The Lesson of Quantum Theory, edited by J. de Boer, E. Dal and O. Ulfbeck

Niels Bohr: The Man and his Legacy

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1. Introduction

Commitment, *diligence*, *openness*. The year 1985 marks the 100th anniversary of the birth of Niels Bohr—and of seventy million other human beings born in the same year. What is special about this one man of blue eyes and average height, always lighting a match to his pipe but hardly ever managing to smoke it, that we should single him out for special attention? Are we here to put him on a pedestal? No! Niels Bohr was against making a hero of anybody because he was so ready to see the heroic in everybody.

Do we make Niels Bohr the center of this inspiring conference because he elucidated the structure of the atom and the structure of the nucleus, because he masterminded our understanding of the quantum, because of his *genius*? Please, no, he says to us again, and quotes to us with a smile and a wave of his pipe his favorite words from Theodor Fontane:

> Gaben, wer hatte sie nicht?
> Talent, Spielzeug für Kinder!
> Erst der Ernst macht den Mann,
> Erst der Fleiss das Genie;

or, translated:

> Gifts? Who hasn't?
> Talent? Toy for children!
> Commitment only makes the man;
> Only diligence the genius.

Diligence? Sense of commitment? Thousands upon thousands of the seventy million born a hundred years ago lived lives of conscientiousness and drive. What additional trait made Bohr special? Openness! Openness to the most wildly different ways of looking at any issue.

If openness, commitment and diligence were the central features of Bohr the man, and of the way of doing science that he taught the world, how can we be blamed for wanting to recall the blooming of that openness?

Openness manifest in dialog. One of the schoolmates of Niels and his younger brother Harald speaks of the amazement it brought to everyone around the two boys to see their warm-hearted, lively, never ceasing to-and-fro:

> "Their way of thinking seemed to be co-ordinated; one improved on the other's or his own expressions, or defended in a heated yet good-humored manner his choice of words. Ideas changed their tone and became polished; there was no defense of preconceived opinions, but the whole of the argument was spontaneous. This way of thinking *à deux* was so deeply ingrained in the brothers that nobody else could join it."

They formed their own discussion group in university years. They contributed to it in the same lively way. As the evening went on, the others fell silent in delight and admiration as the back-and-forth of the two brothers went on to produce a new position, a new conclusion or a new outlook to which all could subscribe. That was openness in action.

As to the child and the university student, so to the later Bohr dialog was central to openness, and humor the magic element of dialog. Invited to speak to his classmates on their twenty-fifth jubilee, he asked at one point in his talk how had he and his comrades managed to avoid one-sidedness—despite the "strength which it may offer us"? And how had they succeeded in acquiring a more balanced outlook on life? Out of a happy combination, Bohr suggested, of "our academic tradition" and "our Danish popular sense of humor." Like Abraham Lincoln, with his famous method to persuade a reluctant Civil War cabinet to consider a new proposal in a new light, Bohr knew that nothing has more power than a joke to jolt us out of ourselves and into new surroundings with a new outlook on old issues.

All who worked at Bohr's Institute knew his definition of an expert as "a man who knows through his own bitter experience some small fraction of all the mistakes that can be made in his field"; of a workroom as "a room where no one can keep you from working"; and of a pessimist as "one who generally predicts correctly, but gets no satisfaction out of it." For a peaceable way to work out a disagreement nothing was more useful than his definition of a deep truth as "a truth whose opposite is also a deep truth." No one who knew Bohr can forget him in dialog. With five percent of jokes he mixed ninety-five percent of utmost seriousness. He intermingled delight in the lessons of the past with an immense pressure to clear up the puzzle of the present.

The puzzle and the participants: where did they come from? The issue central for the month or for the year Bohr distilled out of dialog with those who were themselves distillers of issues: present and former collaborators and special visitors from all over the world.

Bohr knew that nobody can be anybody without somebodies around. Among the somebodies—for one extended period or another—were Paul Dirac, Rudolf Peierls and E.J. Williams of Britain, Hendrik Casimir, Paul Ehrenfest and Hans Kramers of the Netherlands, Werner Heisenberg and Lise Meitner of Germany, Leon Rosenfeld of Belgium, Wolfgang Pauli of Switzerland, Vladimir Alexandrovitch Fock, George Gamow and Lev Landau of the Soviet Union, Oskar Klein of Sweden, Yoshio Nishina of Japan, and David Dennison, John Slater and Llewellyn Thomas of the United States.

Jumping into the center of the struggle. Dialog provided the climate for advance. Commitment and diligence supplied the driving force. A principle as old as Bohr's soccer dictated the action. Plunge into the middle of the scrimmage! Run with the ball!

There were two balls at the center of the physics arena in the 1910s, the atom and the nucleus. Bohr scored again and again with the nucleus, and still more with the atom. From the mid-1920s onward, he struggled—successfully—with all his force for a mastery of the message of the quantum. After 1943 he threw himself into an endeavour of vital concern to the larger community, how best to come to terms with the reality of nuclear weapons.

2. *The atom*

How does it come that the name of Niels Bohr is imperishably tied to the atom? Many in the 1910s toyed or worked at one or another model of the atom. Even to work at the atom, however, is very different from having Bohr's day and night diligence, Bohr's overriding commitment to solve the riddle of stability, whatever the cost. A secret of his success was the intensity with which he felt the difficulty. Why is the atom stable at all? That was his all-consuming concern, day after day, week after week.

Bohr's doctoral thesis dealt with the electron theory of matter, and in particular with the magnetic properties of a metal. Why does magnetism persist? If it arises from electric charge in motion, why does it not damp out and fade away? "Are there," Bohr asked himself, "forces in nature of a kind completely different from the usual mechanical sort, forces that might keep the electron going forever?" What other possibility was there to make sense of magnetism?

The issue of stability took for Bohr a still more urgent form with Ernest Rutherford's great discovery in late 1910. He, with his collaborators, found that the positive electric charge of an atom and almost all its mass is concentrated in a nucleus ten thousand times smaller than the atom itself. What did this finding mean for the structure of the atom: To understand more deeply what the very question meant, twenty-seven-year-old Bohr moved from Cambridge—where he had gone because of J.J. Thomson's interest in the structure of the atom—to Manchester. He joined the group of eager young discoverers gathered around the forty-one-year-old Rutherford.

The tall, ruddy New Zealander, admired by Bohr, became his mentor and lifelong friend. The spirit of the place was epitomized by Rutherford's statement that others "play games with their symbols but we, *here*, turn out the real solid facts of nature". With what delight Bohr greeted each new finding of each new week! What splendid young colleagues!

One Manchester friend was George de Hevesy, whom Bohr was later to bring to Copenhagen. In 1912 Hevesy worked out the electrochemistry of radioactive substances. Bohr explained Hevesy's systematics in terms of the concept of nuclear isotopes, nuclei with the same outer electronic structure but with different masses and different radioactivities for the central nucleus. These findings and many more, however, left unexplained a puzzle now more urgent than ever.

What keeps matter from collapsing? That great collection of negatively charged electrons that circulate in essentially free space around the positively charged nucleus to constitute a "solid body": Why doesn't it fall together and disappear in a microscopic fraction of a second?

We find many a wild idea of how nature prevents this "electric collapse" in that premier journal of physics of the 1910s, the *Philosophical Magazine*. Give up Coulomb's law for the force between charged particles? Or abandon the familiar expression for the radiation of energy by an accelerated charge? Who hesitated at such suggestions? In contrast to those who made these and other radical proposals, Bohr was what we might call a daring conservative: conservative against postulating any change in the battle-tested laws of physics, but in the application of them, daring.

Bohr did not give up the inverse-square force between electron and nucleus, as did J.J. Thomson. He did not try to claim that a charged particle will circulate in an orbit without radiation. However, he did insist that the quantum must be as essential to the Rutherford atom as it is to the Planck heat radiation. Immediate confirmation that this was the right way to think he found in the very simplest dimensional arguments about atomic sizes and the energy of binding of electrons. Having made clear to himself this wonderful point of the importance of the quantum, Bohr could go on to the next issue, the spectroscopic evidence on hydrogen, ready to appreciate this message as no one before ever had. The circular and elliptic orbits came at the end of this explanation, not at the beginning.

Bohr's very industry on the atom almost kept his findings from the world. We are mistaken if we think of the clarification of the hydrogen atom as the be-all and end-all of his labors at Ernest Rutherford's Manchester center. Week after week went by and still Bohr held off from any publication. Rutherford's expostulations grew stronger. "But," Bohr protested, "nobody will believe me unless I can explain every atom and every molecule." Rutherford was quick to reply, "Bohr, you explain hydrogen and you explain helium and everybody will believe the rest."

Rutherford, it is well known, did not trust theoretical men. "When a young man in my laboratory uses the word 'universe'," he once thundered, "I tell him it is time for him to leave." "But how does it come," he was asked on another occasion, "that you trust Bohr?" "Oh," was the response, "but he's a football player."

We recall that Bohr's original semiclassical theory did not even succeed in explaining the spectrum of helium. Nevertheless, it took less than ten years after his original publication for his general concept of the atom to sweep the field.

The failure of the theory to predict correctly the spectrum of neutral helium was redeemed in part by its triumph in identifying and explaining the slightly shifted spectrum of ionized helium and by the subsequent more precise spectroscopic confirmation of this diagnosis. However, it meant much more for the world's acceptance of the new atomic theory that it made sense and gave reasonable results for the structure of atoms all the way up and down the Periodic Table.

Rutherford, to the end of his life, followed Bohr's work in atomic physics with intense interest. For example, upon the discovery by Johannes Stark of the surprisingly large effect of electric fields on the structure of the lines in the spectrum of hydrogen, Rutherford wrote to Bohr:

> "I think it is rather up to you at the present time to write something on the Zeeman and electric effects, if it is possible to reconcile them with your theory."

Few today know the immense toil on atomic theory in the Copenhagen of the late 1910s and early 1920s. It gave us, before the advent of wave mechanics and Hartree fields, such concepts as the screening number, the self-consistent atomic field, the order of the building of the elements—and even the Pauli exclusion principle before the Pauli exclusion principle! Bohr was never content with pioneering a new domain of physics. He had the doggedness and sense of order to insist that the new idea be tested and exploited to the full to provide a completely harmonious account of a whole domain of experience.

Bohr throughout his life took immense care, and showed a unique ability, to make statements that repay intensive study: repay, because they combine maximum emphasis on what is known with maximum circumspection about what is unknown. Nowhere does this care show earlier, with greater force, than in Bohr's first paper, in 1913, on the structure of the atom:

> "The principal assumptions used are:
>
> (1) That the dynamic equilibrium of the systems in the stationary state can be discussed by help of the ordinary mechanics, while the passing of the systems between different stationary states cannot be treated on that basis.
>
> (2) That the latter process is followed by the emission of a *homogenous* radiation, for which the relation between the frequency and the amount of energy emitted is the one given by Planck's theory."

The discovery of the structure of the atom marks an immortal step in mankind's eternal search for a world of understandability. Copernicus and Darwin had taken away solidity. Bohr brought it back. Copernicus had dethroned man from the center of the universe. Darwin had taken away plan for the origin of man himself. Bohr built for man, and for the first time, a solid floor for comprehending that physical world in which we live and move and have our being. His theory, though not fully complete or perfect, allowed mankind to resume faith in a world built on regularities. Atoms understood, one could move up to chemistry; and chemistry understood, one could move up to biology and the other sciences.

Under the floor of atomic physics many an unknown still reposed, and among them two where again Bohr led the way: the structure of the nucleus and the mystery of the quantum.

3. The quantum

Many a mystery was left unsolved by Bohr's achievement in understanding the structure of the atom. When an electron jumps from a large orbit to a smaller one, what is it doing as it passes from the one to the other? How does it know to which orbit to jump? And when to make the jump? Today, thanks to no one more than Bohr himself, we have learned that these questions are largely meaningless. Where did the art come from of asking in this domain questions that will be sensible and that will give sensible answers? Out of the dialogs that Bohr carried on year after year in the 1920s at Copenhagen with concerned colleagues from near and far. We are amazed to see how far Bohr could advance into this uncharted territory without benefit of modern quantum theory. We remember the words of Albert Einstein, after he first met Bohr, "I am now reading your great works and, whenever I get stuck anywhere, I see your eager young face before me, smiling and explaining." We remember, too, Einstein's words about Bohr late in life, he "has the highest form of musicality in the sphere of science."

Ideas that Bohr could only shadow forth in earlier years he could at last formulate with compelling vision when Werner Heisenberg's 1925 matrix mechanics, Erwin Schrödinger's 1926 wave mechanics, and Max Born's 1926 probability interpretation of this formalism came to the service of science. When does the electron jump from the Bohr level of higher energy to the Bohr level of lower energy? A wrong question, he could now explain. No device that can measure the energy or frequency or wave length of the radiation given out in this transition with the required precision can co-exist with a device that will measure the time of emission of this radiation. Where is the electron located during the time of the transition? That, too, Bohr could now explain and expound in terms more compelling than those used in his great 1913 paper—and in terms more quantitative, too.

Heisenberg had joined Bohr in the work of making these considerations more quantitative. While Bohr was away in February 1927, Heisenberg wrote up his own conclusions for publication in a paper that did not satisfy Bohr when he saw it. Heisenberg tells us:

> "He pointed out to me that certain statements in this first version were still incorrectly founded, and as he always insisted on relentless clarity in every detail, these points offended him deeply."

So Heisenberg improved his paper but still made its theme indeterminism or "Unbestimmtheit", often inadequately translated as "uncertainty" or the "uncertainty principle." In contrast, Bohr continued his struggle—in endless dialogs with Heisenberg, Pauli, Oskar Klein and other close colleagues—to formulate the deeper lesson of quantum theory. Only in September 1927, at the Como International Physical Congress, was Bohr prepared to make his first statement on the more fundamental point that nature is trying to teach us.

In today's language we might put Bohr's point in these terms. Nature does not exist "out there", independent of us. We ourselves, through our choice of means of observation, are inescapably involved in what is going on. We are not observers only. We are also participators. Or as Bohr puts the central ideal, it is impossible to make "any sharp separation between the behavior of atomic objects and the interaction with the measuring instruments [employed]."

To Bohr the point at issue is not some technical detail of physics. It is human knowledge itself. It is not for nothing that he titles a 1934 collection of his essays, *Atomic Theory and the Description of Nature* and two later collections both *Atomic Physics and Human Knowledge*. All his life he struggled with the problem of knowledge. As a result of the climactic years of 1925–1927, he came to a strong position:

> "... 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 simpl[e]...[B]y the word, 'experiment,' we refer to a situation whereby we can tell others what we have done and what we have learned ... [T]herefore, the account of the experimental arrangement and the results of the observations must be expressed in unambiguous language ... [that is, using] the terminology of [every day] classical physics."

How does Bohr's principle of complementarity fit into this view of knowledge? It is an absolutely central point. Nature—or, in more direct terms, our knowledge of nature—is so built, Bohr tells us, that

> "any given application of classical concepts precludes the simultaneous use of other classical concepts which in a different connection are equally necessary for the elucidation of the phenomena."

We know how uncomfortable these ideas made Einstein. He, who in 1905 had been the first to teach us that "God plays dice," had by 1927 become so upset by wave mechanics, indeterminism, and complementarity that he turned to the directly opposite motto, "God does not play dice."

Einstein's opposition to the new views marked the beginning of a great debate between him and Bohr. In all of the history of thought in recent centuries I know no dialog between two greater men, over a deeper issue, reaching over a longer period of time, at a higher level of colleagueship. It extended over the twenty-eight years from 1927 to Einstein's death in 1955. In the first six years Einstein brought up one idealized experiment after another to prove the logical inconsistency of quantum theory. Each Bohr turned around—often in a dramatic encounter—to establish more strongly than ever the soundness of the theory. Beginning in 1933 Einstein sought to show that quantum theory is incompatible with any reasonable idea of "reality". To this objection Bohr replied in effect that, "your concept of reality is too limited."

No idea that Einstein brought forth in this period was more interesting than the so-called Einstein–Podolsky–Rosen experiment. In it, two particles or photons fly away in different directions from a common starting point. According to quantum theory, what one can say with certainty about the one particle depends on which complementary feature of the second particle one has chosen to measure. At least half a dozen different versions of this experiment have been proposed and performed, and hundreds of papers have been written on the subject. The conclusions of quantum theory have been firmly upheld.

The debate over the EPR experiment had one great fruit. It moved Niels Bohr yet another step ahead in formulating the central idea of quantum theory, the concept of the elementary quantum phenomenon. In today's language, we can say that, "No elementary quantum phenomenon is a phenomenon until it is brought to a close by an irreversible act of amplification, such as the electron avalanche of a Geiger counter or the click of a photodetector or the blackening of a grain of photographic emulsion." Speak of the particles flying apart in the EPR experiment as endowed with this, that, or the other polarization; with this, that, or the other direction of vibration? Wrong! We have no right to attribute such a direction of polarization to either particle in all its long flight from point of production to point of detection. The direction of polarization is there, but we do not know it? No. We mistake the whole nature of things if we attribute a direction to the polarization of either particle in default of a suitable measurement.

How hard it has been to spread this central concept of the elementary quantum phenomenon! How many fruitless discussions and papers there still are today which seek to derive "communication at a speed in excess of the speed of light" or "action at a distance" or some other revolutionary doctrine from the EPR experiment!

The plain fact is that the revolutionary doctrine is quantum theory itself. That theory stands battle-tested today, more than half a century after its original formulation. No one has ever been able to find any logical inconsistency in it. No purported disagreement between experiment and the predictions of the theory has ever stood the test of time. Today quantum theory stands as the overarching principle of twentieth-century physical science, and the elementary quantum phenomenon stands forth as its most revolutionary feature.

In a taped interview at Carlsberg the late afternoon before his unexpected death, Bohr declared:

> "...they [certain philosophers] have not that instinct that it is important to learn something and that we must be prepared to learn something of very great importance... They did not see that it [the elementary quantum phenomenon] provides an objective description—and that it was the only possible objective description."

Piet Hein speaks for all of us when he says:

> "I'd like to know
> What this show
> Is all about
> Before it's out."

No deeper salient has any man ever captured in the realm of the unknown than did Niels Bohr and his great colleagues. No retreat is possible. At the tip of the salient flutters in the breeze the flag he set up, with his message of the elementary quantum phenomenon. Where more clearly than here lies the entry to that great territory beyond, still awaiting conquest, the mystery of existence itself?

Surely existence is so ramified that only mathematics will be able to bring it all in order, so preposterous that only philosophy will be able to see the grand plan of it, so quantum-connected that only physics will be able to put to it the right questions!

4. The compound nucleus, the liquid-drop model and the collective model

Loyalty to every great issue that he had ever dealt with was a hallmark of Niels Bohr and the institute he founded. Loyalty to the physics of the atom, in all its marvelous development over the years. Loyalty to the issue of the quantum, that ever-pursued Merlin, ever-changing shape during pursuit. And loyalty to the structure of the nucleus, the subject to which Bohr had already begun making important contributions during the early days with Rutherford. Developments were soon to show that his contributions to elucidating the structure of the nucleus had only begun.

Around Eastertime in 1935 Christian Møller returned to Copenhagen from a visit to Rome and the group of Enrico Fermi, Eduardo Amaldi, O. D'Agostino, Ettore Majorana, Franco Rasetti and Emilio Segré and reported their astonishing finding. Slow neutrons, passing through selected materials like silver, cadmium and boron, and interacting with the atomic nuclei of those substances, encountered effective target areas or "cross-sections" enormously larger than the cross-sectional area of the nucleus itself. How come?

Møller was only about a third of the way through reporting these results to the score of colleagues in the little conference room of the Institute when Bohr rose and intervened. How could such large probabilities for the nucleus to intercept a neutron be at all compatible with any picture of the nucleus as an open planetary system? Surely something very important lay hidden in the new findings. "Now it comes," he said, as he paced back and forth, "now it comes, now it comes." And suddenly it really did come. Then and there he sketched out the concepts of what came to be known as the *compound-nucleus model* of nuclear reactions. It has been employed decade after decade since that time in dozens of laboratories to understand hundreds of nuclear reactions.

According to the new model, the addition of energy or a new particle to a target nucleus promotes that system to a new state, a compound nucleus. That compound nucleus can get rid of this energy by one or another of numerous competing mechanisms: re-emission of the original particle with the original or reduced energy; emission of a photon and simultaneous drop to a lower energy level or to the ground state of the nucleus itself; or emission of a proton, neutron or alpha particle. Know for a given nucleus its possible energy levels and know for each energy level the probability per second that the nucleus will change this, that, or the other way: to know these is, according to the idealized compound-nucleus model, to know all of nuclear physics. Even today this simple program offers the simplest known method to forecast the yield in almost any transmutation experiment.

All those nuclear energy levels and their break-up probabilities, however: how were they to be predicted? What is still today the most economical road to an approximate estimate is provided by the *liquid-drop model* of the nucleus. There had been two or three proposals in the past to compare the normal nucleus to a quiescent liquid drop. Bohr now had a powerful motive to transform a conceptual toy to a work-a-day tool. How better than by studying the modes of vibration of the drop could one predict the excitations of the nucleus? And how more simply than via the concept of evaporation from the surface could one understand the relative emission rates of this, that, and the other particle? Nuclear physics of a newly quantitative form was on the march!

No other workable tools were available four years later but the compound nucleus and the liquid drop to understand the mechanism of fission. Those concepts plus the leadership of Niels Bohr sorted out by mid-1939 the vitally different roles of uranium-235 and uranium-238. Still more important for the future, those ideas made it possible to forecast the fissility of plutonium-239 before that element had even been seen, let alone manufactured, in what was to be mankind's first great venture into alchemistry, with all its fateful consequences.

Bohr's contributions to nuclear physics did not stop with the war and its aftermath. He had a significant influence, both jointly with his son Aage, and jointly with one and another close collaborator, in bringing into the world the *collective* or *unified model* of the nucleus and nuclear reactions, that ties together in a larger unity the *independent particle* model of Hans Jensen and Maria Mayer with the older compound-nucleus and liquid-drop models of the nucleus.

5. The Niels Bohr Institute

What is a responsible institute? The puzzles of the nucleus, after the war, won more attention than the remaining puzzles of the atom. The worldwide nuclear research budget grew at least a hundredfold. The Blegdamsvej Institute, despite a modest increase in funding and manpower, remained tiny by comparison. How then does it come about that Copenhagen, with Niels Bohr gone, is still recognized as the world center for the understanding of the nucleus as well as the atom and the quantum?

How come? Because Bohr's spirit remains. Commitment, diligence and openness are its watchwords. Jokes still light the way. No more responsible man of science has the world ever seen than Niels Bohr. No more responsible physics institute does there exist in all the world today than this one at Copenhagen, his living reincarnation.

How does the responsible institute greet the finding of a discrepancy? With welcome.

How does it respond to an unexpected finding? With joy.

How does it greet an outsider's totally new and successful way of looking at things? With full openness.

Why? Why this welcome to a problem, a paradox or a total upset? Because great advance, Bohr's example teaches us, comes only out of problem, difficulty or apparent paradox. Yes, for the responsible institute as for the responsible individual, commitment only makes its soul. Only diligence creates its genius. Only willingness to give open jury trial to every new development gives it its power to move successfully into the unknown.

6. Weapons and the open world

From nuclear weapons to the doctrine of the open world. September 1, 1939 was a day to remember. World War II began. The green-covered journal, *Physical Review*, published that day Niels Bohr's paper on "The Mechanism of Nuclear Fission," destined to influence the wartime nuclear physics programs of the Atlantic powers and Germany, the Soviet Union, and even Japan. The paper written, Bohr had returned from Princeton to Copenhagen. In the coming time of crisis he wanted more than ever to be with his family, his colleagues and his fellow countrymen. Invitation after invitation to stay overseas in safety he turned down.

No one who wants an example of what it is to be loyal to one's own country can do better than to look at Niels Bohr. In Denmark's darkest days those who had taken her liberty were trying to snuff out her soul. To overwhelming force, the people of the country and their king presented unbending moral resistance. At the center of their spiritual unity stood Denmark's men of learning under the leadership of Niels Bohr. To hold high Denmark's values Bohr and other leaders created and disseminated at their peril a great book entitled *Danish Culture*.

To belong to Denmark, truly to belong to Denmark, as H.C. Andersen put it in Bohr's favorite song and Denmark's national anthem:

> In Denmark I was born
> There is my home
> There are my roots
> From there my world goes,

always meant, in his view, a special opportunity—and special responsibility—to exert a constructive influence on the relations between the larger powers. Therefore—when under peril to his life he escaped in a small boat in late 1943 and came into touch with the progress of the atomic bomb—he turned, as no one else so effectively could, from the dangers of the weapon to its possibilities for bringing about a better world.

In a memorandum to President Franklin D. Roosevelt on the third of July, 1944, Bohr urged that America and Britain inform other allied nations about the new weapon before it was used, and consult with them on measures of control. Agreement on control, he also emphasized, would work for a greater openness between nations. The same points he made even more strongly in a long discussion with the president in August 1944 and in a subsequent memorandum. Bohr's ideas form the foundation of present-day thinking about control.

How can we know Bohr, the man, unless we conceive in imagination the hours, days and months that he devoted to developing the interlinked doctrines of control and openness; the leaders in America and Britain—including Winston Churchill—with whom he conferred; his repeated wartime crossings of the Atlantic—Europe to America on empty troop ships, America to Europe by flying boat—and the draft paper after draft paper that he prepared?

Fate frustrated Bohr's 1944 goal of man-to-man discussions among Churchill, Roosevelt and Stalin. No agreement was reached between the great powers for the control of A-bombs before the secret of their existence burst upon an unprepared world.

By the time the H-bomb began to loom upon the scene, in early 1950, Bohr's thinking had changed. He recognized that no progress toward control could take place without an atmosphere of greater confidence. Therefore, the proposed approach to the problem had to be turned about. He had believed that control of the new devices should be the first step in openness among nations. By 1950 he had realized that the approach had to be the direct opposite: first openness and then, on that foundation, control.

Few men have the vision and courage to try to induce all mankind to accept a new moral concept of such scope—the principle of the open world. But Bohr saw no other way. That was the compulsion that drove him to send to the United Nations, from Copenhagen, on the ninth of June, 1950 his famous Open World letter. It would have been more widely advertised if news of it had not been drowned out a few days later by the totally unexpected invasion of South Korea by North Korea. In his letter, Bohr reasons:

> "The very fact that knowledge is in itself the basis for civilization points directly to openness as a way to overcome the present crisis.... [F]ull mutual openness, only, can effectively promote confidence and guarantee common security...
>
> Such a stand would ... appeal to people all over the world, fighting for fundamental human rights, and would greatly strengthen the moral position of all supporters of genuine international cooperation. At the same time, those reluctant to enter on the course proposed would have been brought into a position difficult to maintain since such opposition would amount to a confession of lack of confidence in the strength of their own cause when laid open to the world."

How are we to assess the doctrine of the Open World today? All but dead? Don't newspapers forget it, historians neglect it, statesmen belittle it?

Let us tell the newspapers, those historians, those statesmen to look again and look deeper. Let us remind them that a great idea is a seed; that it lies buried underground for a time in the dark, germinating in the minds of thinking men and women; that there it gathers nourishment and strength, until in due season it bursts forth into light with all its power.

From the smallness of the seed, the onlooker has more than once underestimated the greatness of the growth.

What casual bystander who glimpsed a French thinker dreaming of a Statue of Liberty foresaw that one day two-hundred-forty million people across the ocean would look upon his Liberty, with her torch upraised to all the world, as their dearest national symbol?

Who that ever met that gentle philosopher and writer, Hu Shih, realized that his poems, set to music, would be the inspiration of soldiers on the famous Long March, turning point of the Chinese revolution?

Who that looked on Julia Ward Howe, rocking her baby's cradle in the dark hours of the night, and writing, knew that her "Battle Hymn of the Republic", would one day be counted by Abraham Lincoln as worth a division to the Union cause?

Niels Bohr's doctrine of the Open World: is it not destined to become in the fullness of time the moral undergirding for an association of Friends of Civilization, a vibrant union of liberty and social justice, a spontaneous gathering together of free peoples? More rally to the cause of the Open World each passing year.

Here and there work today those poets, writers and artists that Niels and Margrethe Bohr loved to help, to encourage and to have at their home. Out of the hands of one, shall we see some day a poem or song, on Bohr's message, of worldwide impact? From the chisel of another, a sculpture that grips the mind and moves the heart with its summons to an Open World?

Let us never forget these words in Bohr's famous letter:

> "The efforts of all supporters of international co-operation, individuals as well as nations, will be needed to create in all countries an opinion to voice, with ever-increasing clarity and strength, the demand for an open world."

7. Bohr's legacy

What lies ahead of peril and promise? We mortals do not know whence we come, who we are or where we are going. We live still in the childhood of mankind. As this beautiful blue globe of ours floats on through space, men of science search a hundred skies for what they hold of peril and promise, from the nature of a particle to the principles of communication, and from the sociology of an achieving society to the architecture of a biological molecule. The responsibility for discovery society lays on the community of science. On its findings rest the fears and hopes of all the years. Nothing has more to do with the success of the search than the warm colleagueship of the searchers, their commitment, their diligence, their openness—or, in a single word, their responsibility.

Responsible science. What makes a responsible group, a responsible university department, a responsible institute? No example ranks higher in all the world than this Copenhagen Institute with its wonderful collegiality. The way of doing science that Bohr and his institute taught the world is, beyond all Bohr's own spectacular discoveries, his greatest legacy.

That legacy is no miracle. It was built on character—the character of Niels and Margrethe Bohr and the group of colleagues Niels gathered about him.

One of his classmates and comrades through life, Ole Chievitz, said of Niels Bohr after his death: "he was a *good* man—the best man I ever knew."