

– contrasting demographic trends, high in the developing countries and very slow, if not negative, in the developed countries;
– the critical problem of energy and the depletion, within the medium term, of petroleum reserves;
– the problem of renewal of all kinds of industrial raw materials;
– the problems posed by urban growth, the mastery of agricultural techniques, soil and forest conservation, health and communications;
– the daunting problems of pollution in all its forms.

Finally, the emergence of developing nations which have an ever-increasing demographic weight – and sometimes possessing resources of vital importance for the whole world and thus financial strength – stresses the urgency of finding solutions to bridging the technological gap. This must be done in order to rapidly improve the living conditions of these peoples, for whom lagging behind becomes increasingly intolerable.

Among the numerous studies carried out during the last fifteen years on these problems, one only need mention the work of the Club of Rome, which elicited universal interest. Their first report – published one year before the quadrupling of petroleum prices in September 1973 – was a serious warning, even if their predictions were very imperfect, if not erroneous, as the work of the University of Sussex and further reports of the Club of Rome later demonstrated. Other work worth mentioning in this field includes the recent Leontieff report and the highly optimistic speculations of the Hudson Institute.

Whoever the author and whatever his viewpoint, one of the universally agreed keys to a promising future is the reduction – as quickly and definitively as possible – of the technological gap between developed and developing countries. This is a unanimous conclusion, and one of the most urgent aims of nations is to find and implement measures to reduce the technological gap. However, a consensus on the measures to be employed is still far from being achieved, as is evident from the meetings of the Henri Laugier Association held in November 1977 at Unesco House in Paris on '*Découverte et innovation scientifique au service du Tiers Monde*' (Scientific discovery and innovation for the Third World).

We shall limit ourselves to considering one of the essential elements for reducing this technological gap, or rather one of the elements for the 'technological emergence of developing countries'. It is the *human aspect* of the problem, a prerequisite for the success of any endeavour in this direction, which must precede and accompany the necessary material investment.

HUMAN ASPECTS OF TECHNOLOGICAL AND SCIENTIFIC EMERGENCE: THE PLACE OF THE SCIENTIST IN DEVELOPING COUNTRIES

Scientific and technological maturity in the advanced countries has been a slow process, more than a century long, and if today science and technology produce spectacular and rapidly evolving results, it should not be forgotten that this required the accumulation of knowledge and techniques over the years.

Can this process be shortened? Can the elements required to enable a young country to benefit from and participate in scientific progress be transferred over a short period?

Various examples give an affirmative answer to this query. Taking Japan as a case in point, it has, in some thirty years, achieved a remarkable technological breakthrough, starting, however, with a considerable economic, industrial and financial infrastructure. Several studies have been published explaining the reasons for this success [2]. It should be stressed that to achieve such a breakthrough the basic factor is the *will* of the nation as a whole. The minimum infrastructure needed also deserves close analysis.

If we consider solely the place of the scientist in society, it should, in particular, be recalled that Unesco's work in this connection has given rise to some very important documents, especially the Draft Programme of Studies on Human Implications of Scientific Advance including Misuse of Science submitted to the eighteenth General Conference of Unesco in November 1974, and the recommendations on the status of scientific workers, adopted by the same Conference. A third important document is the Resolutions and Recommendations of the Unesco International Computation Centre colloquium held in Tunis in October 1976. These papers indicate the basic orientations required to facilitate the implantation and development of science and technology in developing countries. Without going into the details of the recommendations which are all important and which we think call for the earliest possible implementation, we shall give some of the guidelines which should, in our opinion, form a basis for action.

GENERAL MEASURES

Make a clear and judicious choice of scientific and technological objectives in each country. Do not attempt an attack on all fronts. Dispersed efforts discourage people.

Concentrate efforts, giving maximum attention to the needs and means of each country.

Take advantage of the experience of other countries (Israel, China, Japan, USSR, Western countries, etc.) and take into account all known failures.

Establish realistic teaching and research methods, without necessarily imitating the developed countries.

As to higher education, take fully into account the often over-abundant possibilities in the major Western universities.

Resort to the U. N. University, still little known.

SPECIFIC MEASURES

Strongly motivate researchers by associating them with the ventures undertaken so that they feel involved, appreciated and useful.

Give researchers true human responsibilities involving their judgement and enthusiasm.

Undertake action so that true solidarity among the international scientific community benefits those who attempt the difficult task of creating new research groups in developing countries.

Organize effective training programmes for researchers from developing countries, whose training could, in our opinion, be quite easily envisaged on a large scale in developed countries, as a voluntary contribution.

This action could be accompanied by projects to establish research groups which would receive these young researchers. Here again, the developed countries must make a voluntary and generous effort.

Visits can also easily be undertaken by senior researchers from developed countries to new countries.

Material aspects of the career of the researchers and technicians who will be associated with the immense task of awakening developing countries to science is of course important. In our opinion it is not the only, nor the main aspect. It is the human aspect that predominates: hundreds of thousands of enthusiastic young people must be trained and introduced to scientific thought so that they may enable their own countries to benefit from science.

CONCLUSION

This 'crusade' – in the best sense of the word – for science and technology requires a particularly intense effort. To conclude, we shall return to the proposal we made in Tunis which aims at creating, under the auspices of Unesco, a World Science and Technology Intercountries Exchange Committee. This Committee would above all be devoted to exchanges between scientists and to the advancement of scientists.

The generosity of man is not an empty word, nor is the universality of man. We feel it is quite feasible, in the scientific world as a whole, to foster this effort which must be undertaken if we do not want the technology gap to widen, with dramatic consequences. A voluntary contribution to this effort must come from each developed country. Given the stakes, this stipulation is perfectly realistic, and one of the first tasks of the Committee would be to establish the magnitude and form of the contribution, i.e., exchange and training of researchers and the establishment of research groups.

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The Impact of Modern Scientific Ideas on Society

In Commemoration of Einstein

Edited by

COLETTE M. KINNON

with

A. N. KHOLODILIN and J. G. RICHARDSON

The quintessence of Einstein's imagination is perhaps to be found in his ability to perceive the connection between concepts which, until then, had been thought either to be incompatible or contradictory and which, in turn, reconstructed the field of physics by bringing increasing coherence and harmony into it.

Albert Einstein was born in Ulm, West Germany in 1879 and it was to this city that many international scientists gathered as part of UNESCO's celebrations of the hundredth anniversary of Einstein's birth. The symposium served as a poignant case for international understanding and reconciliation especially when one remembers the injustices Einstein suffered in Germany during the 1930s.

The symposium devoted itself to the theme of 'The Impact of Modern Scientific Ideas on Society'. Einstein's scientific development made a huge impact upon our overall understanding of nature and the world, whose consequences we still see today. But it was the same man, however, who bore witness to the fact that scientific ideas do not always have purely positive effects on our world.

Thus, the moral dilemma for the scientist is that he or she cannot wholly evade responsibility for the consequences that his or her theories may have for the world in which we live. This volume, as well as highlighting Einstein's scientific contributions, examines this dilemma and its implications.

Audience

The volume will interest physicists as well as historians and philosophers of science.

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