Paul Adrien Maurice Dirac was the last survivor of the group of young men who in the three years from 1925 to 1928 created quantum mechanics. Together they overthrew the foundations of classical physics and established the new foundations on which all our modern understanding of atoms and particles, fields and interactions, chemistry and molecular biology is based. Dirac was at the age of twenty-three one of the leaders of the quantum revolution. At the age of twenty-five he made, alone, his most famous and original discovery, the Dirac equation, which describes the behavior of an electron with almost perfect accuracy. He won the Nobel Prize for physics in 1933. He continued thereafter to publish important and original contributions to physics, always in his personal and inimitable style. In this brief memoir I will not attempt to describe the substance of his discoveries but will concentrate on the question of style. The Dirac style has an importance transcending the particular field of science in which he worked.

To give to nonexperts a true impression of the Dirac style, it is best to use his own words. Here is Dirac, at the age of seventy, talking to a mixed audience at the University of Miami in Coral Gables. The title of his talk was "Basic Beliefs and Fundamental Research."

There is one fairly obvious way of getting a new theory. Keep close to the experimental results, hear about all the
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latest information that the experimenters obtain, and then proceed to set up a theory to account for them. That is a more or less straightforward procedure and there are many physicists working on such lines, competing with one another, and it might develop somewhat into a rat-race. Of course it needs rather intelligent rats to take part in it. But I don't want to speak about this method of procedure.

There is another way in which a theoretical physicist may work which is slower and more sedate and may lead to more profound results. It does not depend very closely on experimental work. This consists in having some basic beliefs and trying to incorporate them into one theory. Now why should one have basic beliefs? I don't know that I can explain that. It's just that one feels that nature is constructed in a certain way and one hangs onto the idea rather like one might hang onto a religious belief. One feels that things simply have to be on these lines and one must devise a mathematical theory for incorporating the basic belief.

These two styles of theorizing are well known in the history of science. Historians call the first style Baconian and the second Cartesian. Our young colleagues today, with less awareness of their place in history, are accustomed to call the two styles "bottom-up" and "top-down." Dirac in his talk went on to explain how the very greatest theoretical physicists, in particular Newton and Einstein, worked from the top down, deducing laws of nature from fundamental beliefs rather than inducing laws from the results of experiment. Dirac himself is in modern times the supreme example of a top-down physicist. Here is what he says about himself:

My own early work was very much influenced by Bohr orbits, and I had the basic belief that Bohr orbits would provide the clue to understanding atomic events. That was a mistaken belief... I found out that my own basic belief was wrong and I had to go over to quite a new line of thinking. I had to have some more general basis for my work, and the only reliable basis I could think of, the only basis which was sufficiently general so as to secure me from making the same mistake again, was to set up a principle of mathematical beauty: to say that we don't really know what the basic equations of physics are, but they have to have great mathematical beauty. We must insist on this, and that is the only feature of the equations that we can have confidence in and insist on... How can one make beauty a fundamental test for the correctness of a physical theory? Well, it is quite clear that beauty does depend on one's culture and upbringing for certain kinds of beauty, pictures, literature, poetry and so on... But mathematical beauty is of a different kind. I should say perhaps it is of a completely different kind and transcends these personal factors. It is the same in all countries and at all periods of time... Well, that is the essence of what I wanted to tell you. In fact one can feel so strongly about these things, that when an experimental result turns up which is not in agreement with one's beliefs, one may perhaps make the prediction that the experimental result is wrong and that the experimenters will correct it after a while. Of course one must not be too obstinate over these matters, but still one must sometimes be bold.

Dirac was bold. His confidence in his own instinct for mathematical beauty led him in succession to three fundamental discoveries: first, the general abstract formulation of quantum mechanics; second, the correct quantum description of electromagnetic radiation processes; and third, the Dirac equation for the electron. In each case he was led not merely to a new physical law but to a new style of mathematical description of nature. And in each case the experiments proved him right, although, as he hints in the Coral Gables lecture, there were initially some contradictory experimental results which he was bold enough to ignore.

Dirac's fundamental belief, the belief that the basic criterion for choosing a physical theory should be aesthetic, proved itself in his hands overwhelmingly successful. Nature agreed with his criterion. And this agreement between Nature's and Dirac's notions of beauty presents us with a new example of an old philosophical riddle. Why should Nature care about our feelings of beauty? Why should the electron prefer a beautiful equation to an ugly one?
one? Why should the universe dance to Dirac's tune? These are deep questions which neither scientists nor philosophers know how to answer. Dirac, by his style of discovery, has posed these questions more sharply than anyone else. More even than Newton and Einstein he used the criterion of beauty consciously and directly as a way of finding truth.

Inevitably, it happened as Dirac grew older that his aesthetic judgment became less sure. He came to Princeton in 1950 when the new quantum electrodynamics of Schwinger and Feynman had achieved spectacular successes in explaining some fine details of experiments in atomic physics. The theories of Schwinger and Feynman were in essence nothing more than clarifications of the quantum theory of radiation invented by Dirac in 1927. Schwinger and Feynman left untouched the basic physical concepts of Dirac and added only new mathematical tricks and techniques of calculation. The new tricks were elegant and gave results confirmed by experiment. I was delighted that these technical advances had increased the power and scope of Dirac's theory. I confidently expected that Dirac would be equally delighted by the new triumphs of his twenty-three-year-old brainchild. I brashly approached Dirac and asked him, "Well, Professor Dirac, what do you think of these new developments in quantum electrodynamics?" He answered my question, as he always answered questions, quietly and precisely: "I might have thought that the new ideas were correct if they had not been so ugly." That was his verdict. There was nothing more to be said. Now, thirty-six years later, it appears that in the matter of quantum electrodynamics Nature disagrees with Dirac's aesthetic judgment and agrees with Schwinger and Feynman. But the last word has not been said. Quantum electrodynamics is not a closed and completed chapter of science. It could still happen, as Dirac surmised, that a wider perspective may ultimately make the tricks of Schwinger and Feynman superfluous.

Dirac's claim for the primacy of aesthetic judgment in physics has acquired a new immediacy in recent years with the advent of superstring theory. Superstrings are enormously popular among theoretical physicists of the younger generation. The quest for mathematical beauty has led the devotees of superstrings to a world of abstraction far removed from mundane experiment. The superstring theory is not merely untested by existing experiments; it does not yet lead to any specific consequences that might be tested by experiment in the future. Faith in superstring theory rests upon an extreme form of Dirac's philosophy. The theory is put forward as a likely foundation for the whole of physics, simply by virtue of its incomparable beauty, and in spite of the fact that it is presently untestable. We must admire the courage and skill of the superstring fraternity, even if we do not share their faith. Perhaps Nature will in the end smile upon their efforts, as she smiled upon Dirac's electron.

Another area of science in which Dirac has been active is cosmology. Here too he was guided by his aesthetic principles rather than by the detailed observations of astronomers. His starting point was the notion that the fundamental laws of nature ought not to contain any arbitrary large numbers. In fact, we find one such large number conspicuously built into our existing physics, namely the ratio between the strengths of electric and gravitational forces. This ratio is a pure number independent of the units of measurement and has a value roughly equal to $10^{39}$. Dirac considered it unacceptable for a number of this size to occur a priori in the basic laws of physics. He remarked that the present age of the universe measured in atomic units of time is a number of the same order of magnitude. Therefore, he said, it makes sense to assume that the two large numbers are equal, that the ratio between electrical and gravitational force is now as large as it is because we are observing it at a correspondingly large number of atomic units of time after the beginning of the universe. Upon this basis Dirac built an unorthodox cosmology. The main features of the Dirac cosmology are that space-time in the large has zero curvature and that the strength of gravitational forces decreases with time. Both these predictions of Dirac's theory are testable, and both are consistent with present-day observations. Within a few years, using precise data obtained from the tracking of planetary spacecraft, the hypothesis of a decreasing strength of gravity should be definitely confirmed or rejected.

I have no space here to enlarge upon Dirac's personal life, his character, his family, and his famous silences. Others who knew him better have written more substantial memoirs of his life. The memoirs abound with "Dirac stories," typically recording a con-
conversation in which Dirac disposed of a large subject with few words. My favorite Dirac story comes from his brother-in-law, Eugene Wigner. Wigner was sitting with Dirac at a lunch table while heated arguments were going on. Dirac sat, as usual, silent. Finally, Wigner addressed him directly: “Well, Paul, everybody would like to hear what you think about this. Why don't you say something?” Dirac replied, “There are always more people wanting to talk than people wanting to listen.”