

## DIRAC AND THE AESTHETIC EVALUATION OF THEORIES

by

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### § 1. Introduction

In 1963 an article by P.A.M. Dirac appeared in *Scientific American* which commented upon the role of aesthetic factors in scientific practice.<sup>1</sup> The article suggests that aesthetic factors are important not only in directing the line of scientists' research, but also in permitting the evaluation of the theories formulated by that work according to the degree of their aesthetic worth. That these two roles of aesthetic factors were for Dirac indissolubly linked is shown by his treatment. He makes it clear, for instance, that the strategy of choosing those theories for pursuit which afforded aesthetic satisfaction is for him inseparable from the subsequent practice of evaluating theories in part upon their possession of aesthetic qualities:

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.<sup>2</sup>

Passages of Dirac's article are frequently cited in discussions of scientific methodology.<sup>3</sup> Many authors, however, reproduce the text only to cast

<sup>1</sup> An account of Dirac's life and work is offered in Dalitz and Peierls, 1986. Reminiscences of and comments on Dirac's work appear in Kursunoglu and Wigner Eds., 1987, and in J.G. Taylor Ed., 1987.

<sup>2</sup> Dirac, 1963, p. 47.

<sup>3</sup> Passages from Dirac, 1963, are quoted in e.g. Osborne, pp. 160-1, 1964 and p. 292, 1984, Holton, pp. 255-6, 1973, Wechsler, p. 5, 1978, Barrow, p. 350, 1988a, and Simonton, pp. 192-3, 1988.

doubt on its cogency, and in particular to deny the unity which Dirac asserted between the heuristic and the evaluative functions of aesthetic factors in science. While many writers, as we shall see, are quite happy to admit that scientific research may be spurred and guided partly by aesthetic concerns, they dismiss Dirac's suggestion that aesthetic factors can be of use too in the evaluation of theories. For instance, J.D. Barrow questions whether any sense can be discerned in Dirac's views on this matter:

Is Dirac saying anything sensible about aesthetics when he argues that it is of paramount importance to have 'beauty' in one's equations, or is he merely revealing a rather limited personal experience and appreciation of things other than equations?<sup>4</sup>

D.K. Simonton, for his part, seems to rule out that, whatever Dirac wrote about the topic, he could ever have applied his own injunctions and subjected a theory to an aesthetic evaluation: 'No scientist, including Dirac, would ever be so bold as to justify a theory on so irrational a basis as "beauty".'<sup>5</sup> There appears abroad, in short, some reluctance to assign sensible content to an important part of Dirac's methodological writings.

This paper argues that Dirac's views on the evaluative use of aesthetic criteria are on the contrary cogent and well-founded, and carry considerable interest for the philosopher of science. As a preliminary, §2 ascribes the tendency to dismiss Dirac's methodological pronouncements to the influence of logical positivism. §3 reconstructs Dirac's views about the importance of aesthetic factors both as heuristic guides to research and as evaluative criteria; in §§4 and 5 arguments are set out which might have led Dirac to embrace the beliefs which he professed, and evidence from his writings is adduced to suggest that he indeed reasoned along those lines. The paper closes with a brief examination of some methodological implications of Dirac's views.

## § 2. *The positivist treatment of aesthetic factors in science*

Positivism established a demarcation between two contexts which, it was alleged, the scientist's work traverses: an arational 'context of discovery' in which theory-generation occurs by enigmatic intuitions or conjectures, and

<sup>4</sup> Barrow, p. 1, 392, 1988b, Barrow further comments on Dirac's views on aesthetic criteria in science in his, pp. 345-52, 1988a.

<sup>5</sup> Simonton, p. 193, 1988.

a 'context of justification' where inference from empirical data tests the products of the former stage and assures the rationality of theory-succession.<sup>6</sup> The distinction was voiced by, for instance, R.S. Rudner:

In general, the context of validation is the context of our concern when, regardless of how we have come to discover or entertain a scientific hypothesis or theory, we raise questions about accepting or rejecting it. To the context of discovery, on the other hand, belong such questions as how, in fact, one comes to latch on to good hypotheses, or what social, psychological, political, or economic conditions will conduce to thinking up fruitful hypotheses.<sup>7</sup>

Those who introduced the distinction between the context of discovery and that of justification believed that philosophy consisted chiefly of the study of logical relationships between propositions; in consequence, they thought that all philosophical analysis of science ought to be directed at processes of justification, and none to strategies of discovery.<sup>8</sup> K.R. Popper advocates both the distinction between contexts of discovery and of justification and the positivist allotment of philosophical interest to the latter term exclusively. Under the characteristic heading *Elimination of Psychologism* he writes:

The initial stage, the act of conceiving or inventing a theory, seems to me neither to call for logical analysis nor to be susceptible of it. [ . . . ] There is no such thing as a logical method of having new ideas, or a logical reconstruction of this process. My view may be expressed by saying that every discovery contains 'an irrational element', or 'a creative intuition', in Bergson's sense.<sup>9</sup>

It is through statements of preference of this form that positivism dismisses from rational attention the province of scientific discovery.

The aesthetic factors which operate in science are by most people intuitively perceived as non-quantitative, non-empirical, imprecise and arational, of the same species as the 'psychological conditions' of scientific thought of which Rudner speaks or the 'creative intuitions' of Popper. Acting on this conviction, positivist philosophy of science first consigns scientists' aesthetic references to the context of discovery, and secondly presumes that as a consequence they are not susceptible to rational analysis.<sup>10</sup>

<sup>6</sup> This distinction originated with Reichenbach, pp. 6-7, 1938, though it was foreshadowed in certain aspects by Herschel, p. 164, 1830. The history of the distinction and of criticism of it is retraced by Hoyningen-Huene, 1987.

<sup>7</sup> Rudner, p. 6, 1966. The author's term 'validation' is a synonym of 'justification'.

<sup>8</sup> The differential allocation of interest was first endorsed by the originator of the modern version of the discovery/justification distinction, Reichenbach, p. 289, 1949: "The philosopher of science is not much interested in the thought processes which lead to discovery."

<sup>9</sup> Popper, pp. 31-2, 1959.

<sup>10</sup> Thus for instance Popper states that a consideration of elegance "has little interest from the point of view of the theory of knowledge: it does not fall within the province of logic, but merely indicates a

One of the most comprehensive illustrations of the positivist attitude towards aesthetic factors in science is offered by H. Feigl, who endorses the denial in three stages of their philosophical interest. He first distinguishes between studies of discovery and of validation:

The distinction [. . .] between the *historicosociological* narratives, analyses, causal accounts of the origins, developments, conflicts, and *Zeitgeists* of scientific ideas on the one hand, and the *logico-methodological* reconstructions of scientific knowledge claims, on the other hand [. . .], remains (and, as I see it, *should* remain) at least a most important first approximation if we are to retain even a minimum of clear thinking in these badly confused matters.<sup>11</sup>

He initially betrays no preference among the modes of inquiry delineated in this passage, but soon there remains no doubt which he believes holds interest for the philosopher:

Consider, just as prime examples, the writings of Galileo and Newton. Their formulations usually came 'after the fact' of their discoveries—experimental or theoretical. This is prototypical of all *good* philosophy of science. In Newton's formulation of his assumptions (postulates), definitions (explications), and *regulae philosophandi* (precepts), we find one of the truly great masters giving us a rational reconstruction of his theoretical achievements.<sup>12</sup>

Having characterized what he understands as 'good philosophy of science', Feigl excludes from its domain the study of aesthetic factors, confining their operation to the context of discovery where philosophy has no jurisdiction:

A few words on some misinterpretations stemming from predominant concern with the history and especially the *psychology* of scientific knowledge. In the commendable (but possible 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.<sup>13</sup>

According to the positivist, then, the sole merit one may ascribe to aesthetic intuitions is that of having a valuable heuristic role in the arational process of theory-generation: they are barred from playing a part in theory-evaluation.

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preference of an *aesthetic or pragmatic* character" *ibid.*, p. 137; emphasis in the original.

<sup>11</sup> Feigl, p. 4, 1970, emphasis in the original. After a so emphatic endorsement of one of the main tenets of logical positivism it is surprising a few pages on to read an abjuration: "I personally abandoned, long ago, whatever adherence I had to positivistic [. . .] philosophies of science", *ibid.*, p. 7.

<sup>12</sup> *Ibid.*, p. 6; emphasis in the original.

<sup>13</sup> *Ibid.*, pp. 9-10; emphasis in the original.

It is most plausibly on the basis of this image of science that some commentators are moved to dismiss Dirac's insistence that one should allot an evaluative role to aesthetic criteria. Dirac's remarks, however, are conceived from without the positivist view of science.

### § 3. The scope of operation of aesthetic criteria

A component of the positivists' view about aesthetic factors in scientific methodology is the thesis that such factors operate only as heuristic guides to research, in what they would term the 'context of discovery', and not as criteria of theory-evaluation in the context of justification.

The positivists are undoubtedly correct in reporting an incidence of aesthetic considerations in the context of discovery: it transpires from historiography that scientists' decisions to expend work on the development of a particular theory are frequently taken in part on the strength of that theory's aesthetic features.<sup>14</sup>

Dirac for one admitted turning to aesthetic criteria in determining priorities for his own research.<sup>15</sup> He believed also that some scientists among his contemporaries relied in part on aesthetic criteria in determining where best to apply their efforts, and he recounts two episodes in which he believes decisions to pursue a certain line of research were taken on the strength of the aesthetic rather than of the empirical merits of the theories concerned.

The first episode took place during Einstein's development of the general theory of relativity:

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.<sup>16</sup>

The second episode in which, as Dirac believes, aesthetic considerations took a hand in determining the direction of research unfolded during the

<sup>14</sup> Comments on the heuristic role of aesthetic factors may be found in Mamchur, 1987.

<sup>15</sup> As Krusch p. 51, 1987 reports, 'Dirac stated that, ". . . the elegance of the formulation was very important in choosing the direction for one's research.'" Dirac speaks further of the heuristic role of the beauty of mathematical expressions in his 1982a.

<sup>16</sup> Dirac, p. 44, 1980a, Chandrasekhar, pp. 52-5, 1988, expresses doubts that in his search for a theory of gravitation Einstein was motivated by aesthetic factors to the extent to which Dirac supposes.

development of quantum mechanics in the years after 1925. In the following passage Dirac contrasts the style of work of E. Schrödinger with that of W. Heisenberg, who a short time previously had enunciated a matrix formulation of the theory:

Heisenberg worked keeping close to the experimental evidence about spectra [ . . . ]. Schrödinger worked from a more mathematical point of view, trying to find a beautiful theory for describing atomic events [ . . . ]. He was able to extend De Broglie's ideas and to get a very beautiful equation, known as Schrödinger's wave equation, for describing atomic processes. Schrödinger got this equation by pure thought, looking for some beautiful generalization of De Broglie's ideas, and not by keeping close to the experimental development of the subject in the way Heisenberg did.<sup>17</sup>

These two historiographic accounts lend themselves easily to incorporation into the positivist view of science. After all, it is a tenet of the positivist view of methodology that scientists are both liable and entitled to draw upon sources of arational inspiration in their effort to generate hypotheses later to be tested by empirical means. Dirac's narratives above may be interpreted as accounts of cases in which the arational mental processes of scientists engaged in hypothesis-generation were prompted or inspired by aesthetic imagery rather than by any other particular psychological *motif*.

However, Dirac's image of science enters into conflict with the positivist model when he turns to discuss the good-making requirements of theories. Positivists hold firm views about which criteria ought to be employed in theory-evaluation: they believe that the merits attributed to a theory ought to depend exclusively upon its relationship with empirical data, and hence that the sole evaluative criteria admissible in science are logical-empirical. On this view, a theory will be judged on its internal consistency, the accuracy of its predictions, the breadth of its explanatory scope, and perhaps on certain other similar criteria, but not on its possession of any extra-empirical virtues, such as metaphysical or aesthetic qualities.

Dirac dissents: he believes that aesthetic factors take a hand not only in directing processes of theory-formulation, but also in contributing to the assessment of the theories which have thereby been generated.<sup>18</sup> He left many assertions to this effect, the more univocal of which are cited in the remainder of this paper; one may ponder upon a statement he made in Moscow in 1955 as an initial indication of his views. As R.H. Dalitz

<sup>17</sup> Dirac, pp. 46-7, 1963. A detailed historical account of the rise of wave mechanics is offered in Miller, pp. 125-83, 1984.

<sup>18</sup> Some further considerations about the basis of the evaluative use of aesthetic criteria in science are contained in my (1989).

recounts, 'When asked to write briefly his philosophy of physics, he wrote on the blackboard "PHYSICAL LAWS SHOULD HAVE MATHEMATICAL BEAUTY" and this has been preserved there to this day'.<sup>19</sup> It was at least in part on such a criterion that Dirac extended support to the general theory of 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.<sup>20</sup>

Thus, while positivists admit that aesthetic factors may play a part in the context of discovery, but deny their legitimacy in the context of justification, Dirac appears to believe that the procedures typical of both stages may make recourse to aesthetic considerations. By what arguments, the positivist will ask, can such a view be supported?

#### § 4. *Aesthetic criteria in theory-endorsement*

In certain models of science, it is not invariably justified to reject a theory of which an empirical test has delivered what on a *prima facie* view is an unfavorable verdict. P. Duhem and W.V. Quine have suggested that the entity which is put to the test in an experiment or other empirical trial is not an isolated proposition or theory, but rather an extended theoretical corpus or conjunction of theories. Quine maintains that the object at issue in a scientist's empirical test is the overall body of his or her beliefs, drawn from all fields of science, logic and mathematics, and including common-sense beliefs. An unfavorable empirical result does not militate against a single theory within this whole, not even against the individual theory which may purportedly be at jeopardy: rather, such a result counts against the legitimacy of one's holding to the overall body of beliefs which entered into the test. One may harmonize such a result with any particular theory – even the

<sup>19</sup> Dalitz, p. 20, 1987. This story is told also in Dalitz and Peierls, p. 159, 1986.

<sup>20</sup> Dirac, p. 10, 1980b. The view that part of the support to which the general theory of relativity is entitled derives from the theory's aesthetic qualities is widespread. A.M. Taylor, for instance, writes that 'the elegant beauty of the theoretical edifice [of general relativity] is thought sufficient reason for believing it to be true', p. 38, 1966. Bergmann, p. 30, 1982, too supports Dirac's view, attributing the diffusion of Einstein's general theory of relativity jointly to empirical and aesthetic factors: "From a logical point of view, the progress toward general relativity depended on a number of choices to be made; its eventual adoption, first by Einstein himself and later by the community of physicists, depended on the esthetic appeal of the finished theory and on its confirmation by experiment and observation." A further appraisal of the aesthetic properties of the theory of general relativity is contained in Chandrasekhar pp. 148-55, 1987.

one which was allegedly at issue – by introducing into some other component of the overall body of beliefs alterations sufficient to return the body to consistency with the sum of empirical data collected.<sup>21</sup> Duhem's view, while similar to that of Quine, denies that the result of logic or mathematics are susceptible to revision by appeal to experience in the way which Quine allows: nonetheless, for Duhem too the whole of empirical science hangs in the balance in an experiment which purports to test an individual theory within it.<sup>22</sup>

On this view, the amount of information carried by the report of an unfavorable experimental outcome is sharply reduced. The unfavorable outcome of an empirical test now condemns not an isolated theory but a conjunction of theories: it informs us that a certain conjunction is false but does not indicate in which conjunct the error resides.

It is not necessary to embrace Duhem and Quine's holistic view of theory-assessment to be persuaded that unfavorable experimental outcomes do not militate against isolated theories. Many a substantive theory in the physical sciences is of too high a degree of generality to issue any determinate empirical predictions except in conjunction with some auxiliary or subsidiary hypotheses. Any purported test of such a theory is in reality a test of the conjunction of the theory and of the auxiliary hypotheses which have been bound to it. A conflict between this conjunction and the data implies that the conjunction as a whole is empirically inadequate, but fails to retrace the inadequacy to any particular conjunct: the experimental discrepancy may be explained by the assertion that the theory is in error, but equally by the assertion that the theory is true or close to the truth, the error lying in some other conjunct, one of the auxiliary hypotheses.<sup>23</sup>

On this more modest supposition as well as in the scenario envisaged by Duhem and Quine, an unfavorable empirical result is an insufficient base upon which to ground the determinate verdict that a particular theory is invalid: the scientist must look, as the source of such sufficient grounds, to criteria other than the verdict of experiment.

There is considerable evidence both that Dirac was aware of this limitation on the determinancy of the verdicts delivered by unfavorable empirical

<sup>21</sup> Quine, 1951.

<sup>22</sup> Duhem, pp. 180-90, 1906.

<sup>23</sup> The implications of this eventuality for theory-assessment are examined by e.g. Lakatos, p. 100-2, 1970.

results, and that he thought that to overcome this limitation scientists should make recourse to aesthetic evaluations of theories. His discussion of the merits of the general theory of relativity illustrates his beliefs in this regard. First of all he judges, as the previous section intimated, that there are reasons for which to embrace the theory other than the degree of its consonance with empirical data:

One has a great confidence in the theory arising from its great beauty, quite independent of its detailed successes. [. . .] One has an overpowering belief that its foundations must be correct quite independent of its agreement with observation.<sup>24</sup>

If one believed that, independently of its empirical virtues, the aesthetic features of a theory were able to warrant such confidence in its basic validity, it would be natural to turn to aesthetic criteria to determine whether one should meet a *prima facie* unfavorable empirical result by abandoning the theory itself or alternatively by doubting the auxiliary hypotheses which accompanied the theory in its trial.

This is just the use to which Dirac supposes that aesthetic criteria may be put. He muses on the eventuality that the general theory of relativity might in its early days have received an unfavorable empirical verdict:

Suppose a discrepancy had appeared, well confirmed and substantiated, between the theory and observations. [. . .] Should one then consider the theory wrong? [. . .] I would say that the answer to the last question is emphatically No. [. . .] Anyone who appreciates the fundamental harmony connecting the way Nature runs and general mathematical principles must feel that a theory with the beauty and elegance of Einstein's theory *has* to be substantially correct. If a discrepancy should appear in some application of the theory, it must be caused by some secondary feature relating to this application which has not been adequately taken into account, and not by a failure of the general principles of the theory.<sup>25</sup>

Dirac thus believes that an evaluation on aesthetic criteria can reveal the substantial truth of a theory which – on account of, say, having faced its experimental test in conjunction with inadequate auxiliary hypotheses – has received a *prima facie* unfavorable empirical verdict. If aesthetic evaluations indeed possessed this power, it would clearly be warranted on some occasions to maintain allegiance to a theory – overruling an unfavorable empirical verdict which it had supposedly received – by appeal to its favorable aesthetic evaluation.

<sup>24</sup> Dirac, p. 44, 1980a.

<sup>25</sup> *Ibid.*, pp. 43-4; emphasis in the original.

The belief that a theory may be retained in the face of unfavorable empirical results if it possesses qualities perceived otherwise than via empirical testing is manifested by many scientists, among whom was Einstein.<sup>26</sup> As did Dirac, Einstein attributed great importance to the aesthetic features of theories.<sup>27</sup> Perhaps, therefore, Einstein believed like Dirac that it is to aesthetic criteria that one should appeal in justifying the retention of a theory which has encountered an unfavorable empirical outcome. Certainly this is the view which appears to be read in Einstein by Dirac: 'Einstein seemed to feel that beauty in the mathematical foundation was more important, in a very fundamental way, than getting agreement with observation.'<sup>28</sup>

#### § 5. *Aesthetic criteria in theory-rejection*

If, for the reasons displayed in the previous section, it is sometimes warranted to retain allegiance to a theory despite its notionally having failed some empirical test, one is at other times justified in withholding allegiance from a theory which has apparently demonstrated predictive adequacy by passing such a test. After all, true conclusions can be entailed by valid arguments from false premises: therefore some theories which have passed their empirical tests ought nonetheless – if only one knew – to be rejected.

The decision to overrule the verdict issued by experimental tests and reject such theories clearly cannot be justified by further appeal to empirical criteria of theory-evaluation: such theories have, by hypothesis, satisfied the empirical tests to which they were subjected, so the application of any such criteria would serve to heighten rather than lessen the degree of one's allegiance to the theory. The decision to overrule an empirical verdict must instead be prompted by the application of some additional, extra-empirical evaluative criteria. The obligation upon those methodologists who wish to reserve the faculty to overrule the verdicts of empirical tests

<sup>26</sup> Rosenthal-Schneider, p. 523, 1980, tells of the now famous episode in which Einstein manifested confidence in the validity of the general theory of relativity regardless of the outcome of observations performed on Eddington's eclipse expedition.

<sup>27</sup> For evidence of Einstein's views on the aesthetic properties of theories, see e.g. Whitrow (Ed.), pp. 19, 82, 1967.

<sup>28</sup> Dirac, p. 83, 1982b.

and reject theories which appear to have scored an empirical success is to indicate to which extra-empirical criteria they propose to this end to make recourse. Dirac offered a distinctive solution to this problem: he believed that theories which have so far enjoyed empirical success may nonetheless be condemned on the grounds of their being aesthetically displeasing.

Dirac's view in this matter becomes apparent in his reflections on the merits of quantum electrodynamics. This theory numbered at the time – as it does now – among the empirically most successful modern accounts of a body of experimental data: it gives values for such physical quantities as the Lamb shift and the anomalous magnetic moment of the electron which agree with measurement within the bounds of experimental accuracy, which amounts to a few parts per million. However, quantum electrodynamics yields these outstanding predictive results only after certain infinities, which during calculations appear in the values attributed to the electron mass and charge, are excised by a mathematical procedure developed by J. Schwinger, R.P. Feynman and others, and named 'finite renormalization'.<sup>29</sup>

Because of the necessity of applying renormalization procedures in its interpretation, quantum electrodynamics struck and continues to strike many physicists as aesthetically displeasing: Dirac was among those who refused on these grounds to accept it. He manifested no reservation about its ability to account for experimental data; his scepticism was concerned entirely with what he considered to be the unacceptable inelegance of the manipulation necessary to draw from it determinate predictions. He expressly noted in quantum electrodynamics the cohabitation of empirical virtues and aesthetic shortcomings, and directed his repeated criticism exclusively to the latter features of the theory. He wrote in a formulation typical of his concerns:

Recent work by Lamb, Schwinger, Feynman and others has been very successful [. . .] but the resulting theory is an ugly and incomplete one, and cannot be considered as a satisfactory solution of the problem of the electron.<sup>30</sup>

<sup>29</sup> Accounts of the development of quantum electrodynamics, of the introduction of the renormalization procedure and of its empirical successes are given by Weinberg, pp. 21-30, 1977, Aramaki (1987), and Schwinger (1989).

<sup>30</sup> Dirac, p. 291, 1951, Shanmugadhasan, p. 53, 1987, tells of an episode in which Dirac issued a similar judgment of the theory: he writes that in 1945 Dirac 'emphasized that he did not believe his quantum electrodynamics was the right theory because it was so complicated and ugly.'

Quantum electrodynamics was not the sole theory to meet Dirac's displeasure on aesthetic grounds independently of the degree of empirical success which it had demonstrated. For instance, Dirac unfavorably rated the non-linear spinor theory of Heisenberg on a blatantly aesthetic canon: 'My main objection to your work is that I do not think your basic (non-linear field) equation has sufficient mathematical beauty to be a fundamental equation of physics.'<sup>31</sup>

In such cases aesthetic evaluative criteria seem in Dirac's mind to acquire the power to discern the truth-value of theories which have only fortuitously satisfied the empirical criteria applied to it. Just as in his view aesthetic criteria can preserve a good theory from refutation in the face of apparently unfavorable empirical results, so they can prompt the abandonment or at least the mistrust of a theory of which the empirical track-record is as yet satisfactory.

The previous section concluded with the suggestion that there was some affinity between the views of Dirac and of Einstein on the wisdom of retaining allegiance to an aesthetically pleasing theory regardless of any temporary empirical failings on its part. Einstein seems to have shared also something of the view of Dirac's explored in the present section: he too seems to have found it natural to harbor suspicion on aesthetic grounds against theories which had demonstrated empirical competence. In his long resistance to quantum mechanics, for instance, Einstein never failed to pay tribute to the theory's predictive accuracy and power, but repeatedly expressed reservations about its acceptability on the strength of the quasi-aesthetic unease which it caused in him.<sup>32</sup>

The response of Dirac to the observation that empirically-successful theories may nonetheless be false, and that therefore empirical criteria alone are insufficient to indicate which theories ought to be rejected, bears similarity also to the solution given classically in natural philosophy. That true conclusions may follow by valid arguments from false premises was well known to Aristotelian scholasticism, which in response founded a distinction between a 'thesis' and a 'hypothesis'. A hypothesis was a set of

<sup>31</sup> Quoted in Brown and Rechenberg, p. 148, 1987. The passage is contained in a letter of Dirac of March 1967.

<sup>32</sup> For evidence of the quasi-aesthetic nature of Einstein's resistance to quantum mechanics see e.g. Hoffman, p. 195, 1972.

propositions able to save the phenomena of a certain domain, i.e. able successfully to predict the results of certain observations; it was not necessarily true. A thesis consisted of a theorem established – in the Aristotelian sense – ‘scientifically’, or validly deduced from evident first principles and thus indubitably true. The adequacy of a hypothesis was gauged by appeal to empirical criteria, but clearly these would have been on their own insufficient to identify satisfactory theses. For this task a supplementary set of evaluative criteria, of extra-empirical nature, was required: a satisfactory thesis was detected in part by, say, its consistency with scripture.<sup>33</sup> While the set of supplementary criteria envisaged by twentieth-century physicists is different from that of Aristotelian scholastics, it is interesting to see solutions of the same form being proposed, at an interval of several centuries for the same methodological problem.

#### § 6. *Summary and implications*

It transpires from a careful reading of Dirac’s arguments, notwithstanding the doubts expressed by Barrow and Simonton, not only that he genuinely proposed that scientists should subject theories to aesthetic evaluations, but also that he perceived cogent reasons for so doing. He appears to have been motivated by an understanding of the limitations of empirical criteria of theory-assessment, and of the scientist’s frequent practical need to make recourse to a supplementary set of evaluative criteria in order to decide choices among competing theories.

Of course, the methodologist who wishes to develop Dirac’s theory of the role of aesthetic criteria has yet many questions to answer. Chief among these is, what justification can be adduced for turning to aesthetic criteria rather than to any other set of extra-empirical criteria in hoping to settle cases of theory-choice?

One may envisage two possible answers to this. It may be that some *a priori* reason could be discerned for believing that theories which exhibit certain aesthetic features are *ceteris paribus* more likely to be true than theories of different aesthetic form; this belief might descend, for instance, from the assumption that the natural world itself possesses a certain aes-

<sup>33</sup> An account of the epistemological debates concerning the use of hypotheses and of theses in Renaissance astronomy is contained in Jardine, pp. 697-702, 1988.

thetic form. Alternatively, one might imagine casting an inductive eye over the history of science and establishing that theories demonstrating certain aesthetic features had as a matter of contingent fact tended to be closer to the truth – as this was later revealed – than other theories. While each of these routes offers some prospect for grounding Dirac's methodological injunctions at a deeper conceptual level, it seems that Dirac developed neither systematically himself.

Those sceptical of the worth of Dirac's remarks on the role of aesthetic evaluative criteria, perhaps believing that a theory's beauty is apprehended – if at all – by a purely subjective process unsusceptible to rational analysis, have concluded that they must therefore not have been intended, or at any rate must be taken, as serious contributions to a model of scientific methodology. If displayed as an honest and thoughtful response to certain well-known methodological problems, however, Dirac's remarks on the role of aesthetic criteria in theory-evaluation appear to assume more rational sense than his fiercest critics might allow. Dirac's critics can question, perhaps, his choice to make recourse to aesthetic criteria rather than any other, but they too – if they propose to compile a convincing portfolio of scientists' evaluative procedures – will be compelled to face in some way or other the problems deriving from the limitations of empiricism.<sup>34</sup>

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<sup>34</sup> I presented some ideas relating to the themes of this paper at a seminar at the Department of History and Philosophy of Science, King's College, London, in October 1988. I benefited greatly from the reactions and suggestions of those present.

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