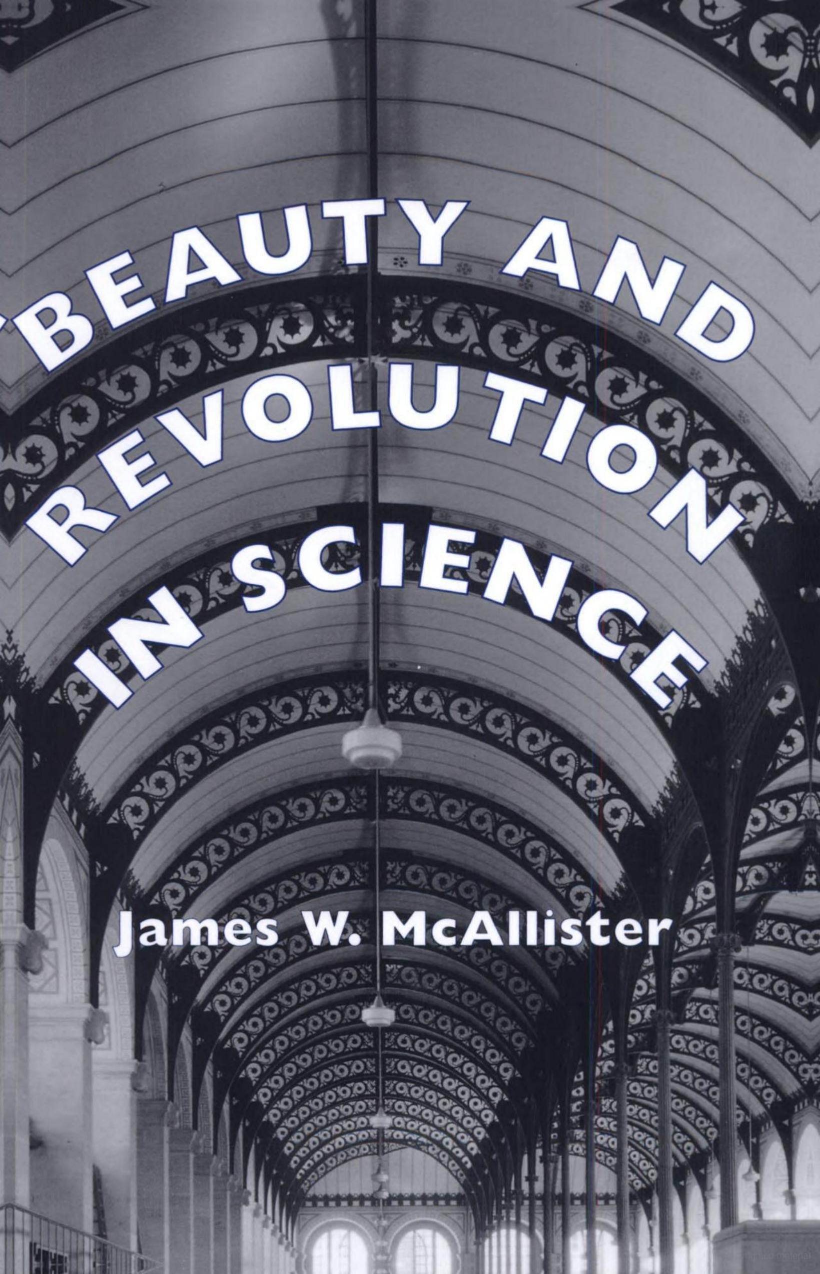
BEAUTY AND
REVOLUTION
IN SCIENCE
James W. McAllister

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J. W. McA.

BEAUTY & REVOLUTION IN SCIENCE

Introduction

Ever since what we know as science first arose, philosophers have striven to describe and understand scientific practice by constructing models of it. Scientific practice shows great variety, however: it takes different forms in different branches of science, historical periods, research schools, and individual scientists. No unified model is yet available that accounts for scientific practice in all this variety. As long as such a model eludes us, the best way to describe and understand scientific practice is to construct various partial models, each of which accounts reasonably well for one or another facet of the subject matter. For this reason, philosophy of science abounds with partial models of scientific practice.

We can conceive of these partial models as arranged on levels corresponding to their breadth of scope. Models on the highest level, such as falsificationism and inductivism, aim to account for the broadest features of scientists' work or the largest-scale developments in the history of science, but are insufficiently articulated to explain more detailed features of scientific practice, such as scientists' resistance to new theories or their recourse to thought experiments. Models on intermediate levels, such as accounts of analogical reasoning, shed light on individual methodological devices but do not presume to describe every instance of theory succession. Models on yet lower levels, which chronicle particular periods in the development of a science, may show excellent accord with historical evidence but do not lend themselves to generalization. At the lowest levels are found items of scientists' autobiography: their occasional reflections about the problems on which they have worked and the approaches that they have used.

The logical relations among these models are intricate. Many of the models occupying the highest level, like falsificationism and inductivism, contradict one another and must therefore be regarded as rivals. Models at the lowest levels may conflict with each other too, but more typically they treat distinct historical episodes and are therefore logically independent of one another. Each of the highest-level models is consistent with some lower-level models and typically with more and more numerous models at lower and lower levels: very many items of scientists' testimony are consistent with falsificationism, for instance. It is therefore possible to arrange a selection of partial models of science into a pyramidal structure containing one top-level model, several medium-level accounts, and many low-level models. A well-formed pyramid of models will offer its user an understanding of features of science on all scales, from the broadest sweep to the smallest detail. Each philosopher of science holds explicitly or implicitly to such a pyramid of models, which provides his or her view of scientific practice. Much of the debate in philosophy of science is occupied with comparing the merits of alternative pyramids of models.

This book is a contribution to what I regard as the most convincing of the pyramids of models about science presently available. The top level of this pyramid is occupied by the model that I shall call "the rationalist image" of science. The rationalist image holds that there exists a set of precepts for investigating and reasoning about the world that have a privileged relationship with reality: the precepts of rationality. The rationalist image commits its adherents to providing rationalist accounts of all features of scientific practice, though of course not to describing all scientists' acts as rational. This book contributes to the pyramid of models headed by the rationalist image by constructing a rationalist model of two features of scientific practice that have so far evaded explanation on rationalist principles: the appeal that scientists make to aesthetic criteria in evaluating their theories, and scientific revolutions.

The model that I present in this book is a medium-level model of scientific practice, of a scope intermediate between the loftiest generalization and the historical case study. Models on this level can match neither the peremptory simplicity of top-level models nor the detail and sensitivity of historical studies of individual episodes. The latter is certainly the more serious limitation, and one that I make no attempt to conceal in the model that I offer. I invite anyone who wishes to obtain the finest-grained picture of particular episodes in the history of science, such as the rise of heliocentrism in astronomy or of quantum theory in physics, to look elsewhere. Here we deal at a somewhat higher level of generality, searching for the elements that are common to classes of historical episodes and accepting the loss of detail that this entails.

The plan is as follows. Chapter 1, "Two Challenges to Rationalism," points out that rationalists have for some decades met difficulty both in explaining why scientists should make such extensive appeal to aesthetic considerations in theory evaluation as they do, and in giving a convincing account of scientific revolutions. The aim of this book is to remedy this deficiency of rationalist accounts of science. Chapter 2, "Abstract Entities and Aesthetic Evaluations," presents the conceptual apparatus that we will employ in this task. Throughout this book, our attention will be directed at the aesthetic properties of scientific theories themselves, which are abstract entities, and not at the properties of representations of theories in concrete form, such as in texts and diagrams. Chapter 2 draws this distinction and conducts a brief polemic against one nonrationalist view of science, the actor-network theory, that neglects the concept of scientific theory in favor of that of inscription. Further, this chapter portrays scientists as holding to aesthetic criteria, each of which attributes aesthetic value to a particular property of theories.

Chapter 3, "The Aesthetic Properties of Scientific Theories," surveys some of the properties of theories to which scientists have attached aesthetic value. I group the aesthetic properties that theories may show into classes: for example, one such class comprises the various symmetry properties that theories can show. This survey provides evidence that scientific communities perform two sorts of evaluations of theories: one is directed at ascertaining the theories' likely empirical performance, whereas the other employs terms of aesthetic appreciation.

What is the relation between evaluations of these two sorts? A spectrum of possible answers can be envisaged, each claiming that aesthetic judgments are reducible to a particular extent to empirical judgments. At one extreme of this spectrum lies the claim that scientists' aesthetic evaluations are disinterested about the empirical virtues of theories, so that scientists' aesthetic and empirical evaluations of theories are independent of one another. If this claim were correct, one would expect to find in the historical record no systematic correlation between the aesthetic and empirical verdicts that scientists have actually passed on theories. At the other extreme of the spectrum is the view that scientists' aesthetic judgments and their empirical judgments are nothing but manifestations or aspects of one another. Two forms of this view may be envisaged: the first portrays aesthetic judgment as an aspect of empirical judgment, while the second reduces empirical judgment to aesthetic judgment. In either case, the aesthetic and empirical verdicts that scientists pass on theories would always necessarily agree.

These extreme views are discussed in Chapter 4, "Two Erroneous Views of Scientists' Aesthetic Judgments." I give reasons, in the form mainly of evidence from scientists' practice, for rejecting each of them as a model of how scientists reach their aesthetic evaluations of theories. In Chapter 5, "The Inductive Construction of Aesthetic Preference," I present a third model as superior. According to this new model, a scientific community's aesthetic preferences are reached by an induction over the empirical track record of theories: a community attaches to each property of theories a degree of aesthetic value proportional to the degree of empirical success of the theories that have exhibited that property. I call this procedure the "aesthetic induction."

On my view, we have no guarantee that there is a correlation between particular aesthetic properties and high degrees of empirical adequacy in theories. Like all policies of inductive projection, however, the aesthetic induction can be expected—provided that it is pursued for long enough—to discern any such correlation that may exist. We examine in Chapter 6, "The Relation of Beauty to Truth," the possibility that the aesthetic induction may discern such a correlation in the course of the history of science. Many twentieth-century scientists, including Albert Einstein, seem to have concluded that such a correlation has already been found, but we shall see that the evidence does not support this conclusion.

Scientists frequently judge theories for the simplicity properties that they exhibit, and philosophers of science have devoted much discussion to this practice. No agreement has so far been reached about the extent to which scientists' simplicity considerations are empirical or aesthetic. In a reexamination of this issue in Chapter 7, "A Study of Simplicity," I suggest that scientists in fact appeal to two separate simplicity criteria: one that attaches value to a particular form of simplicity, and one that (usually) favors theories in which this form is shown to a higher degree. Whereas there may be some justification for the latter criterion on empirical grounds, I suggest that the former is an aesthetic criterion, which is periodically updated by inductive projection. This means that if there is some form of simplicity that is strongly correlated with empirical adequacy, the scientific community is capable of identifying it, provided that science is pursued for long enough.

The aesthetic induction explains how scientists' criteria for theory choice evolve gradually, but it is unable on its own to account for scientific revolutions, in which standards for theory choice change suddenly. Chapter 8, "Revolution as Aesthetic Rupture," shows how the model of scientific practice so far constructed can be extended to describe revolutions. Consider the sequence of empirically successful theories adopted by a scientific community. If each of these theories shows aesthetic properties similar to those of its predecessors, the aesthetic induction will be able to revise the community's aesthetic canon sufficiently promptly that the community's empirical and aesthetic criteria in cases of theory choice will tend to agree. But if theories in the sequence suddenly come to show aesthetic properties that are unprecedented, the aesthetic induction may be unable to revise the aesthetic canon sufficiently quickly to reflect this development. The community's aesthetic criteria will therefore enter into conflict with its empirical criteria. I interpret a scientific revolution as the rupture with an aesthetically defined tradition that empirically minded scientists in such circumstances perform.

Lest my claim that scientists' aesthetic preferences are shaped by utilitarian concerns and through inductive projection should seem implausible, I present in Chapter 9, "Induction and Revolution in the Applied Arts," a view of the formation of styles in the applied arts. Design in the applied arts is constrained both by the technical means available and by the aesthetic canons that are in force. A new material cannot be exploited to the full in structures unless their design responds to its characteristics. But the first designs that exploit a new material in a substantial way frequently strike onlookers as aesthetically unappealing, since the aesthetic canons that predominate at any time are generally tailored to the peculiarities of longer-established technical means. I show that the aesthetic canons by which designs are appraised in the applied arts evolve in response to utilitarian concerns: the community comes to value designs in which technical innovations can be exploited most thoroughly. There are close parallels between this process in the applied arts and the phenomena that we have been discussing in scientific practice. From these parallels I draw two conclusions: first, it does not conflict with our understanding of aesthetic canons in the arts to suggest that scientists' aesthetic preferences are shaped by inductive projection over the perceived empirical performance of their theories; second, aesthetic preferences in practices as different as the sciences and the applied arts are shaped partly by habituation to the forms associated with success.

Chapters 10, "Circles and Ellipses in Astronomy," and 11, "Continuity and Revolution in Twentieth-Century Physics," contain case studies that display the power of this model of scientific practice to account for historical episodes. Two pairs of episodes are discussed: the rise of Copernicus's theory and Kepler's theory in mathematical astronomy, and the rise of relativity theory and quantum theory in physics. Each of these four episodes is frequently portrayed as a revolution, but I shall argue that only the second of each pair should be considered revolutionary.

The final chapter, "Rational Reasons for Aesthetic Choices," returns to the two challenges to the rationalist image of science. We examine anew to what extent scientists' practice of evaluating theories for their aesthetic properties has a rational justification, and to what extent the occurrence of revolutions shows that there is no such thing as scientific rationality. I aim to show that, contrary to the fears of some philosophers and the hopes of others, the rationalist image of science is not undermined by either scientists' appeals to aesthetic considerations or their participation in revolutions.

Two Challenges to Rationalism

One can always make a theory, many theories, to account for known facts, occasionally even to predict new ones. The test is aesthetic.
—George Thomson, *The Inspiration of Science*

1. The Rationalist Image of Science

According to the rationalist image of science, there exists a set of precepts for conducting science—the norms of rationality—which admits of some principled and extrahistorical justification. There is, in other words, a basis for forming and judging decisions and policies in scientific practice that does not depend on convention, fashion, or other local or historical phenomena. A subsidiary claim made by the rationalist image of science is that, while individual decisions and policies of scientists in history may deviate from those that would have been advised on rational grounds, such deviations have not been excessively wide or persistent: actual science is predominantly rational. As many philosophers of science have noted, the rationalist image is a convincing high-level model of scientific practice: it accounts persuasively for much behavior of scientists and for many episodes of the history of science.[1]

In recent decades, however, two bodies of historical evidence have emerged that have led some philosophers and historians of science to question the adequacy of the rationalist image of science. The first of these establishes that the development of science is punctuated by revolutions, events in which a community's norms for the formulation and assessment of theories change radically. The second body of evidence establishes that scientists make substantial and systematic appeal to aes-

1. I regard what I call the rationalist image as the model of science underlying such works as Popper (1959), Lakatos (1970), Laudan (1977), and Newton-Smith (1981).

thetic preferences in judging available theories and in choosing between them. We shall be reviewing this evidence in detail at the appropriate junctures.[2]

These bodies of evidence weigh against the rationalist image in the following manner. Take first the occurrence of revolutions. The model of such events that has so far had the most influence among philosophers and historians, that of Thomas S. Kuhn, claims on some interpretations that revolutions consist of a change of the community's criteria for theory assessment in their entirety: no methodological precept survives a revolution unaltered. This means that there is no set of methodological precepts which retains validity throughout the history of science and therefore that there can exist no canon of rationality. Supporters of this view would regard the phrase "canon of rationality" as, at most, a synonym for "style of reasoning"—a label to be applied to whichever set of basic methodological precepts is obeyed at a particular time in a community.[3] A similar conclusion is reached by many of those who remark on the incidence of aesthetic judgments in science. Most people regard aesthetic preferences as irremediably emotive and idiosyncratic, and consequently presume scientists' aesthetic preferences to be unrelated to empirical adequacy or to any other rationally desirable property of theories. On this view, for scientists to rely on aesthetic criteria in judging theories is irrational. This view of scientists' aesthetic preferences is put forward for instance by Helge Kragh:

> The principle of mathematical beauty, like related aesthetic principles, is problematical. The main problem is that beauty is essentially subjective and hence cannot serve as a commonly defined tool for guiding or evaluating science. It is, to say the least, difficult to justify aesthetic judgment by rational arguments. [. . .] I, at any rate, can see no escape from the conclusion that aesthetic judgment in science is rooted in subjective and social factors. The sense of aesthetic standards is part of the socialization that scientists acquire; but scientists, as well as scientific communities, may have widely different ideas of how to judge the aesthetic merit of a particular theory. No wonder that eminent physicists do not agree on which theories are beautiful and which are ugly.[4]

2. Evidence for believing that the development of science is punctuated by revolutions is surveyed in I. B. Cohen (1985), pp. 40–47. Previous books on aesthetic factors in science are Wechsler (1978), Curtin (1982), Chandrasekhar (1987), Rescher (1990), and Tauber (1996), though only parts of these discuss the role of aesthetic considerations in the evaluation of theories. Alexenberg (1981), pp. 146–202, interviews scientists on aesthetic experiences that they have undergone in their work.

3. Kuhn (1962).

4. Kragh (1990), pp. 287–288.

If this view of scientists' aesthetic preferences is correct, the progression of science, which is no more than the outcome of a sequence of acts of theory choice, is influenced systematically and substantially by irrational factors.

This book aims to defuse the threat posed to the rationalist image of science by these two bodies of historical evidence. I shall try to show that both the evidence of the occurrence of revolutions and the evidence of scientists' appeal to aesthetic considerations are consistent with the rationalist image. The intended outcome of my treatment is a rationalist view of science that allows us to accept both that scientific method has undergone radical and sudden transformations, and that aesthetic considerations are among the grounds on which scientific communities choose between competing theories.

On the account that I shall offer, these two phenomena of science are closely interrelated. Indeed, the occurrence of scientific revolutions is a consequence of scientists' use of aesthetic criteria for theory evaluation. If this is so, the key to a rationalist understanding of scientific revolutions lies in scientists' aesthetic preferences. The bulk of the book will thus be devoted to this second topic: we shall return to revolutions in Chapter 8.

2. A Rationalist Model of Theory Evaluation

The component of the rationalist image brought most directly into question by the historical evidence about the occurrence of revolutions and the incidence of aesthetic judgments is its account of scientists' evaluations of their theories. We should therefore begin our defense of the rationalist image by recalling how rationalists view the practice of theory assessment in science. There are of course several alternative models of this practice that a rationalist may advance: here I pick one that has been set out by W. H. Newton-Smith, and which I shall call the "logico-empirical model" of theory assessment.[5]

This model is based on the following premises. Science's ultimate goal is the production of the most complete and accurate account possible of the universe. Theories approximate to this ideal to the degree to which they possess the property "empirical adequacy." The statement that a theory has empirical adequacy to the highest degree possible means that its claims are true of all observable phenomena, including phenomena in the past and phenomena in other ways inaccessible to us; the statement that a theory has empirical adequacy to a somewhat lesser degree means

5. Newton-Smith (1981), pp. 208–236.

that its claims are true of a similar proportion of observable phenomena. Scientific realists, who would say that the ultimate goal of science is the production of an account of the universe that is true, can nonetheless concur with this analysis, since they see the degree of empirical adequacy of a theory as a consequence of its being to a corresponding degree close to the truth.[6]

It might initially seem that the only criterion for theory assessment that the logico-empirical model need recommend is a criterion of empirical adequacy itself: "Prefer a theory that has a higher degree of empirical adequacy to one that has a lower degree of it." However, the meaning of "empirical adequacy" makes it impossible to use this criterion in practical choices among theories. The only way in which we could establish that a theory possesses empirical adequacy to the highest degree possible would be to demonstrate that it accords with all empirical data that could be gathered from all sources over unlimited time spans; similarly, we could establish that a theory has a particular lesser degree of empirical adequacy only by showing that it accords with a corresponding proportion of those data. Obtaining a direct reading of the degree of a theory's empirical adequacy would therefore involve ascertaining the proportion of all empirical data with which the theory accords. But, even if the notion of counting and comparing the number of the confirmed and disconfirmed predictions of a theory could be made precise, such a task cannot be completed in a finite time for generalizations of wide scope other than tautologies or contradictions. Thus, the criterion of empirical adequacy itself does not provide a practical basis for choosing among competing theories.[7]

We can, however, identify other criteria that are diagnostic of high degrees of empirical adequacy in theories and that yield their verdicts quickly enough to be useful in theory evaluation. We may construct a set of such criteria by considering what properties a theory must possess if it is to have a high degree of empirical adequacy: it should exhibit accord with a high proportion of the phenomena investigated hitherto and show some promise of according with a high proportion of phenomena not yet studied. On this basis, the logico-empirical model prescribes criteria such as the following:

1. The criterion of consistency with extant empirical data: other cir-

6. For the agreement of both instrumentalists and scientific realists with the claim that science aims at theories that have empirical adequacy to high degree, see van Fraassen (1980), p. 12, and Churchland (1985), pp. 38–39.

7. I have investigated these consequences of the meaning of "empirical adequacy" for theory assessment in McAllister (1993).

cumstances being equal, a theory should be more highly valued if its implications agree with what is now known of phenomena.

2. The criterion of novel prediction: a theory should further be valued if it offers predictions of, and subsequently accords with, data that were not available when the theory was formulated, or at least that were not taken into account in its formulation. After all, if the sole empirical requirement of theories were that they should accord with data gathered previously, a theory constructed deliberately to account for available data would have to be given a high score; and it is possible in any circumstance to construct infinitely many such theories.

3. The criterion of consistency with current well-corroborated theories: a new theory should be more highly valued if, other circumstances being equal, it coheres with other theories that received high scores on the previous criteria. As a supporter of scientific realism would argue, a set of true theories about the world would all be consistent with one another; so, if we now have any theories that we think are close to the truth, we should wish any new theory that we adopt to be consistent with them.

4. The criterion of explanatory power: while a new theory is minimally required not to contradict well-established theories, it should be more strongly valued if it can provide an explanation of the generalizations that they contain. Such an attainment suggests that the theory has identified a pattern or mechanism underlying the data, and it offers a prospect that the theory will accord with sets of data yet to be gathered.

An addition to this list of criteria is made necessary by the following consideration. If all that we wanted from science were theories that are logically compatible with data, we would be satisfied with theories that are tautologies and logical contradictions. After all, there is no logically possible state of affairs that a tautology rules out, and any prediction whatever can be derived from a contradiction. But such statements cannot be regarded as having high degrees of empirical adequacy, as their predictions are not determinate: they do not allow us to distinguish the universe that we inhabit from all other logically possible universes. In order to prevent our empirical criteria for theory choice from leading us to embrace tautologies and contradictions, the logico-empirical model must add to the above list two further criteria:

5. The criterion of empirical content: theories must not be tautologies.

6. The criterion of internal consistency: theories must not contain internal contradictions.

The logico-empirical model of theory assessment has the task of accounting on rationalist principles for scientists' preferences among theories. It discharges this task well: very many choices among theories that scientists perform can be explained by supposing that they are decided on criteria such as the six listed above. The logico-empirical model of theory assessment is thus a valuable extension of the rationalist image of science.

This model fails, however, to provide the rationalist image with a satisfactory response to the two bodies of historical evidence whose challenge we are examining. Consider first the evidence that science undergoes revolutions. How can the logico-empirical model account for this fact? The logico-empirical model's six criteria for theory assessment listed above are derived exclusively from an analysis of "empirical adequacy." Therefore, if these criteria are valid, they must be valid at all times, unless the goal of science changes. This ensures that the logico-empirical model has no resources to explain how a scientist at one time can hold to criteria for theory assessment different from those of scientists of any other time. But scientific revolutions are episodes in which scientists' criteria for theory assessment change: so the logico-empirical model is incapable of explaining revolutions.

Similarly, the logico-empirical model is unable to make sense of the evidence that scientists appeal to aesthetic criteria in deciding among theories. Being couched entirely in terms of logical and empirical concerns, it lacks the apparatus to analyze aesthetic preferences. If the aesthetic predispositions of scientists are as idiosyncratic and irreducible to rational deliberation as many suppose them to be, then theory succession could hardly follow the path that the logico-empirical model prescribes.

I conclude that the logico-empirical model of theory assessment is not sufficiently sophisticated to account for the evidence of either the occurrence of revolutions or the incidence of aesthetic considerations in theory choice. Of course, it is open to the logico-empirical model to dismiss aspects of scientific practice by calling them irrational; but this option amounts to declaring parts of scientific practice inexplicable, to which rationalists should resort only in localized and exceptional cases. The rationalist image can meet the challenge posed by the evidence of the occurrence of revolutions and the incidence of aesthetic considerations in theory choice, but only if provided with a richer model of scientists' preferences among theories.

3. Aesthetic Factors in Discovery and Justification

In this section and the next, we examine two past attempts made by rationalists to dismiss the evidence of scientists' use of aesthetic criteria in theory choice. If either of these attempts had succeeded, rationalism would not be troubled by the need to account for scientists' aesthetic preferences among theories. Unfortunately, for reasons that will become clear, both fail.

The first attempt was made by logical positivism, a brand of rationalism that rose to prominence in the 1920s and long remained influential. Logical positivists advanced the thesis that a scientist working on a theory successively enters two "contexts." First is the "context of discovery," in which the scientist originates the theory by means of intuitions or conjectures. These acts are not guided by precepts of logic or rationality and therefore cannot be analyzed within a rationalist framework: there can be no logic of scientific discovery but only a psychology of it. Thereafter the scientist enters the "context of justification," in which he or she tests the theories that have been originated in the context of discovery. This testing occurs on logical and empirical criteria, and assures the rationality of theory succession.[8]

Logical positivists conceded that aesthetic factors could affect a scientist's behavior in the context of discovery, since they thought that a scientist could be inspired to formulate a hypothesis by a stimulus of any sort. But they rejected the suggestion that aesthetic factors played any part in the context of justification, presumably because they could conceive of no way in which aesthetic criteria could be assimilated to logical or empirical criteria. This attitude toward aesthetic factors in science is expressed by Herbert Feigl:

> A few words on some misinterpretations stemming from predominant concern with the history and especially the *psychology* of scientific knowledge. In the commendable (but possibly utopian) endeavor to bring the "two cultures" closer together (or to bridge the "cleavage in our culture") the more tender-minded thinkers have stressed how much the sciences and the arts have in common. The "bridges" [. . .] are passable only in regard to the *psychological* aspects of scientific [. . .] creation [. . .]. Certainly, there are esthetic aspects of science [. . .]. But [. . .] what is primary in the appraisal of scientific knowledge claims is (at best) secondary in the evaluation of works of art—and vice versa.[9]

According to logical positivism, therefore, there exists no such phenomenon as scientists' aesthetic evaluation of their theories and therefore no such phenomenon that need trouble philosophers of science. It is possi-

8. The origin and reception of the distinction between contexts of discovery and of justification are studied by Hoyningen-Huene (1987).

9. Feigl (1970), pp. 9–10.

ble that scientists are affected by aesthetic factors in discovery, but drawing up an account of that phenomenon would be a task for biographers and psychologists of scientists rather than for philosophers of science.

Logical positivism has generally been superseded within philosophy of science, but it still overshadows the discussion of the role of aesthetic factors in science. The view persists that whereas aesthetic factors may be important in the creation of a theory, only empirical criteria can play a role in its acceptance. For example, Dean K. Simonton writes: "No scientist, including Dirac, would ever be so bold as to justify a theory on so irrational a basis as 'beauty.' "[10]

Logical positivists were undoubtedly correct in reporting an incidence of aesthetic considerations in the context of discovery: it frequently happens that a scientist picks the theories on which he or she will work in part on the strength of their aesthetic properties.[11] But in denying that aesthetic considerations play a part in scientists' assessments of theories, logical positivists neglected two facts. First, it is possible to regard intellectual creations of many kinds, ranging from mathematical proofs to chess games, as works of art. When we consider intellectual creations in this manner, we are led to appraise them for their aesthetic properties, and this aesthetic appraisal affects our overall view of and regard for them. It would be unusual if scientists were not tempted sometimes to regard scientific theories as works of art and to allow their overall view of them to be affected by aesthetic judgment. Of course, scientists frequently do surrender to both temptations. Ernest Rutherford, speaking in 1932, offers an example of this tendency:

> I think that a strong claim can be made that the process of scientific discovery may be regarded as a form of art. This is best seen in the theoretical aspects of Physical Science. The mathematical theorist builds up on certain assumptions and according to well understood logical rules, step by step, a stately edifice, while his imaginative power brings out clearly the hidden relations between its parts. A well constructed theory is in some respects undoubtedly an artistic production. A fine example is the famous Kinetic Theory of Maxwell. [. . .] The theory of relativity by Einstein, quite apart from any question of its validity, cannot but be regarded as a magnificent work of art.[12]

10. Simonton (1988), p. 193. For another recent denial that aesthetic factors play an important role in theory justification, see Engler (1990), p. 31.

11. Some comments on the heuristic role of aesthetic factors in science are to be found in Mamchur (1987).

12. Quoted from Badash (1987), p. 352. A discussion of the incidence of aesthetic factors in both the pursuit and the justification of theories is given by Chandrasekhar (1989).

Second, logical positivists omitted to recognize that scientists in their own work do not distinguish sharply between a context of discovery and one of justification. In most cases, the factors that lead a scientist to formulate a theory having certain properties also play a role in shaping the community's opinion about that theory's worth. In particular, it appears that scientists appeal to aesthetic factors both in their efforts to originate hypotheses and in their evaluations of theories that have been proposed in their community. By dismissing scientists' aesthetic evaluations of their theories as unimportant, logical positivists fail to render justice to this aspect of scientific practice.

The discrepancy between scientists' actual uses of aesthetic considerations and the logical positivist account of them is revealed by the writings of P. A. M. Dirac. In his many reflections on the role of aesthetic factors in his own work and in scientific practice generally, Dirac stressed their influence both as heuristic guides and as grounds for theory evaluation. First, as he admitted, Dirac used aesthetic criteria to decide priorities in his own research.[13] He thought that many of his colleagues worked in the same way. For instance:

> When Einstein was working on building up his theory of gravitation he was not trying to account for some results of observations. Far from it. His entire procedure was to search for a beautiful theory [. . .]. Somehow he got the idea of connecting gravitation with the curvature of space. He was able to develop a mathematical scheme incorporating this idea. He was guided only by consideration of the beauty of these equations. [. . .] The result of such a procedure is a theory of great simplicity and elegance in its basic ideas.[14]

Second, Dirac relied on aesthetic criteria also in assessing theories. "Context of discovery" and "context of justification" merge indissolubly in such statements as the following: "It is more important to have beauty in one's equations than to have them fit experiment. [. . .] It seems that if one is working from the point of view of getting beauty in one's equations, and if one has really a sound insight, one is on a sure line of progress."[15] As Richard H. Dalitz recalls, in Moscow in 1955, "When asked

13. Dirac discusses his use of the aesthetic properties of mathematical expressions as heuristic guides in Dirac (1982a). Krisch (1987), p. 51, reports: "Dirac stated that, '. . . the elegance of the formulation was very important in choosing the direction for one's research.' "

14. Dirac (1980a), p. 44. Chandrasekhar (1988), pp. 52–55, expresses doubts that in his search for a theory of gravitation Einstein was motivated by aesthetic factors to the extent to which Dirac supposes.

15. Dirac (1963), p. 47.

to write briefly his philosophy of physics, he wrote on the blackboard 'PHYSICAL LAWS SHOULD HAVE MATHEMATICAL BEAUTY'."[16] It was at least in part on such a criterion that Dirac extended support to the theory of general relativity: "The foundations of the theory are, I believe, stronger than what one could get simply from the support of experimental evidence. The real foundations come from the great beauty of the theory. [. . .] It is the essential beauty of the theory which I feel is the real reason for believing in it."[17]

Thus, while logical positivists admit that aesthetic factors may play a part in the context of discovery but deny that they have any incidence in the context of justification, Dirac believes that the procedures typical of both stages make recourse to aesthetic considerations. If we wish to account for behavior such as that which Dirac notes, we will require a view of science more richly articulated than that of the logical positivists.

4. The Boundaries of Scientific Behavior

The second attempt that has been made by rationalists to dismiss the problem posed by scientists' aesthetic evaluation of theories is more subtle. Some authors admit that whereas aesthetic criteria are sometimes used by scientists in evaluating theories, this behavior is not scientific and thus does not enter the scope of descriptions of scientific practice.

Logical positivists defined scientific behavior so narrowly as to equate it with empiricist behavior. On their view, the task of scientists is to collect, process, summarize, and explain empirical data: all other actions are nonscientific and are induced by influences acting on science from without. For instance, Philipp Frank in the 1950s drew a distinction between two sets of criteria for theory evaluation, which he termed the "scientific" and the "extrascientific." The scientific criteria are agreement with observations and logical consistency: criteria of all other sorts are extrascientific.[18] On this view, any nonempirical concern that scientists may have is an external influence, perturbing science from its proper course. Since Frank would allocate aesthetic factors to the category of extrascientific criteria, he would maintain that they need not be considered in an account of scientific practice.

While few authors define scientific behavior as narrowly as the logical positivists, many continue to believe that whereas evaluating theories

16. Dalitz (1987), p. 20.
17. Dirac (1980b), p. 10.
18. Frank (1957), p. 359.

on the basis of empirical criteria pertains to science, appeals to aesthetic considerations do not. This belief is often expressed in the claim that scientists resort to aesthetic criteria only as tiebreakers, when they must choose among theories that empirical criteria have shown to be equally worthy. This claim is put forward by Fritz Rohrlich: "There is [. . .] great beauty in a physical theory. [. . .] It is that beauty which affects the credibility of one theory over another in the absence of more stringent criteria. For instance, the general theory of relativity is so beautiful that it is preferred over rival theories as long as those rival theories cannot account any better for the empirical facts."[19] This passage implies that aesthetic considerations would cease to carry weight if it were discovered that relativity theory accounts for the empirical facts any better or worse than its rivals. This view amounts to a denial of importance to aesthetic criteria: it allows them onto the scene only in cases where a scientist has ascertained, on empirical criteria, that they will have no consequence.

In reality, as we shall see, far from being wheeled up only when empirical criteria have shown the theories on offer to be equally worthy, aesthetic preferences often overrule the standard empirical criteria in scientists' choices among theories. The situation is therefore not that aesthetic criteria are applied once scientists have ascertained, on empirical standards for the acceptability of theories, which theories they may accept; rather, aesthetic and empirical criteria jointly determine scientists' standards for the acceptability of theories. Historical studies confirm that aesthetic considerations play a role in these decisions.[20]

The aesthetic factors of which we shall construct a model should therefore be considered as fully distinctive of science as scientists' logical or empirical concerns. This does not mean, of course, that no useful distinction can be drawn between scientists' empirical and aesthetic considerations; but it does mean that the distinctions we draw between them cannot be portrayed as a demarcation between the scientific and the extrascientific.

5. A Precursor: Hutcheson's Account of Beauty in Science

The reluctance of philosophers in the twentieth century to attribute roles of much importance to aesthetic judgments in scientific practice may be due partly to the lack of influential accounts of intellectual beauty in

19. Rohrlich (1987), pp. 13–14. For a similar opinion, see Osborne (1986a), p. 12.

20. For instance, Jacquette (1990) shows that Newton's view of what counts as a satisfactory law of nature was based partly on aesthetic considerations.

recent philosophy. Twentieth-century aesthetic theory, which has taken as its central concerns the beauty of artworks and of nature, has paid little attention to the beauty of intellectual constructs. Harold Osborne noted in 1964: "Nowadays the concept of intellectual beauty is not, I believe, commonly repudiated so much as neglected; few of the standard works on aesthetics pay more than lip-service to it and I know of none which has either attempted a deep analysis or given to it equal weight with sensory beauties in the framing of general aesthetic concepts."[21] However, the study of intellectual beauty has fallen into disregard only relatively recently: in eighteenth-century aesthetic theory, for instance, it held an important place. We will begin our investigation of scientists' aesthetic judgments by reviewing one of the most sophisticated eighteenth-century theorists of intellectual beauty, Francis Hutcheson. His views are relevant to our purposes since he explicitly extends his treatment to scientific theories, asserting that theories showing particular properties are to be regarded as beautiful.

Hutcheson's account of the beauty of intellectual constructs follows directly from his more general aesthetic theory. Hutcheson endorses an epistemological tenet that was popular in his time, that the qualities of objects are distinct from, and in fact the causes of, "ideas," which are the only immediate materials of sensory awareness. Beauty is such an idea, occasioned in the mind by particular qualities of external objects. As Hutcheson writes, "the word *beauty* is taken for *the idea raised in us*, and a *sense* of beauty for *our power of receiving this idea*."[22] Hutcheson therefore understands "beauty" not as a property of objects but as the response of an observer's aesthetic perception to qualities of objects:

> Let it be observed that by absolute or original beauty is not understood any quality supposed to be in the object which should of itself be beautiful, without relation to any mind which perceives it. For beauty, like other names of sensible ideas, properly denotes the *perception* of some mind; so *cold, hot, sweet, bitter,* denote the sensations in our minds, to which perhaps there is no resemblance in the objects which excite these ideas in us, however we generally imagine otherwise.[23]

Having specified what kind of thing beauty is, Hutcheson turns to investigate which properties of objects cause the occurrence of ideas of beauty in the mind. "Since it is certain," he writes, "that we have *ideas* of

21. Osborne (1964), p. 160.
22. Hutcheson (1725), p. 34. For commentary, see Kivy (1976), pp. 57–60.
23. Hutcheson (1725), pp. 38–39.

beauty and harmony, let us examine what *quality* in objects excites these ideas, or is the occasion of them."[24] Hutcheson quickly reaches a conclusion: "The figures which excite in us the ideas of beauty seem to be those in which there is *uniformity amidst variety*. [. . .] What we call beautiful in objects, to speak in the mathematical style, seems to be in compound ratio of uniformity and variety: so that where the uniformity of bodies is equal, the beauty is as the variety; and where the variety is equal, the beauty is as the uniformity."[25] The property of "uniformity amidst variety" can be found in scenes in nature and works of art, but also in intellectual constructs: the latter are as capable of raising in us ideas of beauty as are concrete objects.

Hutcheson believes that in the practice of science we obtain special opportunities to perceive uniformity amidst variety and therefore to conceive ideas of beauty. The objects in which the scientist perceives uniformity amidst variety are located on three levels of increasing abstraction.

Objects on the lowest level are the entities and phenomena that constitute the subject matter of science. For instance, stars are arranged in the night sky with a high degree of uniformity amidst variety, and thereby give rise to ideas of beauty in observers. In order to derive a sense of beauty from these entities, ordinary observation of them is sufficient: no particular scientific theory or expertise is required, any more than it would be in order to come to see a landscape as beautiful.[26] Today the beauty of objects on Hutcheson's first level is recognized by astronomers who find beauty in views of celestial bodies and by chemists who speak of beautiful molecules.[27]

The objects on Hutcheson's second level of abstraction are natural regularities which are not directly to be seen in the phenomena but become apparent in the models or accounts put forward by theories. Although these regularities are endowed with uniformity amidst variety and can therefore raise in us ideas of beauty, they are apt to be perceived and therefore appreciated as beautiful only by observers who have some command of scientific theory. For instance, the astronomer sees into celestial motions more regularities than are apparent to the casual observer of the night sky. Isaac Newton's theory in celestial mechanics—which greatly impressed Hutcheson as well as most other eighteenth-century British empiricists—reveals regularities in the relations between such

24. Ibid., p. 39.
25. Ibid., p. 40.
26. Ibid., pp. 41–42.
27. Lynch and Edgerton (1988) discuss the aesthetic features of images of celestial bodies; Hoffmann (1990) surveys the properties of molecules that chemists regard as beautiful.

of music itself: this is how we may come to see it as a fugue or as atonal, perhaps. Clearly, for this procedure to deliver accurate knowledge of the abstract entity, some properties of the rendition must stand in some specified relation to some properties of the abstract entity. Those who advance this response to the puzzle say that if we are to be able to apprehend properties of the abstract entity, they must be transposed into the rendition.[9]

On the model of this response, we could argue that we are able to apprehend some of the properties of a scientific theory upon perceiving some other properties in a representation of the theory in a concrete entity. Some of the properties of a representation of a theory in the form of a text are proper to the representation: the text might be in French, for instance. But some properties of a faithful representation will be owed to the mathematical structure, the logical parsimony, or other properties of the theory, that show through in the rendering. While our apprehension of these properties occurs via the rendering, they may legitimately be retraced to the theory.

A different possible response to the puzzle is the following. What we have been calling the representation of an abstract entity such as a scientific theory should be regarded not as a depiction of the entity but as an algorithm for creating a mental replica of it: consulting a representation of an abstract entity enables me to replicate it in my mind. A person's knowledge of the properties of an abstract entity is thus gained by examining a mental replica of it rather than the concrete representation. For an algorithm to yield a certain product, it is not required that the properties of the algorithm resemble those of the product: consequently, this response does not commit us to claiming that the properties of theories are transposed into concrete representations of them.

4. Aesthetic Values, Properties, and Evaluations

In order to understand scientists' practice of evaluating scientific theories on aesthetic grounds, we need a working conception about what it is for an observer to pass an aesthetic judgment on an object. Analysis of such an act is the task of aesthetic theory. In this section, we draw from present-day aesthetic theory a conceptual apparatus for use in our investigation.

When we make an aesthetic appreciation of an object, we refer to enti-

9. The transposition of aesthetic properties is discussed by Wollheim (1968), pp. 74–84.

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