As recalled in other articles in this issue, Bohr formulated his Complementarity Principle in 1927, and presented it for the first time at a conference in Como, Italy in honour of Alessandro Volta, on September 16, 1927. In later years he came to regard this Principle as having much greater validity than in the interpretation of quantum mechanics, even though it had been discovered in that context. Thus he tried to apply it to psychology, the relationship between physics and life, etc. His first major lecture in these directions was titled ‘Light and Life’ given in Copenhagen in 1932. (It was this lecture that persuaded Max Delbruck, then a theoretical physicist, to turn to biology). A few years later he returned to a similar theme in a 1937 lecture at Bologna in honour of Luigi Galvani. We present here an annotated version of this lecture, prepared by Biman Nath.

N Mukunda

Biology and Atomic Physics

Niels Bohr

Address at the Physical and Biological Congress in memory of Luigi Galvani, Bologna, October 1937.

[Luigi Galvani (1737–1798) was an Italian physician, physicist and philosopher. One of his most famous discoveries was that the muscles of a dead frog’s legs moved when struck by an electrical spark.]

The immortal work of Galvani which inaugurated a new epoch in the whole field of science is a most brilliant illustration of the extreme fruitfulness of an intimate combination of the exploration of the laws of inanimate nature with the study of the properties of living organisms. At this occasion, it may therefore be appropriate to review the attitude which scientists through the ages have taken to the question of the relationship between physics and biology and especially to discuss the outlook created in this respect by the extraordinary development of atomic theory in recent time.

From the very dawn of science, atomic theory has indeed been at the focus of interest in connection with the efforts to attain a comprehensive view of the great variety of natural phenomena. Thus already Democritus, who with so deep intuition emphasized the necessity of atomism for any rational account of the ordinary properties of matter, attempted, as is well known, also to utilize atomistic ideas for the explanation of the peculiarities of
organic life and even of human psychology. In view of the fantastic character of such extreme materialistic conceptions, it was a natural reaction when Aristotle, with his masterly comprehension of the knowledge of his time in physics as well as in biology, rejected atomic theory entirely and tried to provide a sufficiently broad frame for an account of the wealth of natural phenomena on the basis of essentially teleological ideas. The exaggeration of the Aristotelian doctrine, on its side, was, however, clearly brought to light by the gradual recognition of the elementary laws of nature valid as well for inanimate bodies as for living organisms.

[Democritus had tried to explain almost all natural phenomena in terms of atoms. For example, he thought the sensation of taste was entirely a function of the size or shape of the atoms in food and their interaction with atoms in our mouth. He stated that sour taste was the result of angular atoms in twisted configuration, and sweet taste was caused by rounded atoms of a moderate size. Aristotle rejected this tendency of atomists to reduce all explanation to atomic terms, and stated the ‘final cause’ as the controlling force, which was a teleological idea.]

When thinking of the establishment of the principles of mechanics, which were to become the very foundations of physical science, it is, in this connection, not without interest to realize that Archimedes’ discovery of the principle of equilibrium of floating objects, which, according to a familiar tradition, was suggested to him by the sensation of uplift of his own body in a bath tub, might just as well have been based on common experience regarding the loss of weight of stones in water. Likewise it is to be regarded as quite accidental that Galileo was led to the recognition of the fundamental laws of dynamics by observing the pendulum motion of a chandelier in the beautiful cathedral of Pisa, and not by looking at a child in a swing. Yet such purely external analogies were, of course, only of little weight for the growing appreciation of the essential unity of the principles governing natural phenomena, as compared to the deep-rooted similarities between living organisms and technical machinery that were disclosed by the studies of anatomy and physiology, pursued so intensely at the time of the Renaissance especially here in Italy.

The enthusiasm for the prospects opened by the success of the new experimental approach to natural philosophy – encouraged in equal manner by
the widening of the world picture due to the vision of Copernicus and by
the elucidation of circulation mechanisms in animal bodies initiated by Har-
vey's great achievement – found perhaps its most striking expression in the
work of Borelli, who succeeded to clarify in so fine detail the mechanical
function of skeleton and muscles in animal motion. The classical character
of this work is in no way impeded by attempts of Borelli himself and his
followers also to explain nervous action and glandular secretion by means
of primitive mechanical models, the obvious arbitrariness and coarseness
of which soon gave rise to general criticism, still remembered by the semi-
ironical name of ‘iatro-physicists’ attached to the Borelian school. Likewise
the endeavours, sound in their root, to apply the growing knowledge of typ-
ically chemical transformations of matter to physiological processes, which
found so enthusiastic an exponent in Sylvius, rapidly led, by exaggerations
of superficial resemblances of digestion and fermentation with the simplest
inorganic reactions and their rash application to medical purposes, to an op-
opposition which has found its expression in the labelling of such premature
endeavours as ‘iatro-chemistry’.

[Giovanni Borelli, a student of Galileo, tried to explain muscular movement
and other body functions according to the laws of mechanics. For example,
he thought the action of the heart was similar to that of a piston, which led
him to conclude that arteries were elastic in nature. His school of thought, of
medical application of physics, was referred to as ‘Iatro-physics’. Franciscus
Sylvius was a contemporary of Borelli, and held that biological phenomena
could be better understood through chemistry, in terms of acids, alkalis and
of fermentation.]

To us the reasons for the shortcomings of these pioneer efforts to utilize
physics and chemistry for a comprehensive explanation of the properties
of living organisms are evident. Not only had one to wait until Lavoisier’s
time for the disclosure of the elementary principles of chemistry, which were
to give the clue to the understanding of respiration and later to provide
the basis for the extraordinary development of so-called organic chemistry,
but, before Galvani’s discoveries, a whole fundamental aspect of the laws
of physics lay still hidden. It is most suggestive to think that the germ
which, in the hands of Volta, Oersted, Faraday, and Maxwell, was to develop
into a structure rivalling Newtonian mechanics in importance grew out of
researches with a biological aim. In fact, it is difficult to imagine that
the progress from experiments with electrically charged currents could have been achieved if the sensitive instruments necessary for the detection of such currents, afterwards so readily constructed, had not been provided by nature itself in the nervous fabric of higher animals.

[In the preceding paragraph Bohr had put human sense organs at the centre of discoveries in mechanics, when he mentioned the discovery by Archimedes and Galileo. Here he extends it to the discovery of electricity. One wonders if this discovery would have been delayed if our nervous system did not rely on electrical phenomena.]

It is impossible here to sketch, even in outline, the tremendous development of physics and chemistry since the days of Galvani, or to enumerate the discoveries in all branches of biology in the last century. We need only to recall the lines leading from the pioneer work, in this venerable university, of Malpighi and Spallanzani to modern embryology and bacteriology respectively, or from Galvani himself to the recent fascinating researches on nerve impulses. In spite of the far-reaching understanding, thus obtained, of the physical and chemical aspect of many typical biological reactions, the marvellous fineness of structure of the organisms go still so far beyond any experience about inanimate nature that we feel as removed as ever from an explanation of life itself on such lines. Indeed, when we witness the passionate scientific controversies as regards the bearing on this problem of the recent discoveries of the poisoning effects and generative properties of so-called virus, we find ourselves presented with a dilemma just as acute as that with which Democritus and Aristotle were confronted.

In this situation it is again upon atomic theory that interest is concentrated, although against a very different background. Not only has this theory, since Dalton applied with such decisive success atomistic conceptions to the elucidation of the quantitative laws governing the constitution of chemical compounds, become the indispensable foundation and never-failing guide of all reasoning in chemistry; but the wonderful refinement of experimental technique in physics has even given us the means of studying phenomena which directly depend on the action of individual atoms. At the same time that this development has thus removed the last traces of the traditional prejudice that, due to the coarseness of our senses, any proof of the actual existence of atoms would forever remain beyond the reach of
human experience, it has revealed still deeper features of atomicity in the divisibility of matter. We have indeed been taught that the very conceptual frame, appropriate both to give account of our experience in everyday life and to formulate the whole system of laws applying to the behaviour of matter in bulk and constituting the imposing edifice of so-called classical physics, had to be essentially widened if it was to comprehend proper atomic phenomena. In order to appreciate the possibilities which this new outlook in natural philosophy provides with respect to a rational attitude towards the fundamental problems of biology, it will, however, be necessary to recall briefly the principal lines of the development which has led to the elucidation of the situation in atomic theory.

[The advent of modern experimental technique has now made naturally limited human sense organs less important than earlier. One would have hoped that this would lead to a more objective understanding of the relation between atomic and biological phenomena. However, the whole framework of classical physics had to be overturned in order to reconcile with quantum phenomena.]

The starting-point of modern atomic physics was, as is well known, the recognition of the atomic nature of electricity itself, first indicated by Faraday’s famous researches on galvanic electrolysis and definitely established by the isolation of the electron in the beautiful phenomena of electric discharges through rarefied gases, which attracted so much attention towards the end of the last century. While J. J. Thomson’s brilliant researches soon brought to light the essential part played by electrons in most varied physical and chemical phenomena, our knowledge of the structural units of matter was, however, not completed until Rutherford’s discovery of the atomic nucleus, crowning his pioneer work on the spontaneous radioactive transmutations of certain heavy elements. Indeed, this discovery offered for the first time an unquestionable explanation of the invariability of the elements in ordinary chemical reactions, in which minute heavy nucleus remains unaltered, while only the distribution of the light electrons around it is affected. Moreover, it provides an immediate understanding not only of the origin of natural radioactivity, in which we witness an explosion of the nucleus itself, but also of the possibility, subsequently discovered by Rutherford, of inducing transmutation of elements by bombardment with high-speed heavy particles which, in colliding with the nuclei, may cause their disintegration.
It would carry us too far from the subject of this address to enter here further upon the wonderful new field of research opened by the study of nuclear transmutations, which will be one of the main subjects of discussion among physicists at this meeting. The essential point of our argument is indeed not to be found in such new experience but in the obvious impossibility to account for common physical and chemical evidence on the basis of the well-established main features of Rutherford’s atomic model without departing radically from the classical ideas of mechanics and electromagnetism. In fact, notwithstanding the insight provided by Newtonian mechanics into the harmony of planetary motions expressed by the Keplerian laws, the stability properties of mechanical models like the solar system which, when disturbed, have no tendency to return to their original state, have clearly no sufficient resemblance with the intrinsic stability of the electronic configurations of atoms that is responsible for the specific properties of the elements. Above all, this stability is strikingly illustrated by spectral analysis which, as is well known, has revealed that any element possesses a characteristic spectrum of sharp lines, independent of the external conditions to such an extent that it offers a means of identifying the material composition of even the most remote stars by spectroscopic observations.

[See the accompanying article in this issue by Khare (p.885) on a comparison between classical mechanics and electrodynamics and quantum mechanical ideas, with regard to the stability of energy levels in an atom. Although spectral identification of elements preceded the emergence of Bohr’s atomic model, the quantum mechanical calculations helped identify some elements in astronomical objects. For example, when there was a confusion between two sets of spectral lines from helium, Bohr, Heisenberg and Born helped clear it by pointing out that the two electrons in a helium atom can exist in two different states, with their spins either parallel or anti-parallel to each other, which led to two different sets of spectral lines.]

A clue to the solution of this dilemma was, however, already provided by Planck’s discovery of the elementary quantum of action which was the outcome of a very different line of physical research. As it is well known, Planck was led to this fundamental discovery by his ingenious analysis of such features of the thermal equilibrium between matter and radiation which, according to the general principles of thermodynamics, should be entirely independent of any specific properties of matter, and accordingly of any
special ideas on atomic constitution. The existence of the elementary quantum of action expresses, in fact, a new trait of individuality of physical processes which is quite foreign to the classical laws of mechanics and electromagnetism and limits their validity essentially to those phenomena which involve actions large compared to the value of a single quantum, as given by Planck’s new atomistic constant. This condition, though amply fulfilled in the phenomena of ordinary physical experience, does in no way hold for the behaviour of electrons in atoms, and it is indeed only the existence of the quantum of action which prevents the fusion of the electrons and the nucleus into a neutral massive corpuscle of practically infinitesimal extension.

The recognition of this situation suggested at once the description of the binding of each electron in the field around the nucleus as a succession of individual processes by which the atom is transferred from one of its so-called stationary states to another of these states, with emission of the released energy in the form of a single quantum of electromagnetic radiation. This view, intimately akin to Einstein’s successful interpretation of the photoelectric effect, and borne out so convincingly by the beautiful researches of Franck and Hertz on the excitation of spectral lines by impacts of electrons on atoms, did in fact not only provide an immediate explanation of the puzzling general laws of line spectra disentangled by Balmer, Rydberg, and Ritz, but, with the help of spectroscopic evidence, led gradually to a systematic classification of the types of stationary binding of any electron in an atom, offering a complete explanation of the remarkable relationships between the physical and chemical properties of the elements, as expressed in the famous periodic table of Mendeleev. While such an interpretation of the properties of matter appeared as a realisation, even surpassing the dreams of the Pythagoreans, of the ancient ideal of reducing the formulation of the laws of nature to considerations of pure numbers, the basic assumption of the individuality of the atomic processes involved at the same time an essential renunciation of the detailed causal connection between physical events, which through the ages had been the unquestioned foundation of natural philosophy.

[See the accompanying article by Durga Prasad in this issue (see p.897) on the explanation of the periodic table with Bohr’s atomic model. It is interesting to note how Bohr contrasts the two aspects of the emergence of quantum theory: on one hand it achieved, or even went beyond, the Pythagorean goal]
of explaining Nature through pure numbers, and on the other hand, in order to achieve this, the old deterministic principles had to be abandoned.]

Not only was any question of a return to a mode of description consistent with the principle of causality excluded by unambiguous experience of the most varied kind, but it soon proved possible to develop the original primitive attempts at accounting for the existence of the quantum of action in atomic theory into a proper, essentially statistical atomic mechanics, fully comparable in consistency and completeness with the structure of classical mechanics of which it appears as a rational generalization. The establishment of this new so-called quantum mechanics which, as is well known, we owe above all to the ingenious contributions of the younger generation of physicists has, indeed, quite apart from its astounding fruitfulness in all branches of atomic physics and chemistry, essentially clarified the epistemological basis of the analysis and synthesis of atomic phenomena. The revision of the very problem of observation in this field, initiated by Heisenberg, one of the principal founders of quantum mechanics, has in fact led to the disclosure of hitherto disregarded presuppositions for the unambiguous use of even the most elementary concepts on which the description of natural phenomena rests. The critical point is here the recognition that any attempt to analyse, in the customary way of classical physics, the ‘individuality’ of atomic processes, as conditioned by the quantum of action, will be frustrated by the unavoidable interaction between the atomic objects concerned and the measuring instruments indispensable for that purpose.

[We should note that by the word ‘individuality’, Bohr is not referring to any anthropomorphic idea, but to phenomena related to single atoms or photons.]

An immediate consequence of this situation is that observations regarding the behaviour of atomic objects obtained with different experimental arrangements cannot in general be combined in the usual way of classical physics. In particular, any imaginable procedure aiming at the coordination in space and time of the electrons in an atom will unavoidably involve an essentially uncontrollable exchange of momentum and energy between the atom and the measuring agencies, entirely annihilating the remarkable regularities of atomic stability for which the quantum of action is responsible. Conversely, any investigation of such regularities, the very account of which implies the conservation laws of energy and momentum, will in
principle impose a renunciation as regards the space-time coordination of the individual electrons in the atom. Far from being inconsistent, the aspects of quantum phenomena revealed by experience obtained under such mutually exclusive conditions must thus be considered complementary in quite a novel way. The viewpoint of 'complementarity' does, indeed, in no way mean an arbitrary renunciation as regards the analysis of atomic phenomena, but is on the contrary the expression of a rational synthesis of the wealth of experience in this field, which exceeds the limits to which the application of the concept of causality is naturally confined.

[See the accompanying article in this issue by Home (see p.905) on Bohr's ability to synthesize different, sometimes apparently disparate, ideas, and particularly so in the context of his idea for 'complementarity' in Nature.]

Notwithstanding the encouragement given to the pursuit of such inquiries by the great example of relativity theory which, just through the disclosure of unsuspected presuppositions for the unambiguous use of all physical concepts, opened new possibilities for the comprehension of apparently irreconcilable phenomena, we must realize that the situation met with in modern atomic theory is entirely unprecedented in the history of physical science. Indeed, the whole conceptual structure of classical physics, brought to so wonderful a unification and completion by Einstein's work, rests on the assumption, well adapted to our daily experience of physical phenomena, that it is possible to discriminate between the behaviour of material objects and the question of their observation. For a parallel to the lesson of atomic theory regarding the limited applicability of such customary idealisations, we must in fact turn to quite other branches of science, such as psychology, or even to that kind of epistemological problems with which already thinkers like Buddha and Lao Tse have been confronted, when trying to harmonize our position as spectators and actors in the great drama of existence. Still, the recognition of an analogy in the purely logical character of the problems which present themselves in so widely separated fields of human interest does in no way imply acceptance in atomic physics of any mysticism foreign to the true spirit of science, but on the contrary it gives us an incitement to examine whether the straightforward solution of the unexpected paradoxes met with in the application of our simplest concepts to atomic phenomena might not help us to clarify conceptual difficulties in other domains of experience.
[Bohr’s apprehension that the oddities of quantum mechanics might be wrongly related to ideas in mysticism proved right when in the second half of the last century many books were published with such views. His mention of Lao Tse seems farsighted because one of the books that held lay readers’ attention for a long time was named ‘The tao of physics’.

There has also been no lack of suggestions to look for a direct correlation between life and free will and those features of atomic phenomena for the comprehension of which the frame of classical physics is obviously too narrow. In fact, it is possible to point out many characteristic features of the reactions of living organisms, like the sensitivity of visual perception or the induction of gene mutation by penetrating radiation, which undoubtedly involve an amplification of the effects of individual atomic processes, similar to that on which the experimental technique of atomic physics is essentially based. Still, the recognition that the fineness of organization and regulation mechanisms of living beings goes even so far beyond any previous expectation does in no way enable us to account for the peculiar characteristics of life. Indeed, the so-called holistic and finalistic aspects of biological phenomena can certainly not be immediately explained by the feature of individuality of atomic processes disclosed by the discovery of the quantum of action; rather would the essentially statistical character of quantum mechanics at first sight seem even to increase the difficulties of understanding the proper biological regularities. In this dilemma, however, the general lesson of atomic theory suggests that the only way to reconcile the laws of physics with the concepts suited for a description of the phenomena of life is to examine the essential difference in the conditions of the observation of physical and biological phenomena.

First of all we must realize that every experimental arrangement with which we could study the behaviour of the atoms constituting an organism to the extent to which this can be done for single atoms in the fundamental experiments of atomic physics will exclude the possibility of maintaining the organism alive. The incessant exchange of matter which is inseparably connected with life will even imply the impossibility of regarding an organism as a well-defined system of material particles like the systems considered in any account of the ordinary physical and chemical properties of matter. In fact, we are led to conceive the proper biological regularities as representing laws of nature complementary to those appropriate to the account
of the properties of inanimate bodies, in analogy with the complementary relationship between the stability properties of the atoms themselves and such behaviour of their constituent particles as allows of a description in terms of space-time coordination. In this sense, the existence of life itself should be considered, both as regards its definition and observation, as a basic postulate of biology, not susceptible of further analysis, in the same way as the existence of the quantum of action, together with the ultimate atomicity of matter, forms the elementary basis of atomic physics.

[That Bohr was fond of complementarity in different aspects of Nature is evident in this paragraph. He also comes up with an ansatz that could be applied to biological systems, not much different from his ansatz for quantization of stationary levels in atoms.]

It will be seen that such a viewpoint is equally removed from the extreme doctrines of mechanism and vitalism. On the other hand, it condemns as irrelevant any comparison of living organisms with machines, be these the relatively simple constructions contemplated by the old-iatro physicists, or the most refined modern amplifier devices, the uncritical emphasis of which would expose us to deserve the nickname of ‘iatro-quantists’. On the other hand, it rejects as irrational all such attempts at introducing some kind of special biological laws inconsistent with well-established physical and chemical regularities, as have in our days been revived under the impression of the wonderful revelations of embryology regarding cell growth and division. In this connection it must be especially remembered that the possibility of avoiding any such inconsistency within the frame of complementarity is given by the very fact that no result of biological investigation can be unambiguously described otherwise than in terms of physics and chemistry, just as any account of experience even in atomic physics must ultimately rest on the use of the concepts indispensable for a conscious recording of sense impressions.

The last remark brings us back into the realm of psychology, where the difficulties presented by the problems of definition and observation in scientific investigations have been clearly recognized long before such questions became acute in natural science. Indeed, the impossibility in psychical experience to distinguish between the phenomena themselves and their conscious perception clearly demands a renunciation of a simple causal description
on the model of classical physics, and the very way in which words like ‘thoughts’ and ‘feelings’ are used to describe such experience reminds one most suggestively of the complementarity encountered in atomic physics. I shall not here enter into any further detail but only emphasize that it is just this impossibility of distinguishing, in introspection, sharply between subject and object which provides the necessary latitude for the manifestation of volition. To connect free will more directly with limitation of causality in atomic physics, as it is often suggested, is, however, entirely foreign to the tendency underlying the remarks here made about biological problems.

[Bohr again cautions against using the limitations of determinism in atomic physics to deal with free will, and draws our attention to the subtleties involved in distinguishing subject and object in dealing with psychological, and also biological, problems. This, in his view, should lead to a better way of dealing with free will, and hopefully, of integrating biology with physics and chemistry.]

In concluding this address I hope that the temerity of a physicist venturing so far outside his restricted domain of science may be forgiven in view of the most welcome opportunity of profitable discussion offered to physicists and biologists by this gathering to honour the memory of the great pioneer to whose fundamental discoveries both branches of science owe so much.