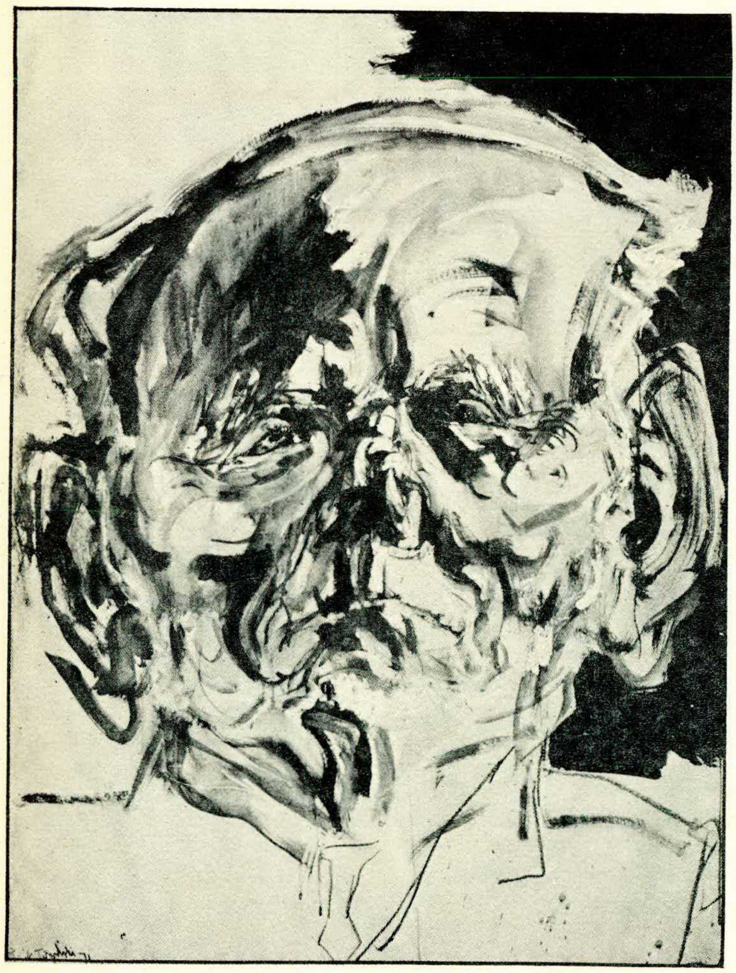
THE PRINCIPLE OF TOLERANCE

by J. Bronowski

"There is no absolute knowledge. And those who claim it, whether they are scientists or dogmatists, open the door to tragedy."



Portrait of Stephan Borgrajewicz by Polish artist Feliks Topolski.

One aim of the physical sciences has been to give an exact picture of the material world. One achievement of physics in the twentieth century has been to prove that that aim is unattainable. Take a good, concrete object: the human face. A blind woman runs her fingertips over the face of a man she senses for the first time, thinking aloud: "I would say that he is elderly. I think, obviously, he is not English. He has a rounder face than most English people. And I should say he is probably Continental, if not Eastern-Continental. The lines in his face would be lines of possible agony. I thought at first they were scars. It is not a happy face."

It is the face of Stephan Borgrajewicz, who like me was born in Poland. In the illustration it is seen by the Polish artist, Feliks Topolski. We are aware that the picture does not so much fix the face as explore it; that the artist is tracing the detail almost as if by touch; and that each line that is added strengthens the picture but never makes it final. We accept that as the method of the artist.

But what physics has now done is to show that that is the only method to knowledge. There is no absolute knowledge. And those who claim it, whether they are scientists or dogmatists, open the door to tragedy. All information is imperfect. We have to treat it with humility. That is the human condition, and that is what quantum physics says. I mean that literally.

Look at the face across the whole spectrum of electromagnetic information. How fine and how exact is the detail that we can see with the best instruments in the world—even with a perfect instrument, if we can conceive one? And seeing the detail need not be confined to seeing with visible light. James Clerk Maxwell in 1867 proposed that light is an electromagnetic wave, and the equations that he constructed for it implied that there are others. The spectrum of visible light, from red to violet, is only an octave or so in the range of invisible radiations. There is a whole keyboard of information, all the way from the longest wavelengths of radio waves (the low notes) to the shortest wavelengths of X-rays and beyond (the highest notes). We shall shine it all, turn by turn, on the human face.

James Clerk Maxwell

The longest of the invisible waves are the radio waves, whose existence Heinrich Hertz proved in the 1880s, and so confirmed Maxwell's theory. Because they are the longest, they are also the crudest. A radar scanner working at a wavelength of a few meters will not see the face at all, unless we make the face also some meters across, like a Mexican stone head. Only when we shorten the wavelength does any detail appear on the giant head: at a fraction of a meter, the ears.

Next we look at the face, the man's face, with a camera which is sensitive to the next range of radiation, to wavelengths of less than a millimeter: infrared rays. The astronomer William Herschel discovered them in 1800 by noticing the warmth when he focused his telescope beyond red light: for the infrared rays are heat rays. The camera plate translates them into visible light in a rather arbitrary code, making the hottest look blue and the coolest look red or dark. We see the rough features of the face: the eyes, the mouth, the nose—we see the heat stream from the nostrils. We learn something new about the human face, but what we learn has no detail.

At its shortest wavelengths, some hundredths of a millimeter or less, infrared shades gently into visible red. The film that we use now is sensitive to both, and the face springs to life. It is no longer *a* man; it is the man we know: Stephan Borgrajewicz. White light reveals him to the eye visibly, in detail: the small hairs, the pores in the skin, a blemish here, a broken vessel there. White light is a mixture of wavelengths, from red to orange to yellow to green to blue and finally to violet, the shortest visible waves. We ought to see more exact details with the short violet waves than the long red waves. But in practice, a difference of an octave or so does not help much.

The painter analyzes the face, takes the features apart, separates the colors, enlarges the image. It is natural to ask: should not the scientist use a microscope to isolate and analyze the finer features? Yes, he should. But we ought to understand that the microscope enlarges the image but cannot improve it: the sharpness of detail is fixed by the wavelength of the light. The fact is that at any wavelength we can intercept a ray only by objects about as large as a wavelength itself: a smaller object simply will not cast a shadow.

An enlargement of over two hundred times can single out an individual cell in the skin with ordinary white light. But to get more detail, we need a still shorter wavelength. The next step, then, is ultraviolet light, which has a wavelength of ten-thousandth of a millimeter and less—shorter by a factor of ten and more than visible light. If our eyes were able to see into the ultraviolet, they would see a ghostly landscape of fluorescence. The ultraviolet microscope looks through the shimmer into the cell, enlarged 3500 times, to the level of single chromosomes. But that is the limit: no light will see the human genes within a chromosome.

Once again, to go deeper, we must shorten the wavelength: next, to the X-rays. However, they are so penetrating that they cannot be focused by any material: we cannot build an X-ray microscope. So we must be content to fire them at the face and get a sort of shadow. The detail depends now on their penetration. We see the skull beneath the skin: for example, that the man has lost his teeth. This probing of the body made X-rays exciting as soon as Wilhelm Konrad Röntgen discovered them in 1895, because here was a finding in physics that seemed designed by nature to serve medicine. It made him a kindly father figure, and he was the hero who won the first Nobel Prize in 1901.

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A lucky chance in nature will sometimes let us do more by a flanking movement: that is, by inferring an arrangement which cannot be seen directly. X-rays will not show us an individual atom, because it is too small to cast a shadow even at this short wavelength. Nevertheless, we can map the atoms in a crystal because their spacing is regular, so that the X-rays will form a regular pattern of ripples from which the positions of the obstructing atoms can be inferred. The method was invented in 1912 by Max von Laue, and was a double stroke of ingenuity, for it was the first proof that atoms are real, and also that X-rays are electromagnetic waves.

We have one more step to take: to the electron microscope, where the rays are so concentrated that we no longer know whether to call them waves or particles. Electrons are fired at an object, and they trace its outline like a knife thrower at a fair. The smallest object that has ever been seen is a single atom of thorium. It is spectacular. And yet the soft image confirms that, like the knives that graze the girl at the fair, even the hardest electrons do not give a hard outline. The perfect image is still as remote as the stars.

We are here face to face with the crucial paradox of knowledge. Year by year we devise more precise instruments with which to observe nature, but when we look at the observations, we are discomfited to see that they are still fuzzy, and as un-

William Herschel

certain as ever. We seem to be running after a goal which lurches away to infinity every time we come within sight of it.

The paradox of knowledge is not confined to the small, atomic scale: on the contrary, it is as cogent on the scale of man, and even of the stars. Let me put it in the context of an astronomical observatory. Karl Friedrich Gauss's observatory at Göttingen was built about 1807. Throughout his lifetime and ever since, astronomical instruments have been improved. We look at the position of a star as it was determined then and now, and we seem

Karl Friedrich Gauss

closer to finding it precisely. But when we actually compare our individual observations today, we are astonished to find them as scattered within themselves as ever. We had hoped that the human errors would disappear, and that we would ourselves have God's view. But it turns out that the errors cannot be taken out of the observations. And that is true of stars, or atoms, or just looking at somebody's picture, or hearing the report of somebody's speech.

Gauss recognized this with that marvelous, boyish genius that he had right up to the age of nearly eighty at which he died. When he was only eighteen years old, when he came to Göttingen to enter the university in 1795, he had already solved the problem of the best estimate of a series of observations which have internal errors. He reasoned then as statistical reasoning still goes today. When an observer looks at a star, he knows that there is a multitude of causes for error. So he takes several readings, and he hopes, naturally, that the best estimate of the star's position is the average: the center of the scatter. So far, so obvious. But Gauss pushed on to ask what the scatter of the errors tells us. He devised the Gaussian curve in which the scatter is summarized by the deviation, or spread, of the curve. And from this came a far-reaching idea: the scatter marks an area of uncertainty. We are not sure that the true position is the center. All we can say is it lies in the area of uncertainty, and the area is calculable from the observed scatter of the individual observations.

Having this subtle view of human knowledge, Gauss was particularly bitter about philosophers who claimed that they had a road to knowledge more perfect than that of observation. Of many examples I will choose one. It happens that there was a philosopher called Friedrich Hegel, whom I must confess I specifically detest. And I am happy to share that profound feeling with a far greater man, Gauss. In 1800 Hegel presented a thesis proving that although the definition of planets had changed since the Ancients, there still could only be, philosophically, seven planets. Well, not only Gauss knew how to answer that: Shakespeare had answered it long before. There is a marvelous passage in *King Lear*, in which the Fool says to the King: "The reason why the seven stars are no moe than seven is a pretty reason." And the King wags sagely and says: "Because they are not eight?" And the Fool says: "Yes indeed. Thou wouldst make a good fool." And so did Hegel. On January 1, 1801, punctually, before the ink was dry on Hegel's dissertation, an eighth planet was discovered: the minor planet Ceres.

History has many ironies. The time bomb in Gauss's curve is that after his death we discover that there is no God's-eye view. The errors are inextricably bound up with the nature of human knowledge. And the irony is that the discovery was made in Göttingen. Ancient university towns are wonderfully alike. Göttingen is like Cambridge in England or New Haven in America: very provincial, not on the way to anywhere—no one comes to these backwaters except for the company of professors. And the professors are sure that this is the center of the world. There is an inscription in the Ratskeller in Göttingen which reads: *Extra Gottingam non est vita* (Outside Göttingen there is no life). This epigram, or should I call it epitaph, is not taken as seriously by the undergraduates as by the professors.

The symbol of the university is the iron statue outside the Ratskeller of a barefoot goosegirl that every student kisses at graduation. The university is a Mecca to which students come with something less than perfect faith. It is important that students bring a certain ragamuffin, barefoot irreverence to their studies: they are not there to worship what is known but to question it.

Like every other university town, the Göttingen landscape is crisscrossed with long walks that professors take after lunch, and the research students are ecstatic if they are asked along. Perhaps Göttingen in the past had been rather sleepy. The small German university towns go back to a time before the country was united (Göttingen was founded by George II as ruler of Hanover), and this gives them a flavor of local bureaucracy. Even after the military might ended and the Kaiser abdicated in 1918, they were more conformist than universities outside Germany.

The link between Göttingen and the outside world was the railway. That was the way the visitors came from Berlin and abroad, eager to exchange the new ideas that were racing ahead in physics. It was a byword in Göttingen that science came to life on the train to Berlin, because that is where people argued and contradicted and had new ideas and had them challenged. In the years of the First World War, science was dominated at Göttingen, as elsewhere, by relativity. But in 1921 there was appointed to the chair of physics Max Born, who began a series of seminars that brought there everyone interested in atomic physics. It is rather surprising to reflect that Max Born was almost forty when he was appointed. By and large, physicists have done their best work before they are thirty (mathematicians even earlier, biologists perhaps a little later). But Born had a remarkable personal, Socratic gift. He drew young men to him, he got the best out of them, and the ideas that he and they exchanged and challenged produced his

Werner Heisenberg

best work. Out of that wealth of names, whom am I to choose? Obviously Werner Heisenberg, who did his finest work with Born. Then, when Erwin Schrödinger published a different form of basic atomic physics, the arguments took place. And people from all over the world came to Göttingen to join in.

It is strange to talk in these terms about a subject which, after all, is done by midnight oil. Did physics in the twenties really consist of argument, seminar, discussion, dispute? Yes, it did. It still does. The people who met in Göttingen, the people who meet in laboratories still, only end their work with a mathematical formulation. They begin it by trying to solve conceptual riddles. The riddles of the subatomic particles—of the electrons and the rest—are mental riddles.

Think of the puzzles that the electron was setting just at that time. The quip among professors

Max Planck

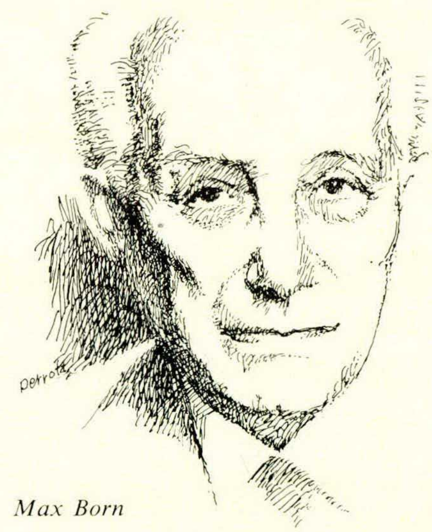
was (because of the way university timetables are laid out) that on Mondays, Wednesdays, and Fridays the electron would behave like a particle; on Tuesdays, Thursdays, and Saturdays it would behave like a wave. How could you match those two aspects, brought from the large-scale world and pushed into a single entity, into this Lilliput of the inside of the atom? That is what the speculation and argument were about. And that requires not calculation, but insight, imagination: if you like, metaphysics. I remember a phrase that Max Born used when he came to England many years after, and that still stands in his autobiography. He said: "I am now convinced that theoretical physics is actual philosophy."

Max Born meant that the new ideas in physics amount to a different view of reality. The world is not a fixed, solid array of objects, for it cannot be fully separated from our perception of it. It shifts under our gaze, it interacts with us, and the knowledge that it yields has to be interpreted by us. There is no way of exchanging information that does not demand an act of judgment. Is the electron a particle? It behaves like one in the Bohr atom. But Louis de Broglie in 1924 produced a beautiful wave model, in which the orbits are the places where an exact, whole number of waves closes round the nucleus. Max Born thought of a train of electrons as if each were riding on a crankshaft, so that collectively they constitute a series of Gaussian curves, a wave of probability. A new conception was being made, on the train to Berlin and the professorial walks in the woods of Göttingen: that whatever fundamental units constitute the world, they are more delicate, more fugitive, more startling than we catch in the butterfly net of our senses.

All those woodland walks and conversations came to a brilliant climax in 1927. Early that year Werner Heisenberg gave a new characterization of the electron. Yes, it is a particle, he said, but a particle which yields only limited information: that is, you can specify where it is at this instant, but you cannot impose on it a specific speed and direction at the setting-off. Or conversely, if you insist that you are going to fire it at a certain speed in a certain direction, then you cannot specify exactly what its starting point is, or its end point.

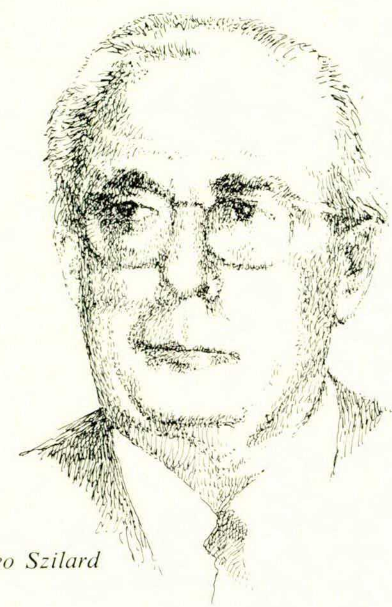
That sounds like a very crude characterization. It is not. Heisenberg gave it depth by making it precise. The information that the electron carries is limited in its totality: that is, for instance, its speed and its position fit together in such a way that they are confined by the tolerance of the quantum. This is the profound idea: one of the great scientific ideas, not only of the twentieth century, but in the history of science.

Heisenberg called this the Principle of Uncertainty. In one sense, it is a robust principle of the



Max Born

everyday. We know that we cannot ask the world to be exact. If an object (a familiar face, for example) had to be exactly the same before we recognized it, we would never recognize it from one day to the next. We recognize the object to be the same because it is much the same: it is never exactly like it was, it is tolerably like. In the act of recognition, a judgment is built in: an area of tolerance or uncertainty. So Heisenberg's principle says that no events, not even atomic events, can be described with certainty: that is, with zero tolerance. What makes the principle profound is that Heisenberg specifies the tolerance that can be reached. The measuring rod is Max Planck's quantum. In the world of the atom, the area of uncertainty is always mapped out by the quantum.


Leo Szilard

Yet the Principle of Uncertainty is a bad name. In science or outside it, we are not uncertain: our knowledge is merely confined within a certain tolerance. We should call it the Principle of Tolerance. And I propose that name in two senses. First, in the engineering sense. Science has progressed step by step, the most successful enterprise in the ascent of man, because it has understood that the exchange of information between man and nature, and man and man, can take place only with a certain tolerance. But second, I also use the word passionately about the real world. All knowledge, all information between human beings, can be exchanged only within a play of tolerance. And that is true whether the exchange is in science, or in literature, or in religion, or in politics, or even in any form of thought that aspires to dogma. It is a major tragedy that, in Göttingen, scientists were refining to the most exquisite precision the Principle of Tolerance and turning their backs on the fact that all around them tolerance was crashing to the ground beyond repair.

The sky was darkening all over Europe. But there was one particular cloud which had been hanging over Göttingen for a hundred years. Early in the 1800s Johann Friedrich Blumenbach had put together a collection of skulls that he got from distinguished gentlemen with whom he corresponded throughout Europe. There was no suggestion in Blumenbach's work that the skulls were to support a racist division of humanity, although he did use anatomical measurements to classify the families of man. All the same, from the time of Blumenbach's death in 1840 the collection was added to and added to, and became a core of racist, pan-Germanic theory which was officially sanctioned by the National Socialist Party.

When Hitler came to power in 1933, the tradition of scholarship in Germany was destroyed almost overnight. Now the train to Berlin was a symbol of flight. Europe was no longer hospitable to the imagination—and not just the scientific imagination. A whole conception of culture was in retreat: the conception that human knowledge is personal and responsible, an unending adventure at the edge of uncertainty. Silence fell, as after the trial of Galileo. The great men went out into a threatened world: Max Born, Erwin Schrödinger, Albert Einstein, Sigmund Freud, Thomas Mann, Bertolt Brecht, Arturo Toscanini, Bruno Walter, Marc Chagall, Enrico Fermi, and Leo Szilard, who arrived finally, after many years, at the Salk Institute in California.

The Principle of Uncertainty or, in my phrase, the Principle of Tolerance, fixed once and for all the realization that all knowledge is limited. It is an irony of history that at the very time when this was being worked out there should rise, under Hitler in Germany and other tyrants elsewhere, a counterconception: a principle of monstrous certainty. When the future looks back on the thirties it will think of them as a crucial confrontation of culture, the ascent of man, against the throwback to the despots' belief that they had absolute certainty.

Leo Szilard was greatly engaged in all these abstractions, and I spent many afternoons in the last year or so of his life talking with him about them at the Salk Institute. Leo Szilard was a Hungarian whose university life was spent in Germany. In 1929 he had published an important and pioneer paper on what would now be called Information Theory: the relation between knowledge, nature, and man. But by then Szilard was certain that Hitler would come to power and that war was inevitable. He kept two bags packed in his room, and by 1933 he had locked them and taken them to England.

It happened that in September of 1933 Lord Rutherford, at the British Association meeting, made some remark about atomic energy never becoming real. Leo Szilard was the kind of scientist, perhaps just the kind of good-humored, cranky man, who disliked any statement that contained the word "never," particularly when made by a distinguished colleague. So he set his mind to think about the problem. He was living at the Strand Palace Hotel–he loved living in hotels. He was walking to work at St. Bartholomew's Hospital, and as he came to Southampton Row he was stopped by a red light. (That is the only part of the story I find improbable: I never knew Szilard to stop for a red light.) However, before the light turned green, he had realized that if you hit an atom with one neutron, and it happens to break up and release two, then you would have a chain reaction. He wrote a specification for a patent which contains the words "chain reaction," which was filed in 1934.

And now we come to a part of Szilard's personality which was characteristic of scientists at that time, but which he expressed most clearly and loudly. He wanted to keep the patent secret. He wanted to prevent science from being misused. In fact, he assigned the patent to the British Admiralty, so that it was not published until after the war. But meanwhile war was becoming more and more threatening. The march of progress in nuclear physics and the march of Hitler went step by step, pace by pace, in a way that we forget now. Early in 1939 Szilard wrote to Joliot Curie asking him if one could make a prohibition on publication. He tried to get Fermi not to publish. But finally, in August of 1939, he wrote a letter which Einstein signed and sent to President Roosevelt, saying (roughly): "Nuclear energy is here. War is inevitable. It is for the President to decide what scientists should do about it."

But Szilard did not stop. When in 1945 the European war had been won, and he realized that the bomb was now about to be used on the Japanese, Szilard marshaled protest everywhere he could. He wrote memorandum after memorandum. One memorandum to President Roosevelt failed only because Roosevelt died at the very time that Szilard was transmitting it to him. Always Szilard wanted the bomb to be tested openly before the Japanese and an international audience, so that the Japanese should surrender before people died.

Szilard failed, and with him the community of scientists failed. He did what a man of integrity could do. He gave up physics and turned to biology–that is how he came to the Salk Institute–and persuaded others too. Physics had been the passion of the last fifty years, and their masterpiece. But now we knew that it was high time to bring to the understanding of life, particularly human life, the same singleness of mind that we had given to understanding the physical world. The first atomic bomb was dropped on Hiroshima in Japan on August 6, 1945, at 8:15 in the morning. I had not been long back from Hiroshima when I heard someone say, in Szilard's presence, that it was the tragedy of scientists that their discoveries were used for destruction. Szilard replied, as he more than anyone else had the right to reply, that it was not the tragedy of scientists: "It is the tragedy of mankind."

There are two parts to the human dilemma. One is the belief that the end justifies the means. That push-button philosophy, the deliberate deafness to suffering, has become the monster in the war machine. The other is the betrayal of the human spirit: the assertion of dogma that closes the mind and turns a nation, a civilization, into a regiment of ghosts–obedient ghosts or tortured ghosts. It is said that science will dehumanize people and turn them into numbers. That is false, tragically false. Consider the concentration camp and crematorium at Auschwitz, where people were turned into numbers. Into its pond were flushed the ashes of some four million people. And that was not done by gas. It was done by arrogance. It was done by dogma. It was done by ignorance. When people believe that they have absolute knowledge, with no test in reality, that is how they behave. That is what men do when they aspire to the knowledge of gods.

Science is a very human form of knowledge. We are always at the brink of the known, we always feel forward for what is to be hoped. Every judgment in science stands on the edge of error, and is personal. Science is a tribute to what we can know although we are fallible. In the end, the words were said by Oliver Cromwell: "I beseech you, in the bowels of Christ, think it possible you may be mistaken."

I owe it as a scientist to my friend Leo Szilard, I owe it as a human being to the many members of my family who died at Auschwitz, to stand by the pond as a survivor and a witness. We have to cure ourselves of the itch for absolute knowledge and power. We have to close the distance between the push-button order and the human act. We have to touch people. □