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Gerald Holton

The Roots of Complementarity

EACH AGE is formed by certain characteristic conceptions, those that give it its own unmistakable modernity. The renovation of quantum physics in the mid-1920s brought into public view just such a conception, one that marked a turning point in the road from which our view of the intellectual landscape, in science and in other fields, will forever be qualitatively different from that of earlier periods. It was in September 1927 in Como, Italy, during the International Congress of Physics held in commemoration of the one-hundredth anniversary of Alessandro Volta's death, that Niels Bohr for the first time introduced in a public lecture his formulation of complementarity.¹ Bohr's audience contained most of the leading physicists of the world in this area of work, men such as Max Born, Louis de Broglie, A. H. Compton, Peter Debye, Enrico Fermi, James Franck, Werner Heisenberg, Max von Laue, H. A. Lorentz, Robert Millikan, John von Neumann, Wolfgang Pauli, Max Planck, Arnold Sommerfeld, Otto Stern, Eugene Wigner, and Pieter Zeeman. It was a veritable summit meeting. Only Einstein was conspicuously absent.

COMO, 1927

In the introduction to his lecture, Bohr said he would make use "only of simple considerations, and without going into any details of technical, mathematical character." Indeed, the essay contained only

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few and simple equations. Rather, its avowed purpose was a methodological one that, at least in this initial announcement, did not yet confess its ambitious scope. Bohr stressed only that he wanted to describe “a certain general point of view . . . which I hope will be helpful in order to harmonize the apparently conflicting views taken by different scientists.”

He was referring to a profound and persistent difference between the classical description and the quantum description of physical phenomena. To review it, we can give four brief examples of the dichotomy:

1. In classical physics, for example in the description of the motion of planets or billiard balls or other objects which are large enough to be directly visible, the “state of the system” can (at least in principle) be observed, described, defined with arbitrarily small interference of the behavior of the object on the part of the observer, and with arbitrarily small uncertainty. In quantum description, on the other hand, the “state of the system” cannot be observed without significant influence upon the state, as for example when an attempt is made to ascertain the orbit of an electron in an atom, or to determine the direction of propagation of photons. The reason for this situation is simple: the atoms, either in the system to be observed or in the probe that is used in making the observation, are never arbitrarily fine in their response; the energy exchange on which their response depends is not any small quantity we please, but, according to the “quantum postulate” (Planck’s fundamental law of quantum physics), can proceed only discontinuously, in discrete steps of finite size.

2. It follows that in cases where the classical description is adequate, a system can be considered closed although it is being observed, since the flow of energy into and out of the system during an observation (for example, of the reflection of light from moving balls) is negligible compared to the energy changes in the system during interaction of the parts of the system. On the other hand, in systems that require quantum description, one cannot neglect the interaction between the “system under observation,” sometimes loosely called the “object,” and the agency or devices used to make the observations (sometimes loosely called the “subject”). The best-known case of this sort is illustrated by Heisenberg’s gamma-ray microscope, in which the progress of an electron is “watched” by

scattering gamma rays from it, with the result that the electron itself is deflected from its original path.

3. In “classical” systems, those for which classical mechanics is adequate, we have both conventional causality chains and ordinary space-time coordination, and both can exist at the same time. In quantum systems, on the other hand, there are no conventional causality chains; if left to itself, a system such as an atom or its radioactive nucleus undergoes changes (such as emission of a photon from the atom or a particle from the nucleus) in an intrinsically probabilistic manner. However, if we subject the “object” to space-time observations, it no longer undergoes its own probabilistic causality sequence. Both these mutually exclusive descriptions of manifestations of the quantum system must be regarded as equally relevant or “true,” although both cannot be exhibited at one and the same time.

4. Finally, we can refer to Bohr’s own illustration in the 1927 essay of “the much discussed question of the nature of light . . . [I]ts propagation in space and time is adequately expressed by the electromagnetic theory. Especially the interference phenomena *in vacuo* and the optical properties of material media are completely governed by the wave theory superposition principle. Nevertheless, the conservation of energy and momentum during the interaction between radiation and matter, as evident in the photoelectric and Compton effect, finds its adequate expression just in the light quantum idea put forward by Einstein.”² Unhappiness with the wave-particle paradox, with being forced to use in different contexts two such antithetical theories of light as the classical wave theory and the quantum (photon) theory was widely felt. Einstein expressed it in April 1924 by writing: “We now have two theories of light, both indispensable, but, it must be admitted, without any logical connection between them, despite twenty years of colossal effort by theoretical physicists.”³

The puzzle raised by the gulf between the classical description and the quantum description was: Could one hope that, as had happened so often before in physics, one of the two antithetical views would somehow be subsumed under or dissolved in the other (somewhat as Galileo and Newton had shown celestial physics to be no different

from terrestrial physics)? Or would one have to settle for two so radically different modes of description of physical phenomena? Would the essential continuity that underlies classical description, where coordinates such as space, time, energy, and momentum can in principle be considered infinitely divisible, remain unyieldingly antithetical to the essential discontinuity and discreteness of atomic processes?

Considering the situation in 1927 in thematic terms, it was by that time clear that physics had inherited contrary themata from the “classical” period (before 1900) and from the quantum period (after 1900). A chief thema of the earlier period was continuity, although it existed side by side with the atomistic view of matter. A chief thema of the more recent period was discontinuity, although it existed side by side with the wave theory of electromagnetic propagation and of the more recent theories associated with de Broglie and Erwin Schrödinger.

In the older physics, also, classical causality was taken for granted, whereas in the new physics the concepts of indeterminacy, statistical description, and probabilistic distribution as inherent aspects of natural description were beginning to be accepted. In the older physics, the possibility of a sharp subject-object separation was not generally challenged; in the new physics it was seen that the subject-object coupling could be cut only in an arbitrary way. In Bohr’s sense, a “phenomenon” is the description of that which is to be observed *and* of the apparatus used to obtain the observation.

Bohr’s proposal of 1927 was essentially that we should attempt not to reconcile the dichotomies, but rather to realize the complementarity of representations of events in these two quite different languages. The separateness of the accounts is merely a token of the fact that, in the normal language available to us for communicating the results of our experiments, it is possible to express the wholeness of nature only through a complementary mode of descriptions.⁴ The apparently paradoxical, contradictory accounts should not divert our attention from the essential wholeness. Bohr’s favorite aphorism was Schiller’s “Nur die Fülle führt zur Klarheit.” Unlike the situation in earlier periods, clarity does not reside in simplification and reduction to a single, directly comprehensible model, but in the exhaustive overlay of different descriptions that incorporate apparently contradictory notions.

Summarizing his Como talk, Bohr in 1949 stressed that the need to express one's reports ultimately in normal (classical) language dooms any attempt to impose a clear separation between an atomic "object" and the experimental equipment:

The new progress in atomic physics was commented upon from various sides at the International Physical congress held in September 1927, at Como in commemoration of Volta. In a lecture on that occasion, I advocated a point of view conveniently termed "complementarity," suited to embrace the characteristic features of individuality of quantum phenomena, and at the same time to clarify the peculiar aspects of the observational problem in this field of experience. For this purpose, it is decisive to recognize that, *however far the phenomena transcend the scope of classical physical explanation, the account of all evidence must be expressed in classical terms.* The argument is simply that by the word "experiment" we refer to a situation where we can tell others what we have learned and that, therefore, the account of the experimental arrangement and of the results of the observations must be expressed in unambiguous language with suitable application of the terminology of classical physics.

This crucial point, which was to become a main theme of the discussions reported in the following, *implies the impossibility of any sharp separation between the behaviour of atomic objects and the interaction with the measuring instruments which serve to define the conditions under which the phenomena appear.* In fact, the individuality of the typical quantum effects finds its proper expression in the circumstance that any attempt of subdividing the phenomena will demand a change in the experimental arrangement, introducing new possibilities of interaction between objects and measuring instruments which in principle cannot be controlled. Consequently, evidence obtained under different experimental conditions cannot be comprehended within a single picture, but must be regarded as *complementary* in the sense that only the totality of the phenomena exhausts the possible information about the objects.⁵

What Bohr was pointing to in 1927 was the curious realization that in the atomic domain, the only way the observer (including his equipment) can be uninvolved is if he observes nothing at all. As soon as he sets up the observation tools on his workbench, the system he has chosen to put under observation and his measuring instruments for doing the job form one inseparable whole. Therefore, the results depend heavily on the apparatus. In the well-known illustration involving a light beam, if the instrument of measurement contains a

double pinhole through which the light passes, the result of observation will indicate that a wave phenomenon is involved; but if the "same" light beam is used when the measuring instrument contains a collection of recoiling scatterers, then the observation results will indicate that a stream of particles is involved. (Moreover, precisely the same two kinds of observations are obtained when, instead of the beam of light, one uses a beam of "particles" such as atoms or electrons or other subatomic particles.) One cannot construct an experiment which simultaneously exhibits the wave and the particle aspects of atomic matter. A particular experiment will always show only one view or representation of objects at the atomic level.

The study of nature is a study of artifacts that appear during an engagement between the scientist and the world in which he finds himself. And these artifacts themselves are seen through the lens of theory. Thus, different experimental conditions give different views of "nature." To call light either a wave phenomenon or a particle phenomenon is impossible; in either case, too much is left out. To call light *both* a wave phenomenon and a particle phenomenon is to oversimplify matters. Our knowledge of light is contained in a number of statements that are seemingly contradictory, made on the basis of a variety of experiments under different conditions, and interpreted in the light of a complex of theories. When you ask, "What is light?" the answer is: the observer, his various pieces and types of equipment, his experiments, his theories and models of interpretation, *and* whatever it may be that fills an otherwise empty room when the lightbulb is allowed to keep on burning. All this, together, is light.

No objections seem to have been raised against Niels Bohr's paper at the Como meeting. On the other hand, at this first hearing the importance of the new point of view was not immediately appreciated. Apparently, a typical comment overheard after Bohr's lecture was that it "will not induce any of us to change his own opinion about quantum mechanics."⁶ A distinguished group of physicists, although a minority in the field, remained unconvinced by and indeed hostile to the complementarity point of view. Foremost among them was Einstein, who heard the first extensive exposition a month after the Como meeting, in October 1927, at the Solvay Congress in Brussels. Einstein had disliked even the earlier Göttingen-Copenhagen

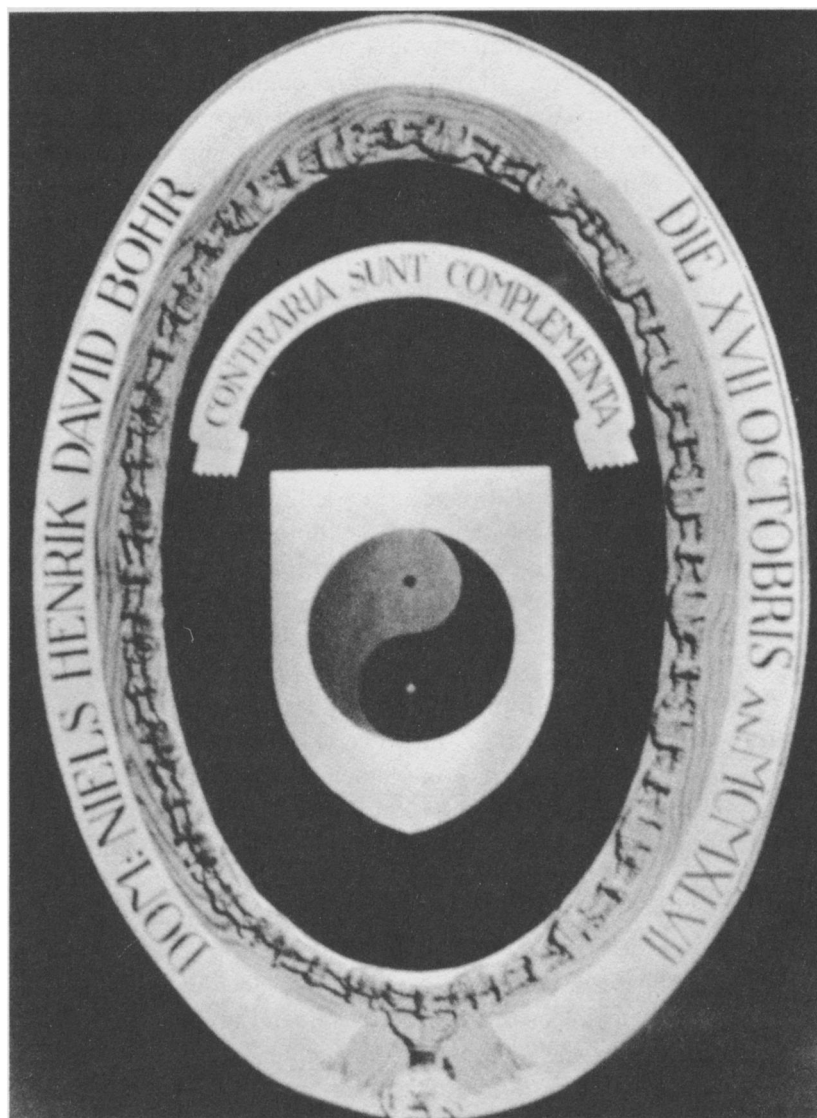
interpretations of atomic physics that were based on the themata of discontinuity and nonclassical causality. He had written to Paul Ehrenfest (August 28, 1926), "I stand before quantum mechanics with admiration and suspicion," and to Bohr (December 4, 1926) Einstein had said, "Quantum mechanics demands serious attention. But an inner voice tells me that this is not the true Jacob. The theory accomplishes a lot, but it does not bring us closer to the secrets of the Old One. In any case, I am convinced that He does not play dice."⁷

Almost a quarter of a century later Einstein was still in opposition, and added two objections to the complementarity principle: "to me it must seem a mistake to permit theoretical description to be directly dependent upon acts of empirical assertions, as it seems to be intended (for example) in Bohr's principle of complementarity, the sharp formulation of which, moreover, I have been unable to achieve despite much effort which I have expended on it."⁸

Bohr himself was aware from the beginning that the complementarity point of view was a program rather than a finished work; that is, it had to be extended and deepened by much subsequent work. It was to him "a most valuable incentive . . . to reexamine the various aspects of the situation as regards the description of atomic phenomena" and "a welcome stimulus to verify still further the role played by the measuring instruments."⁹ However, as we shall see, over the years Bohr came to regard the complementarity principle as more and more important, extending far beyond the original context in which it had been announced. For his later, deep commitment to the conception, and for his awareness of the antiquity of some of its roots, we need cite here only an anecdotal piece of evidence. When Bohr was awarded the Danish Order of the Elephant in 1947, he had to supervise the design of a coat of arms for placement in the church of the Frederiksborg Castle at Hillerød. The device (see the figure on page 158) presents the idea of complementarity: above the central insignia, the legend says "Contraria sunt complementa," and at the center Bohr placed the symbol for Yin and Yang.

LUX VERSUS LUMEN

How did Bohr's complementarity point of view—so far from the older scientific tradition of strict separation between the observer and the observed—come to be developed? Finding the various roots of



Coat of arms chosen by Niels Bohr when he was awarded the Danish Order of the Elephant, 1947. From S. Rozental, ed., *Niels Bohr: His Life and Work as Seen by His Friends and Colleagues* (New York: John Wiley & Sons, Inc., 1967), facing p. 305.

and the likely preparatory conditions for this transforming conception—those in physical theory and those in philosophical tradition—appears to me to be an interesting problem that is far from its unambiguous solution. However, there are already some useful results of the search, particularly insofar as they may have relevance for a better understanding of the mutual interaction of scientific and humanistic traditions.

The first direction to look is the development of the early ideas concerning the nature of light. That a modern thema was already inherent in the formulations that began in antiquity should not surprise us; we know from other studies that despite all change and progress of science, the underlying, important themata are relatively few. In one guise or another they have been the mainstay of the imagination.

One of the favorite ancient ideas concerning the nature of light, originating in the Pythagorean school, postulated that rays are emitted by the eye to explore the world. Euclid spoke of the eye as if it were sending out visual rays whose ends probed the object, somewhat like the stick of a blind man tapping around himself. A somewhat more refined conception of this general sort is still found in Ptolemy in the second century A.D. in the *Almagest*, and so was transmitted to a later period.

There is in these emission theories of light clearly an intimate interaction through contact between the observer and the observed. This is also true for the emanation tradition in another, less materialistic form.¹⁰ Here, objects are thought to impress themselves upon our sight owing to a contact force similar to touch—action at a distance being ruled out in classical physics—and this touch reaches our souls by the action of the *eidola*, or images or shadows which the emitting bodies send out. Plato held that as long as the eye is open, it emits an inner light. For the eye to perceive, however, there must be outside the eye a “related other light,” that of the sun or some other source that allows rays to come from the objects. Once more, a coupling between the outer and the inner world is clearly attempted.

There were immense problems with emission theories. How, for example, can the eye pupil, only a few millimeters wide, admit the image that was emitted by a huge mountain? Nevertheless, the emanation theory was the takeoff point for the optics developed in the seventeenth century. Here we find the modern idea that there is an

infinite number of rays leaving from every point of an illuminated object in all directions. But the observer now stands offstage, and he may or may not be the recipient of some of these ray bundles. The latter are no longer the *lux* of the ancients—*lux* being the word for light when it is regarded as a subjective phenomenon—but rather the *lumen*, a kind of stream of light “objects.”

The modern period started effectively with Kepler, who in his writing on Witelo in 1604 and later in the *Dioptrics* of 1611 described how light is refracted by a sphere, for example in a spherical bottle filled with water; he applied his findings to the pupil of the eye. Here was the basic new idea in the optics of vision: the eyeball, and the lens in front of it, focus the ray bundles that come through the pupil, and at the focus the sensorium is stimulated in some way—*which is simply not discussed as part of optics*. In the *Dioptrics* Kepler showed for the first time how lenses really work. Significantly, most images that can be constructed diagrammatically by ray optics can, in fact, not be seen at all by an eye placed at the instrument. Gone are the *eidola* and the *species*, the “recognition” of soul by soul in Neoplatonist discussion of optics—but gone also is the close coupling of the observer and the observed. The *lumen* had won over the *lux*.

We see how the science of optics became “modern”: by an act of breaking the bonding that was self-evident for the ancients, by disengaging the conceptions of what goes on “out there, objectively speaking” on the one hand, and what the eye does with light on the other hand. At some point someone had to do what Kepler, in preparing for Newton, finally did, namely to get interested in bundles of light rays coming together on a screen outside an eye—or, what is for the physics of light significantly exactly the same thing, on the retina or screen in back of the eye—and to stop thinking about the sense impressions produced at such a focus at the same time. As Müller’s influential *Lehrbuch der Physik* said in 1926, just one year before Bohr’s formulation of the idea of complementarity, the first task of physical optics “is the sharp separation between the objective ray of light and the sensory impression of light. The subject of discussion of physical optics is the ray of light, whereas the inner processes between eye and brain”—says the *Lehrbuch*, dismissing the matter—“are in the domain of physiology, and perhaps also psychology.”

We see here an attempt at precisely the same separation of primary and secondary qualities, between the numerical and affective aspects of nature, that, as it had turned out three centuries before, was the key with which Galileo and others at that time managed to go from the mechanics of antiquity to modern mechanics. We recall that it was Galileo who did for particles, such as falling stones, what Kepler did for light—namely, to remove the language of volition and teleology, and to fortify the notion of “impersonal,” causal laws of motion. The Newtonian science of light has no primary place for the observer and his sense impression. In this manner, the important, basic properties of light could be discovered: the finite propagation speed, the existence of light rays outside the range to which the eye is sensitive, the analogy between light rays and other radiation such as X-rays, and so forth.

The decoupling between *lux* and *lumen*, between subject and object, observer and the observed, and with it the destruction of the earlier, holistic physics, was a painful and lengthy process. The reason why it was ultimately victorious is the reason why the same process in all other parts of science worked: once the separation was made, there ensued a dazzling enrichment of our intellectual and material world. By 1927, a reader of physics texts was bound to feel that the modern theory of light, from electromagnetic theory to the design of optical instruments, devoted its attention entirely to *lumen*, and was a field just as deanthropomorphized as all other parts of the developed physical sciences.

But the seed of a new view of light was present, carried in the early historic development which we have sketched, in the prescientific, commonsense notions that everyone begins with—and in the operational meaning of some of the main concepts of optics. Thus we turn to a second main line of ideas leading to the complementarity point of view.

OPERATIONAL MEANINGS

One of the oldest and most elementary building blocks of optics is: light travels in any homogeneous medium in straight lines. But let us consider for a moment why we believe that this statement is true.

We can check it most directly in an experimental way by inserting a screen or scatterer, such as chalk dust, in different parts of the same

beam. If we consider this closely, we notice that such a method destroys the light beam that we wanted to examine. The insertion of the apparatus interferes with the phenomenon.

This situation is typical on the atomic scale. There are no comparable problems when one wishes to check, say, Newton's first law of motion for ordinary physical objects, for example by watching or photographing a ball rolling on a flat table. We can verify that a material object in a force-free medium will travel in straight lines without drastically interrupting the object's path. The small effects of the apparatus can be removed by calculation. The fact that the observer and the "object" must share between them at least one indivisible quantum is here negligible, that is, can be made an arbitrarily small part of the phenomenon. From past observations we can therefore extrapolate with certainty the paths the object will take in the future. Space-time descriptions and classical causality apply without difficulty. Not so for beams of light and of other particles on the atomic scale. The more certainly we have ascertained their past, the less certainly we can follow their subsequent progress; the effect of the perturbing interaction with the apparatus cannot be taken out by calculation but is intrinsically probabilistic. In fact, owing to the uncertainty principle, it is not even possible to define precisely the initial state of the system in the sense required by the classical view of causality.

If we do not wish to intercept the whole beam, we can try to discover whether a beam goes in a straight line by another method: by placing a number of slits at some distance from one another, but all along the same axis, then checking if light penetrates this whole set of collimators. But there are now two problems. First, how do we know whether the slits are indeed arranged in a straight line? We might check it with a straightedge—but we know the straightedge is straight because we can sight directly along it and see no curves or protrusions. Clearly, this process of sighting, or anything equally effective, relies on using a light beam to sight along the ruler. And that, of course, is circular reasoning, assuming, in setting up the instrument, what the experiment is designed to prove.

The paradox is not inescapable; there are other, although more cumbersome, methods for lining up the slits without assuming anything about light. But again, we run into trouble. The more closely we wish to define the line along which the beam is to travel,

and consequently the narrower we make the slit, the more we find that the beam's energy is spread out into the "shadow," turning, as it were, a corner on going through the slit. This is the phenomenon of diffraction. It is exceedingly easy to demonstrate with the crudest equipment, even just by letting light from a candle pass through the narrow space between two fingers held closely to the eye.

We are dealing here with an instrumental coupling between observer (equipment) and the entity to be observed. As soon as we try to give an operational meaning to the phrase "light travels in any homogeneous medium in straight lines," we see what a poor statement it is.

As a result, a physicist is likely to prefer another statement, more general but which can be reduced in the limit to the one above. It is Fermat's Principle of Least Time, derived from a statement that dates from about 1650. Between any two points, light will go along that path in which the time spent in transit is less than the time that would be spent in any other path. This view explains why a light beam appears to go in a straight line in a homogeneous medium and also how a beam is reflected or refracted at the interfaces of two media. But the statement harbors the curious idea that light is "exploring" to find the quickest path, as if light were scouting around in the apparatus. We get here a hint of instrumental coupling of the most intimate sort. The suspicion arises that the properties we assign to light are to some degree the properties of the boxes through which light has to find its way.

This becomes quite obvious and unmistakable when we turn to another well-known experiment. When light is sent through a double slit, an interference pattern characteristic of the geometry of the arrangement is obtained on a screen. If one of the two slits is blocked off, a rather different pattern of interference results. All this can be easily understood with elementary constrictions from the classical theory of light. However, if a very weak beam of light is used with the double-slit experiment, so that at any given time it is exceedingly unlikely that more than a single photon travels through the apparatus, a remarkable thing will be observed: even though one cannot help using classical language and thinking that a single photon will have to go through either one or the other of the two slits at a given time, it will be found that as long as both slits are kept open, the interference pattern accumulating in due course on a photographic

plate placed at the screen has exactly the same characteristics as that for the earlier double-slit experiment, when the beam was so strong that at any given moment some photons were passing through one of the slits and some photons were passing through the other. Equally remarkable, if one now closes one of the slits toward which the very weak beam of photons is being sent, the interference pattern accumulated over a period changes to the pattern characteristic of a strong light beam passing through a single slit. The fact that for a weak light beam the interference pattern depends on the number of slits available—even though there is no evident way in which the single photon can “know” if the other slit is open—is an indication that the experimental observations of light yield characteristics of the box and its slits as much as of light itself. In short, the experiments are made on the entity light + box. Here, then, in the operational examination of the laws of light propagation is a second path leading to the complementarity idea.

FROM CORRESPONDENCE TO COMPLEMENTARITY

Yet another primary influence on Bohr was, of course, the achievement and failures of physics in his own work from about 1912 to about 1925. Bohr’s model of the hydrogen atom of 1912–1913 is now usually remembered best for the magnificent accomplishment of predicting the frequencies of the emission spectrum. To do this, Bohr essentially tried to reconcile the two apparently antithetical notions about light, both of which had had their successes—the electromagnetic theory of Maxwell, according to which light propagates as a wavelike disturbance characterized by continuity, and, on the other hand, Einstein’s theory that light energy is characterized by discreteness and discontinuity. As Einstein had put it in his 1905 paper presenting a “heuristic” point of view concerning the interaction of light and matter, “The energy in the light propagated in rays from a point is not smeared out continuously over larger and larger volumes, but rather consists of a finite number of energy quanta localized at space points, which move without breaking up, and which can be absorbed or emitted only as wholes.”

By 1912 the indisputable evidence for Einstein’s outrageous notion was not yet at hand, but some experiments on the photoelectric effect, including those with X-rays, began to make it plausible.¹¹

Indeed, it was not until Millikan's experiment, published in 1916, and A. H. Compton's experiment of 1922 that the quantum theory of light was seen everywhere to be unavoidable.

It is therefore, in retrospect, even more remarkable how courageous Niels Bohr's work of 1912–1913 was. Let us recall his model of the hydrogen atom in its initial form, even though it was soon made more accurate, though more complex. Bohr's hydrogen atom had the nucleus at the center (where Ernest Rutherford, in whose Manchester laboratory Bohr was a guest, had just then discovered it to be) and the electron orbiting at some fixed distance around the nucleus. When the sample is heated or the atoms are otherwise excited by being given extra energy, the electron of the excited atom will not be in the normal, innermost orbit, or ground state, but will be traveling in a more distant orbit. At some point the electron will jump from the outer orbit to one of the allowed inner orbits and, in so doing, will give up the energy difference between these orbits, or stationary states, in the form of a photon of energy $h\nu$. This corresponds to the emission of light at the observed frequency ν or the corresponding wave length $\lambda = c/\nu$ (where c is the speed of light). The various observed frequencies emitted from an excited sample of hydrogen atoms were therefore interpreted to be a stream of photons, each photon having the energy corresponding to the allowed transition between stationary states.

The success of the model in explaining all known spectrum lines of hydrogen, in predicting other series that were also found, and in giving a solid foothold on the explanation of chemical properties, could not hide the realization, fully apparent to Niels Bohr himself, that the model carried with it a number of grave problems. First of all, it used simultaneously two separate notions which were clearly conflicting: the classical notion of an identifiable electron moving in an identifiable orbit like a miniature planetary system, and the quantum notion that such an electron is in a stationary state rather than continually giving up energy while orbiting (as it should do on the basis of Maxwell's theory, amply tested for charges circulating in structures of large size). Bohr's postulate that the electron would not lose energy by radiation while in an orbit, but only on transition from one orbit to the other, was necessary to "save" the atom from gradually collapsing with the emission of a spectrum line of continuously changing frequency. Also, contrary to all previous ideas, the

frequency of the emitted photon was not equal to the frequency of the model's orbiting electron, either in its initial or in its final stationary state.

Looking back later on the situation of about 1912, Merle A. Tuve noted that the Bohr atom was "quite irrational and absurd from the viewpoint of classical Newtonian mechanics and Maxwellian electrodynamics. . . . Various mathematical formalisms were devised which simply 'described' atomic states and transitions, but the same arbitrary avoidance of detailed processes, for example, descriptions of the actual *process* of transition, were inherent in all these formulations."¹²

Niels Bohr himself took pains to stress these conflicts from the beginning. In fact, the explanation of the spectral lines, which were the most widely hailed achievement, more or less constituted an afterthought in his own work. His interest was precisely to examine the area of conflict between the conceptions of ordinary electrodynamics and classical mechanics on the one hand and quantum physics on the other. As Jammer pointed out, "Not only did Bohr fully recognize the profound chasm in the conceptual scheme of his theory, but he was convinced that progress in quantum theory could not be obtained unless the antithesis between quantum-theoretic and classical conceptions was brought to the forefront of theoretical analysis. He therefore attempted to trace the roots of this antithesis as deeply as he could. It was in this search for fundamentals that he introduced the revolutionary conception of 'stationary' states, 'indicating thereby that they form some kind of waiting places between which occurs the emission of the energy corresponding to the various spectral lines,' [as Bohr put it in an address of December 20, 1913, to the Physical Society in Copenhagen¹³]." At the end of his address, Bohr said, "I hope I have expressed myself sufficiently clearly so that you appreciate the extent to which these considerations conflict with the admirably coherent group of conceptions which have been rightly termed the classical theory of electrodynamics. On the other hand, by emphasizing this conflict, I have tried to convey to you the impression that it may also be possible in the course of time to discover a certain coherence in the new ideas."

This methodological strategy of *emphasizing conceptual conflict as a necessary preparation for its resolution* culminated, fourteen years later, in the announcement of the complementarity principle. In the

meantime, Bohr formulated a proposal that turned out to be a moderately successful halfway house toward the reconciliation between classical and quantum mechanics, a conception which, from about 1918 on, became known as the correspondence principle.

In essence, Bohr still hoped for the resolution between opposites by attending to an area where they overlap, namely the extreme cases where quantum theory and classical mechanics yield to each other. For example, for very large orbits of the hydrogen atom's electron, the neighboring allowed stationary states in Bohr's model come to be very close together. It is easily shown that a transition between such orbits, on the basis of quantum notions, yields a radiation of just the same frequency expected on classical grounds for a charged particle orbiting as part of a current in a circular antenna—and, moreover, the frequency of radiation would be equal to the frequency of revolution in the orbit. Thus for sufficiently large "atoms," and conversely for sufficiently small "circuits" scaled down from the normal size of ordinary electric experiments, a coincidence, or correspondence, of predictions is obtained from the two theories.

In this manner, classical physics becomes the limiting case of the more complex quantum physics: our more ordinary, large-scale experiments fail to show their inherently quantal character only because the transitions involved are between states characterized by high quantum numbers. In this situation the quantum of action relative to the energies involved in the system is effectively zero rather than having a finite value, and owing to the large number of events, the discreteness of individual events is dissolved in an experienced continuum.

The correspondence principle came to be developed in the hands of Bohr and his collaborators into a sophisticated tool. The basic hope behind it was explained by Bohr in a letter to A. A. Michelson on February 7, 1924:

It may perhaps interest you to hear that it appears to be possible for a believer in the essential reality of the quantum theory to take a view which may harmonize with the essential reality of the wave-theory conception even more closely than the views I expressed during our conversation. In fact on the basis of the correspondence principle it seems possible to connect the discontinuous processes occurring in atoms with the continuous character of the radiation field in a somewhat more adequate way than hitherto

perceived. . . . I hope soon to send you a paper about these problems written in cooperation with Drs. Kramer and Slater.¹⁴

But shortly after the publication in 1924 of the paper by Bohr, Kramer, and Slater,¹⁵ experiments were initiated by W. Bothe and H. Geiger and by A. H. Compton and A. W. Simon—with unambiguously disconfirming results. The correspondence principle, it appeared now clearly, had been a useful patch over the fissure, but it was not a profound solution.

Even before that discovery, major problems known to be inherent in the Bohr atom included the following: the fact that the antithetical notions of the wave (implied in the frequency or wavelength of light emitted) and of the particle (implied in the then current idea of the electron) were by no means resolved, but on the contrary persisted unchanged in the model of the atom; so did the conflict between the antithetical notions of classical causality on the one hand (as in the presumed motion of the electrons in their orbits) and of probabilistic features on the other (as for the transitions between allowed orbits); and even the notion of the “identity” of the atom had to be revised, for it was no longer even in principle observable and explorable as a separate entity without interfering with its state. Each different type of experiment produces its own change of state, so that different experiments produce different “identities.”

Such questions remained at the center of discussion among the most concerned physicists. Schrödinger and de Broglie, for example, hoped to deal with the glaring contrast between the themata of continuity and discontinuity by providing a wave-mechanical explanation for phenomena that previously had been thought to demand a language of quantization. As Schrödinger wrote in his first paper on the subject,¹⁶ “It is hardly necessary to point out how much more gratifying it would be to conceive a quantum transition as an energy change from one vibrational mode to another than to regard it as a jumping of electrons. The variation of vibrational modes may be treated as a process continuous in space and time and enduring as long as the emission process persists.” Thus, space-time description and classical causality would be preserved.

The reception accorded to Schrödinger’s beautiful papers was interesting. Heisenberg had obtained essentially the same results in a quite different way through his matrix mechanics; as Jammer notes,

“it was an *algebraic* approach which, proceeding from the observed discreteness of spectral lines, emphasized the element of *discontinuity*; in spite of its renunciation of classical description in space and time it was ultimately the theory whose basic conception was the *corpuscle*. Schrödinger’s, in contrast, was based on the familiar apparatus of differential equations, akin to the classical mechanics of fluids and suggestive of an easily visualizable representation; it was an *analytical* approach which, proceeding from a generalization of the classical laws of motion, stressed the element of *continuity*.”¹⁷ “Those who in their yearning for continuity hated to renounce the classical maxim *natura non facit saltus* acclaimed Schrödinger as the herald of a new dawn. In fact, within a few brief months, Schrödinger’s theory ‘captivated the world of physics’ because it seemed to promise ‘a fulfillment of that long-baffled and insuppressible desire’ [in the words of K. K. Darrow, *The Bell System Technical Journal* 6 (1927)]. . . . Planck reportedly declared ‘I am reading it as a child reads a puzzle,’ and Sommerfeld was exultant.”¹⁸ So, of course, was Einstein, who as early as 1920 had written to Born, “that one has to solve the quanta by giving up the continuum, I do not believe.”

We are, of course, dealing here with the kind of intellectual commitment, or “insuppressible desire,” that characterizes a true thematic attachment. Rarely has there been a more obvious fight between different themata vying for allegiance, or a conflict between the aesthetic criteria of scientific choice in the face of the same set of experimental data. And nothing is more revealing of the true and passionate motivation of scientists than their responses to each others’ antithetical constructs. In a letter to Pauli, Heisenberg wrote: “The more I ponder about the physical part of Schrödinger’s theory, the more disgusting [*desto abscheulicher*] it appears to me.” Schrödinger, on his side, freely published his response to Heisenberg’s theory: “I was discouraged [*abgeschreckt*] if not repelled [*abgestossen*].”¹⁹

Different aspects of thematic analysis and thematic conflict were the subject of previous articles.²⁰ In these studies I pointed out a number of other theme-antitheme couples, which may be symbolized by $(\theta, \bar{\theta})$. What Bohr had done in 1927, shortly after the Heisenberg-Schrödinger debates, was to develop a point of view which would allow him to *accept both members of the $(\theta, \bar{\theta})$ couple as valid*

pictures of nature, accepting the continuity-discontinuity (or wave-particle) duality as an irreducible fact, instead of attempting to dissolve one member of the pair in the other as he had essentially tried to do in the development of the correspondence-principle point of view. Secondly, Bohr saw that the $(\theta, \bar{\theta})$ couple involving discrete atomism on the one hand and continuity on the other is related to other $(\theta, \bar{\theta})$ dichotomies that had obstinately refused to yield to bridging or mutual absorption (for example, the subject-object separation versus subject-object coupling; classical causality versus probabilistic causality). The consequence Bohr drew from these recognitions was of a kind rare in the history of thought: he introduced explicitly a new thema, or at least identified a thema that had not yet been consciously a part of contemporary physics. Specifically, Bohr asked that physicists accept both θ and $\bar{\theta}$ —though both would not be found in the same plane of focus at any given time. Nor are θ and $\bar{\theta}$ to be transformed into some new entity. Rather, they both exist in the form *either θ or $\bar{\theta}$* , the choice depending on the theoretical or experimental question which you may decide to ask. We see at once why all parties concerned, both those identified with θ and those identified with $\bar{\theta}$, would not easily accept a new theme which saw a basic truth in the existence of a paradox that the others were trying to remove.

POUL MARTIN MØLLER AND WILLIAM JAMES

Another root of the complementarity conception can be discerned in Niels Bohr's work when we carefully read and reread his own statements of the complementarity point of view. For it is at first curious and then undeniably significant that from the very beginning in 1927, Niels Bohr cited experiences of daily life to make apparent the difficulty of distinguishing between object and subject, and, as Oskar Klein wrote in a retrospective essay, in order "to facilitate understanding of the new situation in physics, where his view appeared too radical or mysterious even to many physicists."²¹ In this connection, according to Klein, Bohr chose a particularly simple and vivid example: the use one may make of a stick when trying to find one's way in a dark room. The man, the stick, and the room form one entity. The dividing line between subject and object is not fixed. For example, the dividing line is at the end of the stick when the

stick is grasped firmly. But when it is loosely held, the stick appears to be an object being explored by the hand. It is a striking reminder of the situation described in the classical emanation theory of light in which we first noted the problem of coupling between observer and observed.

On studying Bohr's writings one realizes by and by that his uses of apparently "extraneous" examples or analogies of this sort are more than mere pedagogic devices. In his September 1927 talk, the final sentence was "I hope, however, that the idea of complementarity is suited to characterize the situation, which bears a deep-going analogy to the general difficulty in the formation of human ideas, inherent in the distinction between subject and object." Similar and increasingly more confident remarks continued to characterize Bohr's later discussions of complementarity. Thus in his essay "Quantum Physics and Philosophy" (1958), the lead essay in the second collection of Bohr's essays under the title *Essays 1958–1962 on Atomic Physics and Human Knowledge*,²² Bohr concluded, "It is significant that . . . in other fields of knowledge, we are confronted with situations reminding us of the situation in quantum physics. Thus, the integrity of living organisms, and the characteristics of conscious individuals, and human cultures, present features of wholeness, the account of which implies a typical complementarity mode of description *We are not dealing with more or less vague analogies, but with clear examples of logical relations which, in different contexts, are met with in wider fields.*" It will be important for our analysis to try to discern clearly what Bohr means in such passages.

Some illumination is provided by a story which Niels Bohr loved to tell in order to illustrate and make more understandable the complementarity point of view. Léon Rosenfeld, a long-term associate of Niels Bohr, who has also been concerned with the origins of complementarity, told how seriously Bohr took his task of repeatedly telling the story. "Everyone of those who came into closer contact with Bohr at the Institute, as soon as he showed himself sufficiently proficient in the Danish language, was acquainted with the little book: it was part of his initiation."²³

The "little book" which Bohr used was a work of the nineteenth-century poet and philosopher, Poul Martin Møller. In that light story *The Adventures of a Danish Student*, Bohr found what he called a "vivid and suggestive account of the interplay between the various

aspects of our position.” A student is trying to explain why he cannot use the opportunity for finding a practical job, and reports the difficulties he is experiencing with his own thought process:

My endless enquiries make it impossible for me to achieve anything. Furthermore, I get to think about my own thoughts of the situation in which I find myself. I even think that I think of it, and divide myself into an infinite retrogressive sequence of “I’s” who consider each other. I do not know at which “I” to stop as the actual one, and in the moment I stop at one, there is indeed again an “I” which stops at it. I become confused and feel a dizziness, as if I were looking down into a bottomless abyss, and my ponderings result finally in a terrible headache.

Further, the student remarks:

The mind cannot proceed without moving along a certain line; but before following this line, it must already have thought it. Therefore one has already thought every thought before one thinks it. Thus every thought, which seems the work of a minute, presupposes an eternity. This could almost drive me to madness. How could then any thought arise, since it must have existed before it is produced? . . . The insight into the impossibility of thinking contains itself an impossibility, the recognition of which again implies an inexplicable contradiction.²⁴

Bohr used the situation in the story not as a distant, vague analogy; rather, it is one of those cases which, “in different contexts, are met with in wider fields.” Moreover, the story seems appropriate for two other reasons. Bohr reports that conditions of analysis and synthesis of psychological experiences “have always been an important problem in philosophy. It is evident that words like thoughts and sentiments, referring to mutually exclusive experiences, have been used in a typical complementary manner since the very origin of language.”²⁵ Also, the humane setting of the Danish story, and the fact that it renders a situation in words rather than scientific symbols, should not mislead us into thinking that it is thereby qualitatively different from the information supplied in scientific discourse. On the contrary: Bohr said, in defending the complementarity principle, “The aim of our argumentation is to emphasize that all experience, whether in science, philosophy, or art, which may be helpful to mankind, must be capable of being communicated by human means of expression, and it is on this basis that we shall approach the

question of unity of knowledge.”²⁶ We shall come back to this important statement presently.

Now, one must confess that it is on first encounter curious, and at least for a professional physicist perhaps a little shocking, to find that the father of the complementarity principle, in these passages and others, should frequently have gone so far afield, by the standards of the scientific profession, in illustrating and extending what he took to be the full power of the complementarity point of view. In looking for the roots of the complementarity principle, we might grant more readily the three avenues shown so far, namely through the history of the concept of light, the operational definition of light behavior, and through Bohr’s own work in physics. But in pursuing this new avenue, we seem to be leaving science entirely.

I imagine that many of Bohr’s students and associates listened to his remarks with polite tolerance, perhaps agreeing that there might be a certain pedagogic benefit, but not a key to the “unity of knowledge.” To the typical scientist, the student in Møller’s story who becomes dizzy when he tries to think *about* his own thoughts, because precise “thought” and “thought about thought” are complementary with respect to each other and so mutually exclusive at the same time, would seem somehow to have a problem different from that of the experimenter who cannot simultaneously show both the wave characteristics and the particle characteristics of a light beam. Similarly the intrusion of the student as introspective observer upon his own thought processes seems to have after all only a thin connection with the intrusion of the macroscopic laboratory upon the submicroscopic quantum events being studied.

It was therefore surprising and revealing when it was found recently, almost by accident, that one of the roots of the modern complementarity point of view in Niels Bohr’s own experience was probably just this wider, more humanistic context shown in the previous quotations. The discovery I speak of came about in a dramatic way. A few years ago, the American Physical Society and the American Philosophical Society engaged in a joint project to assemble the sources for the scholarly study of the history of quantum mechanics. This project, under the general directorship of Thomas S. Kuhn, spanned a number of years, and one of its functions was to

obtain interviews with major figures on the origins of their contributions to quantum physics. An appointment for a number of interviews was granted by Niels Bohr, and the fifth interview was conducted on November 17, 1962, by Kuhn and Aage Petersen. In the course of the interview, Petersen, who was Niels Bohr's long-time assistant, raised the question of the relevance of the study of philosophy in Bohr's early thoughts. The following interchange occurred, according to the transcript:

AaP: How did you look upon the history of philosophy? What kind of contributions did you think people like Spinoza, Hume, and Kant had made?

NB: That is difficult to answer, but I felt that these various questions were treated in an irrelevant manner [in my studies].

AaP: Also Berkeley?

NB: No, I knew what views Berkeley had. I had seen a little in Høffding's writings, but it was not what one wanted.

TSK: Did you read the works of any of these philosophers?

NB: I read some, but that was an interest by [and here Bohr suddenly stopped and exclaimed]—oh, the whole thing is coming [back to me]! I was a close friend of Rubin [a fellow student, later psychologist], and, therefore, I read actually the work of William James. William James is really wonderful in the way he makes it clear—I think I read the book, or a paragraph, called . . . No, what is that called? It is called “The Stream of Thoughts,” where he in a most clear manner shows that it is quite impossible to analyze things in terms of—I don't know what to call it, not atoms. I mean simply, if you have some things . . . they are so connected that if you try to separate them from each other, it just has nothing to do with the actual situation. I think that we shall really go into these things, and I know something about William James. That is coming first up now. And that was because I spoke to people about other things, and then Rubin advised me to read something of William James, and I thought he was most wonderful.

TSK: When was this that you read William James?

NB: That may be a little later, I don't know. I got so much to do, and it may be at the time I was working with surface tension [1905], or it may be just a little later. I don't know.

TSK: But it would be before Manchester [1912]?

NB: Oh yes, it was many years before.²⁷

Niels Bohr clearly was interested in pursuing this further—“we shall really go into these things.” But alas, the next day Bohr suddenly died.

There are enough leads to permit plausible speculations on this subject. K. T. Meyer-Abich reports in his interesting book, *Korrespondenz, Individualität und Komplementarität* (Wiesbaden, 1965) that among German scientists it was remembered that Bohr used to cite William James and only a few other Western philosophers. Moreover, Niels Bohr himself, in an article in 1929²⁸ makes lengthy excursions into psychology in order to use analogies that, in Meyer-Abich’s opinion, could well refer directly to William James’s chapter on the “stream of thought” in James’s book, *The Principles of Psychology* (1890). On the other hand, doubts have been raised about the timing. Rosenfeld²⁹ has expressed his strong belief that the work of William James was not known to Niels Bohr until about 1932. He recalls that in or about 1932, Bohr showed Rosenfeld a copy of James’s *Principles of Psychology*. Rosenfeld believes that a few days earlier Bohr had had a conversation with Rubin, the psychologist and Bohr’s former fellow student. Rubin may have sent the book to Bohr after their conversation. Bohr showed excited interest in the book, and especially pointed out to Rosenfeld the passages on the “stream of consciousness.” During the next few days, Bohr shared the same excitement with several visitors, and Rosenfeld retained the definite impression that this was Bohr’s first acquaintance with William James’s work. In Rosenfeld’s opinion, more relevant than speculation concerning an early influence of James was a remark made by Bohr: after discussing his “early philosophical meditations and his pioneering work of 1912–1913, he told me [Rosenfeld] in an unusually solemn tone of voice, ‘and you must not forget that I was quite alone in working out these ideas, and had no help from anybody.’”³⁰

In view of remarkable analogies or similarities between the ideas of James and of Bohr, to be shown below, one can choose either to believe, with Meyer-Abich and Jammer, that Bohr had read James early enough to be directly influenced or to believe, with Rosenfeld,

that Bohr had independently arrived at the analogous thoughts (perhaps brought to them by other forces such as those we have already cited or additional ones such as contemplation of the concepts of multiform function and Riemann surfaces).³¹ In some ways the second alternative is the more interesting though difficult one, for it hints that here may be a place to attack the haunting old question why and by what mechanisms the same themata attain prominence in different fields in nearly the same periods. Still, no matter which view one chooses to take at this time, reading William James's chapter on the "stream of thought" in the light of Bohr's remark in the interview of November 1962 comes as a surprise to a physicist familiar with Bohr's contributions to atomic physics.³²

James first insists that thought can exist only in association with a specific "owner" of the thought. Thought and thinker, subject and object, are tightly coupled. The objectivization of thought itself is impossible. Hence one must not neglect the circumstances under which thought becomes the subject of contemplation. "Our mental reaction to every given thing is really a resultant of our experience in the whole world up to that date. From one year to another we see things in new lights. . . . The young girls that brought an aura of infinity—at present hardly distinguishable existences; the pictures—so empty; and as for the books, what was there to find so mysteriously significant in Goethe?" One can here imagine the sympathetic response of Bohr, who wrote, "for objective description and harmonious comprehension it is necessary in almost every field of knowledge to pay attention to the circumstances under which evidence is obtained."

There is another sense in which consciousness cannot be concretized and atomized. James writes, "Consciousness does not appear to itself chopped up in bits; it flows. Let us call it the stream of thought, of consciousness, or of subjective life." Yet there does exist a discontinuous aspect: the "changes, from one moment to another, in the quality of the consciousness." If we use the vocabulary of quantum theory, James here proposes a sequence of individual changes between stationary states, with short periods of rest in these states—a metaphor that brings to mind Bohr's notion of 1912–1913 of the behavior of the electron in the hydrogen atom. To quote James, "Like a bird's life, [thought] seems to be made of an alternation of flights and perchings. The rhythm of language expresses this, where

every thought is expressed in a sentence and every sentence closed by a period. . . . Let us call the resting places the ‘substantive parts,’ and the places of flight the ‘transitive parts,’ of the stream of thought.”

But here enters a difficulty: in fact, the same one that plagued the student in Møller’s story. The difficulty is, in James’s words, “introspectively, to see the transitive parts for what they really are. If they are but flights to conclusions, stopping them to look at them before a conclusion is reached is really annihilating them.” However, if one waits until one’s consciousness is again in a stationary state, then the moment is over. James says, “Let anyone try to cut a thought across in the middle and get a look at its section, and he will see how difficult the introspective observation of the transitive tract is. . . . Or if our purpose is nimble enough and we do arrest it, it ceases forthwith to be itself. . . . The attempt at introspective analysis in these cases is in fact like . . . trying to turn up the light quickly enough to see how the darkness looks.” Letting thoughts flow, and making thoughts the subject of introspective analysis are, as it were, two mutually exclusive experimental situations.

It is from such a vantage point that one may attempt to interpret some of the novel features of Bohr’s 1927 paper on complementarity to have been influenced either by a reading of James, or by thinking independently on parallel lines—and thereby understand better the final passage in Bohr’s paper: “I hope, however, that the idea of complementarity is suited to characterize the situation, which bears a deep-going analogy to the general difficulty in the formation of human ideas, inherent in the distinction between subject and object.”³³

At this point, one might well ask where the term *complementarity* itself, which Bohr introduced into physics in 1927, may have come from. There are a number of fields from which the term may have been adapted, including geometry or topology. But both Meyer-Abich and Jammer point to a more provocative possibility, namely the chapter “The Relations of Minds to Other Things,” in William James’s *Principles of Psychology* (1890), just one chapter prior to that on the “stream of thought.” In the subsection “‘Unconsciousness’ in Hysterics,” James relates cases of hysterical anaesthesia (loss of the natural perception of sight, hearing, touch, and so on), and notes that P. Janet and A. Binet “have shown that during the times of anaesthesia, and coexisting with it, *sensibility to the anaesthetic parts is also there,*

in the form of a secondary consciousness entirely cut off from the primary or normal one, but susceptible of being *tapped* and made to testify to its existence in various odd ways.”³⁴

The chief method for tapping was Janet’s method of “distraction.” If Janet put himself behind hysteric patients who were “plunged in conversation with a third party, and addressed them in a whisper telling them to raise their hand or perform other simple acts [including writing out answers to whispered questions] they would obey the order given, although their *talking* intelligence was quite unconscious of receiving it.”³⁵ If interrogated in this way, hysterics responded perfectly normally when, for example, their sensibility to touch was examined on areas of skin that had been shown previously to be entirely anaesthetic when examined through their primary consciousness.

In addition, some hysterics could deal with certain sensations only in either one consciousness *or* the other, but not in both at the same time. Here James cites a famous experiment in a striking passage:

M. Janet has proved this beautifully in his subject Lucie. The following experiment will serve as the type of the rest: In her trance he covered her lap with cards, each bearing a number. He then told her that on waking she should *not see* any card whose number was a multiple of three. This is the ordinary so-called “post-hypnotic suggestion,” now well known, and for which Lucie was a well-adapted subject. Accordingly, when she was awakened and asked about the papers on her lap, she counted and said she saw those only whose number was not a multiple of 3. To the 12, 18, 9, etc., she was blind. But the *hand*, when the sub-conscious self was interrogated by the usual method of engrossing the upper self in another conversation, wrote that the only cards in Lucie’s lap were those numbered 12, 18, 9, etc., and on being asked to pick up all the cards which were there, picked up these and let the others lie. Similarly when the sight of certain things was suggested to the sub-conscious Lucie, the normal Lucie suddenly became partially or totally blind. “What is the matter? I can’t see!” the normal personage suddenly cried out in the midst of her conversation, when M. Janet whispered to the secondary personage to make use of her eyes.³⁶

James gives these and other examples to support a conclusion in which he defines the concept of complementarity in psychological research:

It must be admitted, therefore, that in *certain persons*, at least, *the total possible consciousness may be split into parts which coexist but mutually ignore each other*, and share the objects of knowledge between them. More

remarkable still, they are *complementary*. Give an object to one of the consciousnesses, and by that fact you remove it from the other or others. Barring a certain common fund of information, like the command of language, etc., what the upper self knows the under self is ignorant of, and *vice versa*.³⁷

The analogy with Bohr's concept of complementarity in physics is striking, quite apart from the question of the genetic connection between these two uses of the same word.

CHRISTIAN BOHR AND HARALD HØFFDING

Bohr's affinity for ideas analogous to those of William James was preceded by a philosophical and personal preparation that goes back to his childhood. In his essay "Glimpses of Niels Bohr as a Scientist and Thinker," Oskar Klein, one of Bohr's earliest collaborators, provides a revealing picture of the young man.

Niels Bohr himself and his brother Harald, a brilliant mathematician, liked to give examples of the innocently credulous—and at the same time resolute—way in which as a child he accepted what he saw and heard. They also spoke of geometrical intuition he developed so early The first feature appeared for instance in believing literally what he learned from the lessons on religion at school. For a long time this made the sensitive boy unhappy on account of his parents' lack of faith. When later, as a young man, he began to doubt, he did so also with unusual resolution and thereby developed a deep philosophical bent similar to that which seems to have characterized the early Greek natural philosophers.³⁸

Christian Bohr, Niels Bohr's father, was professor of physiology at the University of Copenhagen. His work involved him in one of the important philosophical debates of the last part of the nineteenth century, the differences between and relative merits of the "vitalistic" theories and the mechanistic conceptions of life processes. In several ways, Christian Bohr's interests shaped his son's ideas and preoccupations. We know that as a youth, Niels Bohr was allowed to work in the laboratory of his father and to meet the scholars interested in philosophy with whom Christian Bohr kept close contact, such as Harald Høffding, professor of philosophy at the University in Copenhagen. Høffding often visited the Bohr household, and Niels Bohr attested to the profound influence he received from early

childhood by being permitted to stay and listen during meetings of an informal club made up of his father, Høffding, the physicist Christian Christiansen, and the philologist Hans Thomsen. Høffding, in turn, described Christian Bohr as a scientist who recognized “strict application of physical and chemical methods of physiology” in the laboratory, but who, outside the laboratory, “was a keen worshipper of Goethe. When he spoke of practical situations or of views of life, he liked to do so in a dialectic manner.”³⁹

We may understand the implications of this description best through Oskar Klein, who remembers a characterization which Niels Bohr gave him: “He mentioned his father’s idea that teleology, when we want to describe the behavior of living beings, may be a point of view on a par with that of causality. This idea was later to play an essential role in Bohr’s attempt to throw light on the relation between the biologist’s and the physicist’s way of describing nature.”⁴⁰

Niels Bohr entered the university in 1903 and soon took Høffding’s course in the history of philosophy and logic. He also belonged to a student’s club in which the questions raised in Høffding’s lectures on philosophy were discussed. (Another member was Rubin.) While Bohr, as indicated in his last interview, felt no great attraction to philosophical systems (such as those of “Spinoza, Hume, and Kant”), there is little doubt about the lasting impression Høffding made on Bohr—perhaps most of all because of Høffding’s active interest in the applicability to philosophy of the work of what he called *philosophierende Naturforscher*, from Copernicus to Newton and from Maxwell to Mach. For example, the latter two are discussed at some length in Høffding’s *Moderne Philosophen*, which appeared in 1904 in Danish (1905 in German) as successor to his monumental *History of Modern Philosophy*.

There also appears to have been a personal sympathy between the older and the younger man. While still Høffding’s student, Bohr pointed out some error in Høffding’s exposition, and Høffding, in turn, allowed Bohr to help him correct proofs of the offending passage. A warm friendship developed eventually that was freely acknowledged on both sides, as indicated, for example, by Niels Bohr’s acknowledgment of Harald Høffding’s influence on him, on the occasion of Høffding’s eighty-fifth birthday,⁴¹ and conversely in letters of Høffding to Emile Meyerson in 1926 and 1928.⁴² The first of these letters, incidentally, is dated December 13, 1926, shortly

before Bohr's vacation trip to Norway in early 1927, during which, according to Heisenberg and others, Bohr's ideas on complementarity were developed in the form he announced later in 1927. Another letter was written half a year after the presentation of the complementarity principle at Como. In it, Høffding writes to Meyerson (March 13, 1928): "Bohr declares that he has found in my books ideas which have helped the scientists in the 'understanding' of their work, and thereby they have been of real help. This is great satisfaction for me, who feels so often the insufficiency of my special preparation with respect to the natural sciences."⁴³

Among all the philosophers and scientists discussed by Høffding, it is unlikely that any interested student of Høffding's will have failed to encounter some aspect of William James's work. An admirer, like James, of G. T. Fechner (the father of psychophysics), Høffding devoted his first book to psychology (Danish edition, 1882). At about the time Bohr took his philosophy course, Høffding used the occasion of the St. Louis meeting of 1904 to visit James in the United States. James, in turn, supplied an appreciative preface for the English translation (of 1905) of Høffding's *Problems of Philosophy*—a book which Høffding reported later to have originated in his university lectures in 1902.⁴⁴ And in the same year of Høffding's visit to James, Høffding expressed in his *Moderne Philosophen* his admiration for James's work, to whom the concluding chapter is devoted, with such comments as "James belongs to the most outstanding contemporary thinkers. . . . The most important of his writings is *The Principles of Psychology*."

KIERKEGAARD

In Høffding's own life, a crucial and early influence was the work of Kierkegaard, as he freely confessed.⁴⁵ Høffding reported that in a youthful crisis in which he was near "despair," he had found solace and new strength through Kierkegaard's writings, and he mentions particularly Kierkegaard's work now known as *Stages on Life's Way*. Høffding became known as one of the prominent exponents and followers of Kierkegaard; indeed, the second major work Høffding published was the book *Kierkegaard als Philosoph*.⁴⁶

Whether Niels Bohr caught some of his own interest in Kierkegaard while a student of Høffding is not known, but the fact of this

early interest is well documented. Thus it is remembered that in 1909 Niels sent his brother Harald as a birthday gift Kierkegaard's book *Stages on Life's Way*, with a letter saying, "It is the only thing I have to send; but I do not believe that it would be very easy to find anything better. In any case I have had very much pleasure in reading it, I even think that it is one of the most delightful things I have ever read."⁴⁷ Then he added that he did not fully agree with all of Kierkegaard's views. One can well imagine that Niels Bohr could enjoy the aesthetic experience and the moral passion without having to agree also with the antiscientific attitude of much of the work.

Bohr's remarks about Kierkegaard bring us to the last of the various possible avenues that prepared for the complementarity notion. While this is not the proper place for a searching examination of those elements in Kierkegaard's works for which analogous elements have been noted in Bohr's work,⁴⁸ it will be of interest to remind ourselves of one or two chief features that characterized the writing of both Kierkegaard and his chief interpreter in Denmark, Høffding.

Kierkegaard's existentialism was rooted in German Romanticism, upholding the individual and the momentary life situation in which he finds himself against the rationality and objective abstraction championed by the eighteenth-century Enlightenment. The denial of the subjective, Kierkegaard argued, leads to self-contradictions, for even the most abstract proposition remains the creation of human beings. In a reaction to Hegel and to some aspects of Kant, Kierkegaard wrote about science in his journal: "Let it deal with plants and animals and stars, but to deal with the human spirit in that way is blasphemy, which only weakens ethical and religious passions." Truth cannot be found without incorporating the subjective, particularly in the essentially irrational, discontinuous stages of recognitions leading to the achievement of insight. As J. Passmore writes, "each major step on the way to truth is a free decision. Our progress, according to Kierkegaard, from the aesthetic to the scientific point of view, and then again from the scientific to the ethical and from the ethical to the religious, cannot be rationalized into an orderly, formally justifiable, step from premise to conclusions: It is in each case a leap to a quite new way of looking at things."⁴⁹

What is perhaps of greatest interest to us is the accentuation of the role of discontinuity in Kierkegaard's work. Here we can do no better

than cite at some length the section on Kierkegaard in Høffding's own chief work, *A History of Modern Philosophy*:

[Kierkegaard's] leading idea was that the different possible conceptions of life are so sharply opposed to one another that we must make a choice between them, hence his catchword *either-or*; moreover, it must be a choice which each particular person must make for himself, hence his second catchword, *the individual*. He himself designated his thought "qualitative dialectic," by which he meant to bring out its opposition to the doctrine taught by Romantic speculation of continuous development by means of necessary inner transitions. Kierkegaard regarded this doctrine as pure fantasticalness—a fantasticalness, to be sure, to which he himself had felt attracted.⁵⁰

What is essential for us to notice is that a main feature of Kierkegaard's "qualitative dialectic" is an acceptance of thesis and antithesis, *without* proceeding to another stage at which the tension is resolved in a synthesis. Thus he draws a line between thought and reality which must not be allowed to disappear. Høffding writes: "Even if thought should attain coherency it does not therefore follow that this coherency can be preserved in the practice of life . . . Such great differences and oppositions exist side by side that there is no thought which can embrace them all in a 'higher unity.'" ⁵¹ "Kierkegaard came more and more to regard the capability of embracing great contrasts and of enduring the suffering which this involves as the criterion of the sublimity and value of a conception of life."⁵²

Kierkegaard's stress on discontinuity between incompatibles, on the "leap" rather than the gradual transition, on the inclusion of the individual, and on inherent dichotomy, was as "nonclassical" in philosophy as the elements of the Copenhagen doctrine—quantum jumps, probabilistic causality, observer-dependent description, and duality—were to be in physics.

Now it would be as absurd as it is unnecessary to try to demonstrate that Kierkegaard's conceptions were directly and in detail translated by Bohr from their theological and philosophical context to a physical context. Of course, they were not. All one should do is permit oneself the open-minded experience of reading Høffding and Kierkegaard through the eyes of a person who is primarily a physicist—struggling, as Bohr was, first with his 1912–1913 work on atomic models, and again in 1927, to "discover a certain coherence

in the new ideas” while pondering the conflicting, paradoxical, unresolvable demands of classical physics and quantum physics which were the near-despair of most physicists of the time. It is in this frame of mind that one can best appreciate, for example, Høffding’s discussion of Kierkegaard’s indeterministic notion of the “leap”:

In Kierkegaard’s ethics the qualitative dialectic appears partly in his conception of choice, of the decision of the will, partly in his doctrine of stages. He emphatically denies that there is any analogy between spiritual and organic development. No gradual development takes place within the spiritual sphere, such as might explain the transition from deliberation to decision, or from one conception of life (or “stadium”) to another. Continuity would be broken in every such transition. As regards the choice, psychology is only able to point out possibilities and approximations, motives and preparations. The choice itself comes with a jerk, with a leap, in which something quite new (a new quality) is posited. Only in the world of possibilities is there continuity; in the world of reality decision always comes through a breach of continuity.

But, it might be asked, cannot this jerk or this leap itself be made an object of psychological observation? Kierkegaard’s answer is not clear. He explains that the leap takes place between two moments, between two states, one of which is the last state in the world of possibilities, the other the first state in the world of reality. It would almost seem to follow from this that the leap itself cannot be observed. But then it would also follow that it takes place unconsciously—and the possibility of the unconscious continuity underlying the conscious antithesis is not excluded.⁵³

It is at this point that the writings of Høffding and Kierkegaard most evidently overlap with the teachings of William James. In fact, there are two specific periods where the overlapping conceptions of Kierkegaard, Høffding, and James can plausibly have been influential for Bohr in the sense of providing sympathetic preparation or support. One came in Bohr’s work during the early period, from 1912 through the correspondence point of view (that is, in the analogy between Bohr’s nonclassical transitions of the electron between stationary states on the one hand and Kierkegaard’s “leaps” or James’s transient flights and “transitive parts” on the other hand). The other came in the period from about 1926, when Bohr’s complementarity point of view was being developed; and here we have already pointed to possible sources or antecedents for Bohr’s analogies in passages such as the conclusion of his September 1927

address (“the idea of complementarity is suited to characterize the situation, which bears a profound analogy to the general difficulty in the formation of human ideas, inherent in the distinction between subject and object”), as well as passages in a paper of 1929 (“Strictly speaking, the conscious analysis of any concept stands in a relation of exclusion to its immediate application. . . . The necessity of taking recourse to a complementary, or reciprocal mode of description is perhaps familiar to us from psychological problems. . . . In particular, the apparent contrast between the continuous onward flow of associative thinking and the preservation of the unity of the personality exhibits a suggestive analogy with the relation between the wave description of the motions of material particles, governed by the superposition principle, and their indestructible individuality”).⁵⁴

One characteristic trait of Bohr should not be overlooked in this discussion, for without it the predisposition necessary for reaching the complementarity point of view would have been missing. I refer to Bohr’s well-known dialectic style of thinking and of working. One of those who worked with him longest, Léon Rosenfeld, attests that Bohr’s “turn of mind was essentially dialectical, rather than reflective. . . . He needed the stimulus of some form of dialogue to start off his thinking.”⁵⁵ Rosenfeld also records a well-known dictum of Bohr: “Every sentence I say must be understood not as an affirmation, but as a question.” Bohr’s habit of work was frequently to develop a paper during dictation, walking up and down the room and arguing both with himself and a fellow physicist whom he had persuaded to be his sounding board, transcriber, and critic—and whom he was likely to leave in an exhausted state at the end. As Einstein, Heisenberg, Schrödinger, and many others had to experience, it seemed as if Bohr looked for and fastened with greatest energy on a contradiction, heating it to its utmost before he could crystallize the pure metal out of the dispute. Bohr’s method of argument shared with the complementarity principle itself the ability to exploit the clash between antithetical positions. We have given earlier only the first line of a couplet from Schiller, reported to have been one of Bohr’s favorite sayings: after the line “Only wholeness leads to clarity” there follows “And truth lies in the abyss”:

Nur die Fülle führt zur Klarheit,
Und im Abgrund wohnt die Wahrheit.

Of Niels Bohr stories there are legions, but none more illuminating than that told by his son Hans concerning the fundamentally dialectic definition of truth. Hans reports that one of the favorite maxims of his father was the distinction between two sorts of truth: trivialities, where opposites are obviously absurd, and profound truths, recognized by the fact that the opposite is also a profound truth.⁵⁶ Along the same line, there has been a persistent story that Bohr had been impressed by an example or analogue for the complementarity concept in the mutually exclusive demands of justice and of love. Jerome S. Bruner has kindly given me a first-hand report of a conversation on this point that took place when he happened to meet Niels Bohr in 1943 or early 1944 for the first time: "The talk turned entirely on the complementarity between affect and thought, and between perception and reflection. [Bohr] told me that he had become aware of the psychological depths of the concept of complementarity when one of his children had done something inexcusable for which he found himself incapable of appropriate punishment: 'You cannot know somebody at the same time in the light of love and in the light of justice!' I think that those were almost exactly the words he used. He also. . . . talked about the manner in which introspection as an act dispelled the very emotion that one strove to describe."⁵⁷

COMPLEMENTARITY BEYOND PHYSICS

We can now ask: what was Bohr's real ambition for the complementarity conception? It certainly went far beyond dealing with the paradoxes in the physics of the 1920s. Not only were some of the roots of the complementarity principle outside physics, but so also was its intended range of application. Let me remind you of Bohr's statement: "The integrity of living organisms, and the characteristics of conscious individuals, and most of human cultures, present features of wholeness, the account of which implies a typically complementary mode of description. . . . We are not dealing with more or less vague analogies, but with clear examples of logical relations which, in different contexts, are met with in wider fields."⁵⁸ The complementarity principle is a manifestation of a thema in a sense which I have previously developed⁵⁹—one thema in the relatively small pool of themata from which the imagination draws for all

fields of endeavor. When we devote attention to a particular thema in physics or some other science, whether it be complementarity, or atomism, or continuity, we must not forget that each special statement of the thema is an aspect of a general conception which, in the work of a physicist or biologist or other scientist, is exemplified merely in a specific form. Thus a general thema, θ , would take on a specific form in physics that might be symbolized by θ_ϕ , in psychological investigation by θ_ψ , in folklore by θ_μ , and so on. The general thema of discontinuity or discreteness thus appears in physics as the θ_ϕ of atomism, whereas in psychological studies it appears as the thema θ_ψ of individualized identity. One may express a given θ as the sum of its specific exemplifications, as symbolized (without straining for precision) by the expression:

$$\theta = \sum_{n=\alpha}^{n=\omega} \theta_n$$

From this point of view we realize that Bohr's proposal of the complementarity principle was nothing less than an attempt to make it the cornerstone of a new epistemology. When "in general philosophical perspective . . . we are confronted with situations reminding us of the situation in quantum physics,"⁶⁰ it is not that those situations are in some way pale reflections or "vague analogies" of a principle that is basic only in quantum physics; rather, the situation in quantum physics is only one reflection of an all-pervasive principle. Whatever the most prominent factors were which contributed to Bohr's formulation of the complementarity point of view in physics—whether his physical research or thoughts on psychology, or reading in philosophical problems, or controversy between rival schools in biology, or the complementary demands of love and justice in everyday dealings—it was the *universal* significance of the role of complementarity which Bohr came to emphasize.

Moreover, this universality explains how it was possible for Bohr to gain insight for his work in physics from considerations of complementary situations in other fields. For as Léon Rosenfeld accurately remarks, "As his insight into the role of complementarity in physics deepened in the course of these creative years, he was able to point to situations in psychology and biology that also present complementary aspects; and the considerations of such analogies in

epistemological respect in its turn threw light on the unfamiliar physical problems.”⁶¹ “Bohr devoted a considerable amount of hard work to exploring the possibilities of application of complementarity to other domains of knowledge; he attached no less importance to this task than to his purely physical investigations, and he derived no less satisfaction from its accomplishment.”⁶²

During the last thirty years of his life, Bohr took many opportunities to consider the application of the complementarity concept in fields outside of physics. Rosenfeld reports that the first important opportunity of this kind offered itself when Bohr was invited to address a biological congress in Copenhagen in 1932.⁶³ Starting from the idea of complementarity as used for understanding the dual aspects of light, Bohr then proceeded to point to the application of complementarity relations in biology. Rosenfeld’s account of the talk is worth citing in detail:

This had a special appeal to him: He had been deeply impressed by his father’s views on the subject, and he was visibly happy at being now able to take them up and give them a more adequate formulation. [His father], in the work of the reaction against mechanistic materialism at the beginning of the century, had put up a vigorous advocacy of the teleological point of view in the study of physiology: without the previous knowledge of the function of an organ, he argued, there is no hope of unravelling its structure for the physiological processes of which it is the seed. At the same time, he stressed, with all the authority of a life devoted to the analysis of the physical and chemical aspects of such processes, the equally imperious necessity of pushing this analysis to the extreme limit which the technical means of investigation would permit us to reach . . .

Such reflections came as near as one would expect at the time to establishing a relation of complementarity between the physico-chemical side of the vital processes, governed by the kind of causality they are accustomed to herald as the truly scientific one, and the properly functional aspect of these processes, dominated by teleological or finalistic causality. In the past, the two points of view, under varying forms, have always been put in sharp opposition to each other, the general opinion being that one of them had to prevail to the exclusion of the other, that there was no room for both in the science of life. Niels Bohr could now point out that this last belief was only the result of a conception of logic which the physicists had recognized as too narrow, and that the wider frame of complementarity seemed particularly well suited to accommodate the two standpoints, and make it possible without any contradiction to take advantage of both of them, quite

in the spirit of his father's ideas. Thus an age-long sterile conflict would be eliminated and replaced by a full utilization of all the resources of scientific analysis.⁶⁴

One need not be tempted into imagining Bohr in a Hamletlike striving to establish his father's ideas; but one also need not remain untouched by the closing of the circle. For surely one of the paths leading to complementarity had opened while Niels Bohr was in his father's laboratory and shop club.

In the years following the congress of 1932 Bohr took his point of view before an even wider audience; in addition to his written and spoken contributions before physical scientists, he presented himself at such meetings as the Second International Congress for the Unity of Science in Copenhagen (June 1936) in a discussion on "causality and complementarity"; the International Congress for physics and Biology in October 1937 on "biology and atomic physics"; the International Congress for Anthropology and Ethnology, Copenhagen, 1938, on "natural philosophy and human cultures"; and on many later occasions of a similar sort.⁶⁵

In each of these lectures Bohr provided a new set of illustrations of the common theme. Thus in his address before the anthropologists in 1938, on the eve of World War II, Bohr stressed complementary features of human societies. He also returned to the problem posed by the student (*licentiate*) in Møller's story. As Rosenfeld writes:

He could now look back at the duality of aspects of psychical experience with all the mastery he had acquired over the nature of complementarity relations, and point out that this duality corresponded to different ways of drawing between the psychical process which was chosen as the object of observation and the observing subject: drawing such a separation is precisely what we mean when we speak of fixing our attention on a definite aspect of the process; according as we draw the line, we may experience an emotion as part of our subjective feeling, or analyze it as part of the observed process. The realization that these two situations are complementary solves the riddle of the licentiate's egos observing each other, and is in fact the only salvation from his qualms.⁶⁶

Speaking before the Congress of the Fondation Européenne de la culture in Copenhagen on October 21, 1960, in an address entitled "The Unity of Human Knowledge," Bohr returned again to the need to search, within the great diversity of cultural developments, "for

those features in all civilizations which have their roots in the common human situation.” He developed these ideas in sociological and political contexts, particularly since he was increasingly more preoccupied with helping to “promote mutual understanding between nations with very different cultural backgrounds.”⁶⁷ Deeply concerned about the danger of the Cold War, Bohr spent a good part of his later years on political and social questions, including work on plans for peaceful uses of nuclear energy and for arms control. In these and other articles on this topic, one can discern Bohr’s dissatisfaction with his own state of understanding; the problems posed by national antagonisms did not seem to be fully understandable in the same terms that had seemed to him successful in physics and psychology. As he confessed at the end of his lecture before the American Academy of Arts and Sciences in 1957, “The fact that human cultures, developed under different conditions of living, exhibit such contrasts with respect to established traditions and social patterns allows one, in a certain sense, to call such cultures complementary. However, we are here in no way dealing with definite, mutually exclusive features, such as those we meet in the objective description of general problems of physics and psychology, but the differences in attitude which can be appreciated or ameliorated by an expanded intercourse between peoples.”⁶⁸

Bohr returned to the same theme repeatedly. For example, in the essay quoted earlier, “The Unity of Human Knowledge,” Bohr reexamined the requirement that even the most abstract principles of quantum physics, for example, must be capable of being rendered in commonsense, classical language. “The aim of our argumentation,” Bohr wrote, “is to emphasize that all experience, whether in science, philosophy, or art, which may be helpful to mankind, must be capable of being communicated by human means of expression, and it is on this basis that we shall approach the question of unity of knowledge.”⁶⁹

The last phrase, used in the title of the essay, suddenly puts into perspective for us that Bohr’s manifold and largely successful ambitions place him in the tradition typified by another “philosophizing scientist,” one who belonged to the generation before Bohr—a man whom Bohr, like many others, had read early, and whose views Høffding had described in a sympathetic way in his *Moderne Philosophen* and in *Problems of Philosophy*. It is Ernst Mach.

Bohr seems to have mapped out for himself the same grand, interdisciplinary task—in his forceful and innovative influence on physics and on epistemology, in his deep interest in the sciences far beyond physics itself, even in his active and liberal views on social-political questions. And as physicist, physiologist, psychologist, and philosopher, Ernst Mach had also wanted to find a principal point of view from which research in any field could be more meaningfully pursued. This point of view Mach thought to have found by going back to that which is given before all scientific research, namely the world of sensations. On this basis, Mach had established himself as the patriarch of the Unity of Science movement. In his turn, Niels Bohr, starting from the profound reexamination of the problem of sensation and particularly of object-subject interaction, also hoped he had found (in the complementarity point of view) a new platform from which to evaluate and solve the basic problems in a variety of fields, whether in physics, psychology, physiology, or philosophy.

Bohr's achievement, from 1927 on, of attaining such a principal point of view was not an accidental development. On the contrary, it was the fulfillment of an early ambition. A biographer of Bohr records that "as a young student, fired with the ideas Høffding was opening to him, Bohr had dreamed of 'great inter-relationships' between all areas of knowledge. He had even considered writing a book on the theory of knowledge But physics had drawn him irresistibly."⁷⁰ In the end, Bohr's attempt to understand the unity of knowledge (a topic on which he wrote nearly two dozen papers) on the basis of complementarity could be seen as precisely the fulfillment of the desire to discover the "great inter-relationships among all areas of knowledge."

Bohr's aim has a grandeur which one must admire. But while his point of view is accepted by the large majority in physics itself, it would not be accurate to say that it is being widely understood and used in other fields; still less has it swept over philosophy the way Mach's views did during the generation of scientists brought up before the theory of relativity and quantum mechanics. Even those who in their professional work in physics have experienced the success of the complementarity point of view at first hand find it hard or uncongenial to transfer to other areas of thought and action, as a fundamental thematic attitude, the habit of accepting basic dualities without straining for their mutual dissolution or reduction. Indeed,

we tend to be first of all reductionists, perhaps partly because our early intellectual heroes have been men in the tradition of Mach and Freud, rather than Kierkegaard and James.

Perhaps, also, it is just a matter of time—more time needed to assimilate a new thema widely enough; to sort out the merely seductive and the solid applications; and to learn to perceive the kind of grandeur in the scope of the new notion which Robert Oppenheimer delineated:

An understanding of the complementary nature of conscious life and its physical interpretation appears to me a lasting element in human understanding and a proper formulation of the historic views called psychophysical parallelism. For within conscious life, and in its relations with the description of the physical world, there are again many examples. There is the relation between the cognitive and the affective sides of our lives, between knowledge or analysis, and emotion or feeling. There is the relation between the esthetic and the heroic, between feeling and that precursor and definer of action, the ethical commitment; there is the classical relation between the analysis of one's self, the determination of one's motives and purposes, and that freedom of choice, that freedom of decision and action, which are complementary to it . . .

To be touched with awe, or humor, to be moved by beauty, to make a commitment or a determination to understand some truth—these are complementary modes of the human spirit. All of them are part of man's spiritual life. None can replace the others, and where one is called for, the others are in abeyance . . .

The wealth and variety of physics itself, the greater wealth and variety of the natural sciences taken as a whole, the more familiar, yet still strange and far wider wealth of the life of the human spirit, enriched by complementary, not-at-once compatible ways, irreducible one to the other, have a greater harmony. They are the elements of man's sorrow and his splendor, his frailty and his power, his death, his passing, and his undying deeds.⁷¹

ENDNOTES

¹After much further work, Bohr published the lecture in 1928 under the title "The Quantum Postulate and the Recent Development of Atomic Theory"; it has been reprinted in several places, for example as one of four essays in the collection by Niels Bohr, *Atomtheorie und Naturbeschreibung* (Berlin: Springer, 1931), also published as *Atomic Theory and the Description of Nature* (Cambridge, England: University Press; New York: Macmillan, 1934).

²Bohr, "The Quantum Postulate," in *Atomic Theory and the Description of Nature*, 55.

³A. Einstein, "Das Comptonsche Experiment," *Berliner Tageblatt* (April 20, 1924), supplement, 1, cited by M. J. Klein, *A Twentieth-Century Challenge to Energy Conservation*.

⁴Bohr (in "The Quantum Postulate," *Atomic Theory and the Description of Nature*, 54–55) introduced the need for working out a "complementarity theory" in the following, rather overburdened sentence: "The very nature of the quantum theory thus forces us to regard the space-time coordination and the claim of causality, the union of which characterizes the classical theory, as complementary but exclusive features of the description, symbolizing the idealization of observation and definition respectively." Max Jammer, to whose book *The Conceptual Development of Quantum Mechanics* (New York: McGraw-Hill, 1966, 351) we shall frequently refer, adds: "This statement, in which the term 'complementary' appears for the first time and in which spatiotemporal description is referred to as complementary to causal description, contained the essence of what later became known as the 'Copenhagen' interpretation of quantum mechanics."

Heisenberg's uncertainty principle, formulated early in 1927, had given a first indication of complementary relations between physical concepts, though in a restricted sense. The uncertainty principle tells us that if we attempt to localize a particle in space (or time), we shall, during the measurement process, impart to the particle momentum (or energy) within a range of values that increases as we decrease the size of the space-time region on which we wish to focus attention. Position and momentum are not mutually exclusive notions, since both are needed to specify the state of a system and both can be measured in the same experiment. But they are complementary in the restricted sense that they cannot both at the same time be ascertained with arbitrarily high precision; that is, the more precision is obtained in one measurement, the less it is possible to have in the other. In contrast, the wave-particle aspects of matter are complementary *and* mutually exclusive; an atomic entity cannot exhibit both its particle and its wave properties simultaneously. It is for this reason that textbooks often say that Bohr's statement of complementarity at Como transcended the Heisenberg uncertainty principle.

⁵Niels Bohr, "Discussion with Einstein on Epistemological Problems in Atomic Physics," in *Albert Einstein: Philosopher-Scientist*, ed. P. Schilpp (Evanston, Ill.: The Library of Living Philosophers, 1949), 209–10; italics in original.

⁶Jammer, *Conceptual Development of Quantum Mechanics*, 354.

⁷Translated from *ibid.*, 358.

⁸A. Einstein, "Reply to Criticisms," in Schilpp, *Albert Einstein*, 674.

⁹Bohr, "Discussion with Einstein," in Schilpp, *Albert Einstein*, 218.

¹⁰For some aspects of the early history of the theories of light, see the interesting book by Vasco Ronchi *Optics, the Science of Vision* (New York, 1957), or Johann Müller, *Lehrbuch der Physik* (Braunschweig: F. Vieweg und Sohn, 1926). I have relied on both extensively.

¹¹For example, see W. H. Bragg, *Philosophical Magazine* 20 (1910):358–416.

¹²Merle A. Tuve, in *The Search for Understanding*, ed. Caryl P. Haskins (Washington, D.C.: Carnegie Institution, 1967), 46.

¹³Jammer, *Conceptual Development of Quantum Mechanics*, 87.

- ¹⁴Quoted, with permission, from a letter of Niels Bohr in the American Philosophical Society Library, Philadelphia. I thank Dorothy Goodhue Livingston for having drawn this letter to my attention.
- ¹⁵N. Bohr, H. A. Kramers, and J. C. Slater, "The Quantum Theory of Radiation," *Philosophical Magazine* 47 (1924):785. The German version is in *Zeitschrift für Physik* 24 (1924):69.
- ¹⁶E. Schrödinger, "Quantisierung als Eigenwertproblem," *Annalen der Physik* 79 (1926):375.
- ¹⁷Jammer, *Conceptual Development of Quantum Mechanics*, 271–72; italics in original.
- ¹⁸*Ibid.*, 271.
- ¹⁹As quoted, *ibid.*, 272.
- ²⁰See "On the Thematic Analysis of Science: The Case of Poincaré and Relativity," *Mélanges Alexandre Koyré*, vol. 2 (Paris: Hermann, 1964):257–68; "The Thematic Imagination in Science," in Gerald Holton, ed., *Science and Culture* (Boston: Houghton Mifflin, 1965), 88–108; "Science and New Styles of Thought," *The Graduate Journal* 7 (Spring 1967):399–421.
- ²¹Oskar Klein, "Glimpses of Niels Bohr as Scientist and Thinker," in S. Rozental, ed., *Niels Bohr—His Life and Work as Seen by His Friends and Colleagues* (New York: John Wiley, 1967), 93.
- ²²Niels Bohr, *Essays 1958–1962 on Atomic Physics and Human Knowledge* (New York: John Wiley, 1963), 7; italics supplied.
- ²³L. Rosenfeld, "Niels Bohr in the Thirties," in Rozental, *Niels Bohr*, 121.
- ²⁴Cited in Bohr's essay "The Unity of Human Knowledge" (1960), in *Essays 1958–1962*, and in L. Rosenfeld, "Niels Bohr's Contribution to Epistemology," *Physics Today* 16 (1963):63. In this article and elsewhere, Rosenfeld has insisted on the importance of the story for Bohr; moreover, Rosenfeld believes that the struggle of the student with his many egos was "the only object lesson in dialectical thinking that Bohr ever received and the only link between his highly original reflection and philosophical tradition" (p. 48).
- ²⁵Bohr, "The Unity of Human Knowledge," in *Essays 1958–1962*, 12.
- ²⁶*Ibid.*, 14.
- ²⁷The permission granted by the estate of Niels Bohr and the American Philosophical Society to reproduce this section of the interview is gratefully acknowledged.
- ²⁸Bohr, "The Quantum of Action and the Description of Nature," in *Atomic Theory and the Description of Nature*.
- ²⁹Letter to the author, February 28, 1968.
- ³⁰*Ibid.* In an interview conducted with Werner Heisenberg by T. S. Kuhn for the History of Quantum Physics project on February 11, 1963, Heisenberg volunteered that James was one of Bohr's favorite philosophers; the chapter on the "stream of thought" seemed to have made a profound impression on Bohr. Heisenberg placed these discussions somewhere between 1926 and 1929, most probably around 1927. When told of doubts about the timing, Heisenberg responded that he could not "guarantee" that these discussions with Bohr had not been after 1932.
- ³¹Rosenfeld, "Niels Bohr's Contribution to Epistemology," 49. See also L. Rosenfeld, *Niels Bohr* (Amsterdam: North-Holland Publishing Co., 1945, 1961), 12–13.
- ³²We follow here the sequence given in Meyer-Abich, *Korrespondenz*, 133ff.

- ³³Bohr, "The Quantum Postulate," in *Atomic Theory and the Description of Nature*, 91.
- ³⁴William James, *Principles of Psychology*, vol. 1 (New York: Dover, 1950), 203; italics in original in all passages quoted from *Principles of Psychology*.
- ³⁵Ibid., 204.
- ³⁶Ibid., 206–07.
- ³⁷Ibid., 206.
- ³⁸In Rozental, *Niels Bohr*, 74. One notices here the remarkable similarity of Bohr's experience with that recorded in Einstein's autobiographical notes—the same early religious acceptance in contrast to his parents' beliefs, followed by a loss or rejection of "the religious paradise of youth," as Einstein called it.
- ³⁹As quoted in Rozental, *Niels Bohr*, 13.
- ⁴⁰Klein, "Glimpses of Niels Bohr," 76.
- ⁴¹See Jammer, *Conceptual Development of Quantum Mechanics*, 349.
- ⁴²Ibid., 347, 349.
- ⁴³Ruth Moore, in her book *Niels Bohr* (New York: Knopf, 1966), 432, records that on one wall of Bohr's house in Carlsberg, there "were portraits of those nearest to Bohr, grouped reverentially together": Bohr's father and mother, his brother Harald, his grandfather Adler, and "Bohr's teacher Høffding. If any doubts existed of Høffding's influence on Bohr's life, it was settled by the placement of his portrait."
- ⁴⁴H. Høffding, in R. Schmidt, ed., *Die Philosophie der Gegenwart in Selbstdarstellungen* (Leipzig: Felix Meiner, 1923), 86.
- ⁴⁵For example, *ibid.*, 75.
- ⁴⁶Danish edition, 1892; German edition, 1896.
- ⁴⁷In Rozental, *Niels Bohr*, 27. See also the account of J. Rud Nielsen, "Memories of Niels Bohr," *Physics Today* 16 (1963):27–28. Referring to a visit from Bohr in 1933, Nielsen wrote: "Knowing Bohr's interest in Kierkegaard, I mentioned to him the translations made by Prof. Hollander of the University of Texas, and Bohr began to talk about Kierkegaard: 'He made a powerful impression upon me when I wrote my dissertation in a parsonage in Funen, and I read his works night and day,' he told me. 'His honesty and willingness to think the problems through to their very limit is what is great. And his language is wonderful, often sublime. There is of course much in Kierkegaard that I cannot accept. I ascribe that to the time in which he lived. But I admire his intensity and perseverance, his analysis to the utmost limit, and the fact that through these qualities he turned misfortune and suffering into something good.'"
- ⁴⁸A preliminary treatment of the subject has been made in the section "The Philosophical Background of Non-classical Interpretations," in Jammer, *Conceptual Development of Quantum Mechanics*, 166–80.
- ⁴⁹J. Passmore, *A Hundred Years of Philosophy* (New York: Basic Books, 1966), 480.
- ⁵⁰H. Høffding, *A History of Modern Philosophy*, vol. 2 (New York: Dover, 1955), 286. The work was originally issued in 1893 and intended to cover the ground to 1880. The English translation was published in 1900. Høffding also explored the role of discontinuity in other contexts, for example, in *Moderne Philosophen* (1904), where he contrasts at length the older *Kontinuitätsphilosophie* (as in Taine, Fouillée, Wundt, Ardigò) with the more recent *Diskontinuitätsphilosophie* (for example, Renouvier, "der Nestor der Philosophie der Gegenwart," and Boutroux).

⁵¹Ibid., 287.

⁵²Ibid., 288.

⁵³Ibid., 287–88.

⁵⁴Bohr, “The Quantum of Action,” in *Atomic Theory and the Description of Nature*, 96, 99.

⁵⁵Rosenfeld, “Niels Bohr in the Thirties,” in Rozental, *Niels Bohr*, 117.

⁵⁶Hans Bohr, “My Father,” in Rozental, *Niels Bohr*, 328.

⁵⁷Jerome S. Bruner, private communication to the author, December 25, 1967.

Bruner added a comment which will become relevant to us in what follows below: “I knew Bohr for years afterwards and again spent several hours with him when he was at the Institute for Advanced Study at Princeton, and he came to visit. He had an extraordinary sensitivity for psychological problems, and indeed he once repeated Mach’s famous remark about basically our only two sciences: one treats sensation as external and is physics, the other treats it as internal and is psychology. He did not cite this old saw of Mach’s approvingly, but urged that there was a grain of truth in it.”

⁵⁸Bohr, “Quantum Physics and Philosophy,” in *Essays 1958–1962*, 7.

⁵⁹See note 20, and C. Holton, “Stil und Verwirklichung in der Physik,” *Eranos Jahrbuch* 33 (Zurich: Rhein-Verlag, 1965), particularly 333ff.

⁶⁰Bohr, “Quantum Physics and Philosophy,” in *Essays 1958–1962*, 7.

⁶¹Rosenfeld, “Niels Bohr in the Thirties,” in Rozental, *Niels Bohr*, 116.

⁶²Ibid., 120.

⁶³Niels Bohr, “Light and Life,” address at the Second International Congress for Light Therapy, Copenhagen, August 1932, *Nature* 131 (1933):421–23, 457–59.

⁶⁴Rosenfeld, “Niels Bohr in the Thirties,” in Rozental, *Niels Bohr*, 132–33.

⁶⁵For a partial bibliography of Bohr’s writings, see Meyer-Abich, *Korrespondenz*, 191–99.

⁶⁶Rosenfeld, “Niels Bohr in the Thirties,” in Rozental, *Niels Bohr*, 135–36. A useful summary of Bohr’s views concerning the application of the complementarity conception to physics, biology, psychology, and social anthropology is given in Niels Bohr, “On Atoms and Human Knowledge,” *Dædalus* (Spring 1958), 164–75.

⁶⁷Bohr, “The Unity of Human Knowledge,” in *Essays 1958–1962*, 14–15.

⁶⁸Bohr, “On Atoms and Human Knowledge,” in *Essays*, 174–75.

⁶⁹Bohr, “The Unity of Human Knowledge,” in *Essays*, 14.

⁷⁰Moore, *Niels Bohr*, 406–07. There is a great deal of evidence of the large scale of Bohr’s later hopes along these lines. In his 1933 discussion, J. Rud Nielsen (“Memories of Niels Bohr,” 27) reports: “Bohr talked a good deal about his plans for future publications. ‘I believe that I have come to a certain stage of completion in my work,’ he said, ‘I believe that my conclusions have wide application also outside physics. . . . I should like to write a book that could be used as a text. I would show that it is possible to reach all important results with very little mathematics. In fact, in this manner one would in some respects achieve greater clarity.’ This book, which Bohr referred to as his testament, was never written.”

Similarly, Rosenfeld (“Niels Bohr’s Contributions to Epistemology,” 54) writes: “Bohr had great expectations about the future role of complementarity. He upheld them with unshakable optimism, never discouraged by the scant response he got from our unphilosophical age. . . . Bohr declared with intense animation that he saw the day when complementarity would be taught in the schools and become part of general education.”

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⁷¹J. Robert Oppenheimer, *Science and the Common Understanding* (New York: Simon and Schuster, 1953), 80–82.

Note: An early draft of this essay was presented at the *Tagung of Eranos* (August 1968). I have profited from discussions with students in my seminar, particularly Bernard Lo and Kellogg Steele, and with Dr. Arthur Miller.