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TRUTH AND BEAUTY IN SCIENTIFIC REASON

ABSTRACT. A rationalist and realist model of scientific revolutions will be constructed by reference to two categories of criteria of theory-evaluation, denominated indicators of truth and of beauty. Whereas indicators of truth are formulated *a priori* and thus unite science in the pursuit of verisimilitude, aesthetic criteria are inductive constructs which lag behind the progression of theories in truthlikeness. Revolutions occur when the evaluative divergence between the two categories of criteria proves too wide to be recomposed or overlooked. This model of revolutions depends upon a substantial new treatment of aesthetic criteria in science with which much of the paper will therefore be occupied.

1. TWO PROBLEMS OF RATIONALISM

The rationalist image of science has in recent years been confronted by two seemingly unrelated challenges. The greater of these is the alluring thesis that scientific progress is fractured by revolutions into distinct epochs which adhere to forms of rationality peculiar to each and not shared by adjacent periods. The second, which has hitherto commanded less attention, is the mounting realization that the development of science is shaped partly by factors which relate not to the verisimilitude or empirical adequacy of theories but rather to their aesthetic or formal features. Either of these tenets threatens the rationalist's enterprise of explaining the evolution of science: if there is no paradigm-neutral canon of rationality it becomes impossible to reconstruct past science by reference to a unique or privileged set of norms of inference and assessment; if theory-preference is further vitiated by the aesthetic predispositions of scientists, the resulting edifice appears irremediably contaminated by irrationality.

The aim of the present paper is to dispel both these difficulties of rationalism by showing how the phenomena of radical standard variance and of theory-choice on aesthetic criteria are components of the same, internally coherent image of scientific progress. The result will be a rationalist model of science which nonetheless allows the occurrence of revolutionary discontinuities in standards of theory-assessment and reserves a distinctive role to beauty in the choice among

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theories. The argument will investigate first the role of aesthetic standards in theory-appraisal and attribute their origin to an induction over past science; this treatment will in turn permit a new construal of scientific revolutions as ruptures in aesthetic canon.[1]

2. THE INSUFFICIENCY OF VERISIMILITUDE

Realists prescribe that the ultimate goal of science is the construction of true explanatory theories about phenomena. The stipulation of explanatory power eliminates from the quest tabulations of mere logical theorems or phenomenic accidents and introduces a requirement for theories to grasp the causal mechanisms which underlie reality. As in all search processes, in science it is valuable continually to review when and by which theories progress towards the ultimate end has been accomplished in order to perform the most judicious choices amongst competing theories and to maintain the adherence of the community to the current best theory. The scientist is, however, acting under the disadvantage of possessing no access to the causal mechanisms underlying phenomena except through the theories of which the appraisal is desired. It would therefore be specious to propose to establish by straightforward comparison with a putative 'truth of the matter' whether a theory has fulfilled more closely than its rivals the final goal of true explanation of a given domain of reality. Faced by the unavailability of such immediate means of inspection, realists join antirealists in evaluating theories by less direct, diagnostic criteria.

The members of one class of requirement to be considered significant in theory-assessment would by realists be denominated indicators of truth. These properties are taken by them to constitute an explication of the concept of verisimilitude: presence of these features in a given theory constitutes evidence for its proximity to the imaginary, perfect account. Five such indicators of truth, along with examples of their application in theory-appraisal, shall be outlined: the first two, self-consistency and consistency with extant theories, are logical requirements, while the remaining three, accuracy, predictive range, and fruitfulness, are empirical.

1. Internal consistency: a theory should not harbour internal contradictions on pain of entailing every proposition of its language. Such a flaw was discerned in the Aristotelian theory of free fall, which asserted that heavier bodies fell faster than lighter ones: Galileo

envisaged a heavy body attached by a cord to a lighter one and asked how fast the resulting compound would be expected to fall. On one hand, the light body would retard the heavy one so the velocity of the composite should be less than that of the heavy body alone; on the other, the compound object is heavier that its heavy component mass and should consequently fall faster.[2]

2. Consistency with pre-existing well-corroborated theories: a theory under evaluation should not contradict other, entrenched and observationally successful theories, rather complement them or, if possible, provide deeper explanations of the generalizations which they express. The statistical mechanics of Clausius and Boltzmann was valued partly for its consistency with the predictively successful empirical laws of classical thermodynamics, and furthermore for deriving the equations of state of ideal gases – which in the earlier theory had the status of mere phenomenological generalizations – from the principles of conservation of energy and momentum.

3. Predictive accuracy: deductions from the theory should agree with the results of observation and experiments. Newton rejected the Cartesian theory of vortices as the foundation of celestial mechanics because it was incapable of accommodating among its implications the known elliptical orbits of the planets.

4. Predictive scope: the predictions of a theory should extend beyond the particular range of data that it was initially designed to explain. After nine years' investigations of the orbit of Mars, Kepler published his first two laws in the *New Astronomy* [ ] *with Commentaries on the Motions of Mars*: their empirical domain extends however (within the bounds of non-relativistic accuracy) far beyond the fourth planet of the solar system to all celestial satellites and indeed to all bodies in closed orbits under inverse-square law attractive forces, as Newton's work was to establish.

5. Fruitfulness: a theory should disclose new phenomena or previously unnoted relationships between phenomena already known. In 1873 Maxwell revealed unsuspected links underlying the formerly disjoint sciences of electricity, magnetism, and optics by integrating them into the united structure of electromagnetism. Physics since Einstein has striven further to enrich this theoretical network by searching for a unified field theory, an extension of general relativity to electromagnetic and nuclear forces.

A theory is valued proportionally to the degree to which it exhibits such indicators of truth. Although they may be subject to differing interpretations, their outline is not a matter of current controversy: these properties constitute science's standard means to judge of the truthlikeness or empirical adequacy of theories.

The question yet arises whether these qualities are exhaustive of theoretical desiderata. Many prominent scientists have answered this query in the tacit negative by prescribing quite other requirements in their appraisal of theories: requisites of a certain aesthetic value. G. H. Hardy has, for instance, written:[3]

> The mathematician's patterns, like the painter's or the poet's, must be *beautiful*; the ideas, like the colours or the words, must fit together in a harmonious way. Beauty is the first test: there is no permanent place in the world for ugly mathematics.

P. A. M. Dirac stipulates for theories a similar aesthetic condition:[4]

> 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.

Lastly, Einstein was thus depicted by his son Hans Albert, himself a physicist:[5]

> He had a character more like that of an artist than of a scientist as we usually think of them. For instance, the highest praise for a good theory or a good piece of work was not that it was correct nor that it was exact but that it was beautiful.

Similar words suggest that at least in the view of certain practising scientists, which any rational reconstruction of science has a prima facie obligation to accommodate, there is a second jury sitting over theories beside that of indicators of truth. This parallel tribunal evaluates theories by reference to requirements quite unlike those of predictive accuracy or scope: whereas indicators of truth are interpreted as a token of theories' truthlikeness, the second category of requirement appears to those who apply it not to be correlated to such cognitive success but instead to pertain entirely to internal, formal or aesthetic features of theories. That the intuitions of scientists hold aesthetic features to constitute a class of evaluative criteria quite disjoint from that of indicators of truth is attested by, e.g., H. A. Lorentz in writing that "Einstein's theory [of general relativity] has the very highest degree of aesthetic merit: every lover of the beautiful must wish it is to be true", implicitly acknowledging that a theory may be beautiful and yet not true, or that it may fulfil one class of requirement but not the other.[6] The criteria distinct from but analogous to indicators of truth which are employed by scientists for the aesthetic assessment of theories will in this treatment be dubbed 'indicators of beauty'.

A binary classification of evaluative criteria similar to that outlined here is endorsed in Einstein's view of the desiderata of theories according to which theory-comparision may be conducted on two levels: an external level appertaining to the relationship of the theory to experiment, and an internal one referring to its inner conceptual structure. Einstein summarizes the process of external appraisal by the remark that "the theory must not contradict empirical facts";[7] but concurrence with experiment is not, according to him, a sufficient condition for the acceptability of a theory, for two reasons. First, it is always possible to eliminate discrepancies between theory and experiment by means of ad hoc hypotheses, which, though at times admirably satisfying the requirements of indicators of truth, reduce the scientific worth of the theory.[8] Second, modern physics witnesses an increasing length and complication of the chains of reasoning from the principles of a theory to its observational consequences, so that "the confrontation of the implications of theory by the facts becomes constantly more difficult and more drawn out".[9] Internal evaluative criteria – akin to the present treatment's notion of 'indicators of beauty' – therefore become more influential as the complexity of theories increases. Einstein says these criteria bear upon the 'naturalness' or 'logical simplicity' of concepts and of their interrelations which together constitute the basic principles of a theory. Such criteria are not so precise as to permit a quantitative comparison between the conceptual parameters of rival theories: Einstein particularly rejects numerical measures of logical simplicity because they require an arbitrary decision on what counts as a logically independent expression. Rather, Einstein describes his internal criteria as involving "a kind of reciprocal weighing of incommensurable qualities".[10]

As the following sections will illustrate, the history of science teems with instances in which indicators of beauty appear to have prevailed over empirical criteria in directing theory-formulation. One episode occurred in the development of quantum mechanics from 1925, independently achieved by Heisenberg first and Schrödinger soon afterwards. The story is best reported in the words of their junior colleague, Dirac:[11]

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.

Indicators of beauty are, for some scientists and philosophers, important not only as illustrated above in theory-generation – a possibly arational activity – but also in fully rational theory-choice. For instance, indicators of truth would be insufficient to adjudicate among two or more competing theories which exhibited the same indicators of truth under all possible evidence but possessed some incompatibility (e.g., radically different ontological commitments) which prevented their being considered alternative expressions of a common theoretical substructure. Such underdetermination would place realist science in the plight of the ass of Buridan, evoking two or more equally appealing instantiations of science.[12] To shelter science from this danger, some, like R. Swinburne, have expressed the hope that indicators of beauty would succeed in breaking the impasse and identify one theory as preferable to the others on aesthetic grounds:[13] thus, in the event that rival theories appeared equally truthful, one should, like Paris, choose the most beautiful, for somehow that would hold the most promise.

The above observations establish that distinctive and nontrivial roles are played in science by aesthetic concerns. Twentieth-century philosophy of science which from logical positivism to Lakatos has stressed empirical criteria of theory-choice has long resisted the introduction of indicators of beauty into rational reconstructions of past science: the following will endeavour to show how mistaken this neglect has been.[14] The balance may initially be redressed by a survey of indicators of beauty to complement that of indicators of truth offered above.

3. AESTHETIC CRITERIA OF THEORY-CHOICE

The indicators of beauty which shall be isolated and illustrated are the qualities of simplicity, symmetry, analogical interpretability, and consistency with metaphysical presuppositions. The two latter properties have not hitherto generally been classed as aesthetic criteria but the forthcoming discussion hopes to demonstrate their isomorphism with the former two desiderata of which the aesthetic nature is unquestionable: in any event the four qualities may jointly be taken as the extensional definition of beauty in science to which the present treatment shall adhere, just as indicators of truth explicate what it is for a theory to be proximate to the truth.

Three suggestions will be supported by exemplification in this section: that indicators of beauty are logically distinct from indicators of truth in possessing no correlation to empirical success; that in the history of science there exist many instances of theory-choice which cannot be explained without reference to these aesthetic criteria, thus adducing grounds independent of the subsequent discussion of scientific revolutions to postulate their operation; and last, that although the four indicators of beauty may be discerned in the scientific discussions of any epoch, their content is temporally variable so that theories once thought ugly may have subsequently won strong aesthetic approbation and vice versa.

1. Simplicity. The simple has frequently been attributed a guiding aesthetic role in the history of science, but perceived instantiations of the quality have radically changed in time. Copernicus relates at the opening of his *Commentariolus* that he was disturbed to find in Ptolemaic astronomy such a cumbersome scheme of epicycles, equant points, and eccentric circles:[15]

> A system of this sort seemed neither sufficiently absolute nor sufficiently pleasing to the mind. [...] I often considered whether there could perhaps be found a more reasonable arrangement of circles [...]. The suggestion at length came to me how it could be solved with fewer and much simpler constructions than were formerly used.

John Dalton believed that chemical compounds assumed the numerically simplest combinations of their constituent elements: as a consequence he was led erroneously to attribute to water a formula which would today be expressed as HO rather than H_2O.[16] Ernst Mach proposed for science a regulative principle of economy, suggesting that "science [...] may be regarded as a minimal problem, consisting of the completest possible presentment of facts with the *least possible expenditure of thought*".[17] He accordingly developed an interpretation of Newtonian mechanics shorn of Newton's own concepts of absolute space and time, which he regarded as metaphysical constructs superfluous to the empirical content of the theory; on the same grounds but less progressively, he was one of the last physicists of note to doubt the existence of atoms. Einstein was famously motivated by simplicity; when once commenting upon a discrepancy of as much as ten per cent between a measured gravitational deviation of light and the effect calculated from general relativity, he weighed structural simplicity against any empirical deficiency of the theory:[18]

For the expert, this thing is not particularly important, because the main significance of the theory does not lie in the verification of little effects, but rather in the great simplification of the theoretical basis of physics as a whole.

These observations show simplicity in science not to be susceptible to atemporal definition: Copernicus's faith in the primitive character of circular motion, Dalton's arithmetical simplifications, Mach's anti-metaphysical guillotine, and Einstein's desire to minimize theoretical postulates are quite different from one another. Even among contemporaries there is no unique conception of simplicity, as exemplified by G. Holton: "Einstein and Planck debated strongly in 1914 whether the simplest physics is one that regards as basic *accelerated* motion (as Einstein had come to believe) or *unaccelerated* motion (as Planck insisted)."[19] Indeed, simplification in one respect often involves complication in another: the formulation and solution of problems involving spherical symmetry are simplified by the use of spherical coordinates rather than rectangular, but the latter are intrinsically simpler than the former. As Lakatos concludes: "No doubt, simplicity can always be defined for *any* pair of theories T_1 and T_2 in such a way that the simplicity of T_1 is greater than that of T_2."[20] Second, although it can be shown formally that application of Ockham's Razor leads to hypotheses which are more informative than those yielded by any alternative strategy, there is no reason – in the absence of independent belief in the simplicity of nature such as Leibniz's 'principle of least action' – why that policy should result in hypotheses that are true more often than would any other.[21]

2. Symmetry. This quality is not the symmetry of natural objects, like snowflakes or molecules, which relates to features of beauty perceived in nature, but is rather a symmetry of concepts. There are several historical instances of the impact on theory-generation of considerations of symmetry. Einstein's formulation of the theory of special relativity (or – as he named it in early correspondence – the 'theory of invariants') was heavily motivated by the concerns for

symmetry evinced in the opening sentence of his 1905 paper: "It is known that Maxwell's electrodynamics [. . .] leads to asymmetries which do not appear to be inherent in the phenomena."[22] Again, following Planck's theory of black-body radiation in 1900, the idea gained currency that light exhibited corpuscular aspects: prompted by a yearning for theoretical symmetry which acquired experimental support only some four years later, Louis de Broglie suggested in 1923 that particles correspondingly possessed wave-properties, advancing a relation between the momentum of a particle and the wavelength of the associated undulation which exactly mirrored Planck's equation linking the energy of the light-wave to its frequency. Another testimony of the role of symmetry in theory-formulation is provided by H. G. Cassidy who for good measure lends an artistic overtone to the conception:[23]

> While I was listening to a piano concerto, the idea suddenly occurred to me that it should be possible to prepare electron exchange polymers. I was at once certain that this was feasible, and I felt the fitness of the idea in complementing the already well-known proton exchange polymers. [. . .] Once the symmetry of the relationship became apparent to me I experienced great pleasure and excitement.

Like simplicity, theoretical symmetry cannot be viewed as susceptible of extratemporal definition, since both the conceptual elements to which scientists consider the postulation of symmetry to be applicable and the forms of symmetry which they regard as material will typically change in time; nor is symmetry diagnostic of observational success, unless in individual cases some justification is discovered for postulating symmetry of nature.

3. Analogical interpretability. The devices of metaphor and analogy are sources of aesthetic pleasure in science no less than in literary composition: through their means are erected scientific models, representations of one phenomenon by reference to another which permit inferences to be drawn across domain boundaries. N. R. Campbell is a classic source for the belief that models are indispensable to science: as M. B. Hesse writes,[24]

> [Campbell] considers that we require to be intellectually satisfied by a theory if it is to be an explanation of phenomena, and this satisfaction implies that the theory has an intelligible interpretation in terms of a model, as well as having mere mathematical intelligibility and perhaps the formal characteristics of simplicity and economy.

Satisfaction with a theory thus derives for Campbell from its analogical allusion to known phenomena: the kinetic theory of gases, for instance, exerts appeal through its associated corpuscular model. Such models were most consequentially employed in nineteenth-century theories of the ether; Lord Kelvin wrote: "I never satisfy myself until I can make a mechanical model of a thing. If I can make a mechanical model I can understand it. As long as I cannot make a mechanical model all the way through I cannot understand."[25] These expressions suggest that Kelvin and Campbell looked to models as a source of quasi-aesthetic satisfaction quite distinct from predictive power. The aesthetic appeal of analogy is further illustrated by the development of quantum mechanics from 1913 to 1927, a period which witnessed the loss and recovery of visualizability.[26] In 1913 Bohr proposed a model of the atom which retained its conventional visualization as a miniature planetary system: the subsequent decade revealed an incapacity of this model to describe atoms more complex that the simplest, that of hydrogen. In 1925 Heisenberg originated a new version of quantum mechanics couched in a mathematical formalism uninterpreted by models and referring throughout to particles of an unvisualizable nature: the concept of electron had evolved from analogue of a minuscule billiard-ball to purely abstract entity. Heisenberg asserted that he found this formal approach congenial to his nonvisual mode of thought; Schrödinger was on the contrary disappointed by the lack of visualization and in 1926–1927 created wave mechanics, a theory logically equivalent to Heisenberg's which however pictured subatomic particles as wave packets. Schrödinger later described his reaction to Heisenberg's work:[27]

> My theory was inspired by L. de Broglie [. . .] and by short but incomplete remarks by A. Einstein [. . .]. No genetic relation whatever with Heisenberg is known to me. I knew of this theory, of course, but felt discouraged not to say repelled, by the methods of transcendental algebra, which appeared very difficult to me and by the lack of visualizability.

Schrödinger had restored analogical interpretability at least temporarily to quantum mechanics, in the process testifying to the aesthetic appeal of such figurative devices. Interpretations of the quality of 'visualizability' have been as historically fickle as of the other indicators of beauty: an epoch's preferred source of models, like Kelvin's mechanistic devices, is frequently later dismissed as quite inappropriate, as in Schrödinger's wave mechanics; indeed, models are often contingently prompted by current technology, as exemplified by the images of the nervous system successively inspired by arrangements of pulleys and strings, hydraulic piping and telephone networks. In addition, susceptibility to analogical interpretation – no matter how heuristically valuable – is demonstrably uncorrelated with observational success and is therefore correctly classed as an indicator of beauty rather than truth.

4. Consistency with dominant metaphysical presuppositions. Few have interpreted this quality as aesthetic, yet it resembles the other indicators of beauty in being neither positively correlated to truth (since there is no empirical warrant for the metaphysics of an age) nor susceptible to atemporal definition (for philosophical commitments themselves vary in time); furthermore harmony between theory and preconception yields gratification of a prima facie aesthetic kind. There are many celebrated cases in which this criterion has been used to evaluate theories, often unfavourably. Leibniz contested Newton's theory of gravitation on the purely metaphysical grounds that it violated Cartesian corpuscularism in which space was a *plenum* of particles interacting solely by collision. A remarkably similar story is that of Planck's and Einstein's rejection of quantum physics. To deduce the equation which he had constructed to explain the spectrum of black-body radiation, Planck employed the notion alien to classical physics of the quantum of action. The quantum theory to which this hypothesis led soon demonstrated spectacular predictive success, growing more radical with the work of Einstein, Bohr, and Heisenberg. Planck, an older and conservative scientist, was horrified by the departure which he had himself initiated, recognizing the predictive adequacy of quantum physics but refusing to accept as permanent its discreteness and indeterminism. Einstein's benevolence was longer-lived, but from 1927 he mounted an implacable resistance to its renunciation of causality, believing that any indeterministic description of phenomena was essentially incomplete. Though recognizing in quantum mechanics a measure of aesthetic appeal, he insisted that this was achieved in virtue only of the fact that the theory constituted a limiting case of the future deterministic formulation which alone would capture the full beauty of physical theory:[28]

There is no doubt that quantum mechanics has seized hold of a beautiful element of truth, and that it will be a test stone for any future theoretical basis, in that it must be deducible as a limiting case from that basis, just as [...] thermodynamics is deducible from classical mechanics.

His biographers agree that Einstein's rejection of indeterminism was essentially aesthetic: for him the harmony of the universe would be marred if, to use his own metaphor, God cast dice. The requirement stipulated thus by Leibniz or Einstein that theories should accord with certain current metaphysical presuppositions is clearly a historically variable desideratum since the metaphysics of a community itself evolves. Further, as long as metaphysical presuppositions gain no empirical corroboration – arguably a logical impossibility – there is no reason why adherence to a particular such presupposition should confer on theories any greater truthlikeness than would allegiance to another.

Such have been certain of the aesthetic requirements prescribed of theories in the history of science. It would be arduous to explain the above episodes of theory-assessment on the basis of indicators of truth alone: by reference to aesthetic categories they are, on the contrary, readily reduced to sense. The complementary explanatory power of indicators of truth and of beauty suggests that it is hopeless to propose to reconstruct science in exclusive terms of verisimilitude as has hitherto been almost invariably attempted. On one count, therefore, the acknowledgment and application of indicators of beauty is positively demanded for the accurate reconstruction of past science; on another, however, the splitting of criteria of theory-assessment into two independent categories causes problems of its own to theory-choice. These difficulties must next be engaged.

4. THE INDUCTION TO BEAUTY

The benefit which accrues from a double canon of appraisal of scientific theories is the opportunity that a narrower and more discriminating ideal may thereby be constructed of the object of research, if – as hopefully envisaged by those who would by this means defeat underdetermination – the two evaluations should stipulate complementary qualities of theories to be desirable. The disadvantage is conversely the danger of conflict arising between the canons if in instances of theory-choice their verdicts should diverge. In order to formulate unequivocal principles of choice among theories it is therefore necessary to investigate similar discord and enunciate a procedure for its recomposition.

Such a conflict would be the effect of an imperfect correlation between theory-choices founded on indicators of truth and those based on indicators of beauty. Conflicts would not occur if that correlation amounted to exact coincidence, or in other terms if in every potential case of theory-choice the two classes of indicators agreed upon which theory to recommend. It would be logically possible to ascribe such a coincidence to universal accident, but this assumption would appear unpalatably to construe the beauty of theories as miraculous. Furthermore, postulation of a similar accident could not be regarded as permitting either an epistemologically complete account of past instances of theory-succession or a secure algorithm for scientific progress; both these purposes would require a relation of nomological coincidence, whether deterministic or statistical. Satisfactory understanding of a similar law-like correlation would in turn require a causal explanation of the positive association between truth and beauty, most prima facie plausibly by demonstrating how a theory's endowment of indicators of truth ensures its simultaneous possession of indicators of beauty. Any explanation to this effect (in itself difficult to envisage) would conflate the two categories by reducing indicators of beauty to a subset of indicators of truth, since if a theory lacked features of beauty it would tend also not to be true. Such a conflation would violate the intuition explored above that there exists in theory-evaluation a category of requirement other than indicators of truth. Approaches postulating either an accidental coincidence or a nomological correlation of truth and beauty thus appear equally problematic.

Any other approach would by contrast deny a systematic correlation and therefore allow the occurrence of tensions or conflicts between indicators of truth and of beauty: the danger of overdetermination of theories by criteria of evaluation would then arise since the recommendations of theory-choice of one category would in general not coincide with those of the other. In this case completeness would again not be satisfied unless a procedure were disposed for conflict-resolution. Should choices among theories be decided invariably on indicators of truth? If so, what role is reserved in science for indicators of beauty, save perhaps that of bestowing – *choix accompli* – a gratuitous accolade on those theories which accidentally display beauty in addition to verisimilitude? Alternatively, may indicators of beauty on occasion overrule indicators of truth? If so, what reflection is thereby cast upon science's proclaimed single-minded quest for truth? While it is enviable to unearth one philosopher's stone, to stumble across two is embarrassing indeed.

These problems must be resolved for an exhaustive and harmonious view to emerge of the roles of indicators of truth and beauty in science. The solution to be enunciated hinges on the familiar distinction between the doctrines of metarationalism and metainductivism. According to the former, the norms of scientific methodology are formulated a priori by inference from the nature and goals of science: on this foundationalist account a methodological precept correctly inferred will remain forever valid. Metainductivism holds on the contrary that the norms of scientific methodology are developed and refined by an induction over those amongst all past proposed norms which have demonstrated the most fruitful applicability, so that the battery of norms to which a community adheres may evolve in response to a perceived inferiority of its performance relative to that of an alternative proposed battery. Epistemological theorists generally posit that the scientific community's complex of methodological norms has in toto either demonstrated past fixedness and thus endorsed metarationalism, or undergone evolution and therefore been appropriately modelled by metainductivism. There is, however, no reason why both these modes of method-construction should not operate simultaneously in science on separate categories of methodological norms. The thesis that shall be expounded is that whereas indicators of truth are formulated by inferences from first principles characteristic of metarationalism, indicators of beauty are constructed a posteriori by metainductivism.

Metarationalism is clearly responsible for the genesis of indicators of truth because their inclusion among the desiderata of theories derives entirely from the a priori definition of the goal of science, the complete and true explanatory account of the universe. The requirements of internal consistency or predictive accuracy are prized not because they have previously been witnessed to accompany verisimilitude but because they are the elements of an explication of that very concept: indicators of truth appear in other terms to provide not a mere ampliative connotation but rather an analytic definition of truthlikeness.[29] It remains of course possible for indicators of truth to be inductively learned by a scientific community but this is irrelevant to the a priori logical status of such criteria.

While theories which today demonstrate internal consistency or accord with certain observations will so do forever in virtue of the a priori status of indicators of truth, no-one presumes that indicators of beauty are similarly invariant: it is commonly acknowledged that the perception of a theory as in some sense beautiful may easily be overturned, as occurred when the simplicity of Ptolemaic and Copernican circles was denied by Kepler or when Cartesian corpuscularism was repudiated by Newton. To account for such variability it is here claimed that a community selects its aesthetic canon at a certain date from amongst the aesthetic features of all past theories by weighting each feature proportionally to the degree of empirical success scored to that date by all the theories which have appeared to embody it. The community's aesthetic canon is then composed of the set of such mutually consistent features which have gained the greatest weighting. This is a clearly inductive procedure: as a theory demonstrates empirical success its aesthetic features will gain proportionate weight within the canon which is to serve in the evaluation of current theories, while conversely the aesthetic features of a theory which suffers a streak of empirical failures will win a progressively lesser weighting in theory-preference. A community thus formulates its indicators of beauty by an induction upon the aesthetic properties of those of its theories which exhibit to the greatest degree indicators of truth. A theory appears beautiful in the measure to which it recalls past successes scored by itself and theories formally or aesthetically similar to it: as these instances of success pale by retrospective comparison with the empirical attainments of more recent theories, so too fade their associated aesthetic features to be replaced by a fresh canon. A time-lag thus tendentially opens between empirical and aesthetic evaluations of theories since the latter are generated by induction over the former and therefore exhibit delayed response to any unexpected empirical success or failure of a theory: as a consequence of this lag aesthetic evaluations of theories will tend forever to appear conservative or retrograde by comparison to empirical evaluations. T. H. Huxley's aphorism about "the great tragedy of Science – the slaying of a beautiful hypothesis by an ugly fact – which is so constantly being enacted under the eyes of philosophers"[30] aptly describes the lag of aesthetic appreciation behind empirical assessment. The perceived beauty of a hypothesis is a function of the observational success of anteceding theories aesthetically similar to it; the novel fact appears as yet ugly because unassimilated within a theory of which the aesthetic qualities have been sufficiently weighted by the community. In time the community's indicators of beauty will evolve to render the theory erected about the new fact a structure of sovereign beauty and the disproven hypothesis merely passé.

Considerable evidence for the attribution of indicators of beauty to metainductivism is provided by the observations of the previous section. In general, theories which maintained aesthetic continuity with their successful predecessors have been pronounced beautiful while their competitors which lacerated that continuity have been initially condemned as ugly or displeasing, only for those judgements to be gradually reversed as the aesthetically innovative theory proved its superior possession of indicators of truth. This perceptibly holds for each of the four indicators of beauty. For instance, the heliocentric world view of Copernicus was identified as simple and hence beautiful by him and certain of his contemporaries by reference to the aesthetic canons of the previously successful Ptolemaic astronomy; Kepler's genuinely new astronomy was by Aristotelians and strict Copernicans alike seen as deeply ugly, permeated by imperfect ellipses and occult attractive forces. Similarly the conceptual sparseness of the theory of relativity in which Einstein delighted was a brand of simplicity learned from statistical thermodynamics and Machian mechanics, by both of which Einstein's aesthetic predispositions were avowedly nurtured.[31] Symmetry betrays the same inductive nature: the proposal of de Broglie that particles may exhibit wave-like properties possessed the same symmetry of Maxwell's equations; to its outlook would have appeared alien and therefore aesthetically displeasing the postulation of broken symmetries as in recent gauge-field theories. The construction of analogies is an explicitly inductive procedure since one can model the new only in terms of the old, the atom as a miniature solar system, for instance: the canon which praises a certain class of model, like Kelvin's mechanical devices, as aesthetically valuable must necessarily have been developed no less inductively. The beauty of metaphysical acceptability constitutes an equally clear case: Leibniz's Cartesian opposition to Newtonian gravitation and Einstein's deterministic repudiation of quantum mechanics were the hostility of the old beauty to the ugly new. These episodes of theory-assessment are each explicable by the allegiance of scientists to inductive aesthetic canons.

The present account of indicators of beauty is intended to resemble the Humean explanation of the origin of notions of cause: just as

Hume believed the inductive apprehension of causal links to be unsupportable by nomological data but a nonetheless ineluctable product of a driven mind, aesthetic canons in science boast no systematic relation to truth but spring from the psychological concerns of scientists. Neither Hume's account nor this concludes that notions thus formed are of no value: as causal links are a convenience of the Humean life, so indicators of beauty may here aid theory-construction and choice. It is, however, important to remember the contingent nature of concepts generated by Humean inductions and to avoid attributing to them any necessity.

The queries which opened the present section have thus been answered. There are no nomological connections between truth and beauty, merely inductive associations continually updated by scientists in the light of the degree of success of past theories. With this view of the inductive genesis of aesthetic canons in science it becomes possible to return to the other challenge to rationalist images of science proposed at the outset, the belief in discontinuities of rationality.

5. REVOLUTION AS AESTHETIC RUPTURE

The occurrence of revolutions in science has been acknowledged since the 1930s when G. Bachelard wrote of *ruptures épistémologiques* and L. Fleck of the alternation of successive *Denkstile*.[32] In this tradition T. S. Kuhn views intellectual history as sectioned into periods of 'normal science' defined by paradigms separated from one another by instances of 'radical standard variance', or 'changes in the standards governing permissible problems, concepts, and explanations'.[33] Some difficulty has, however, been encountered since Kuhn's original statement in explicating in what this variance consists, or which specific categories of norms of scientific procedure are liable to such discontinuities. Kuhn has volunteered no adequate elucidation, on the contrary compounding the obscurity when in a subsequent work he professed the opinion that there exist five criteria for theory-evaluation which will be common to the proponents of all paradigms: the qualities of accuracy, consistency, breadth of scope, simplicity and fruitfulness.[34] As long as these criteria are reputed to possess trans-paradigmatic validity and no complementary class of paradigm-bound norm is identified, it remains unclear how radical standard variance could ever arise. Kuhn alleges that although the parties to a dispute agree on the criteria of theory-evaluation, they may differ in the application or the relative weighting of such principles in certain cases:[35] but this is patently not a radical variance, merely an indefiniteness of standards.

It is remarkable that Kuhn's list of values juxtaposes – in terms of the taxonomy developed above – four indicators of truth and one indicator of beauty, simplicity. Kuhn here conflates the two categories, perceiving no need to comment on the difference between the formal, aesthetic quality of simplicity, of which the content is so strongly dependent on historical juncture, and the substantive properties of internal consistency or predictive accuracy which are an explication of the notion of empirical success.[36] A view which uncouples indicators of beauty from indicators of truth can, on the contrary, both allow standard variance and maintain the permanence of criteria of truthlikeness, thereby imparting a measure of continuity to scientific rationality. On this view a revolution consists of a discontinuous change not in the criteria of theory-evaluation in their entirety but solely in the class of indicators of beauty endorsed by a community. The pre- and post-revolutionary states of a science will be united by their indicators of truth in consequence of the a priori formulation of the latter, but will be distinguished by their appeal to different sets of indicators of beauty. This interpretation of the notion of scientific revolution perfectly harmonizes with the example typically offered by Kuhn, the late seventeenth-century transition from the Cartesian visualization of gravity as susceptible of mechanistic explanation to its Newtonian conception as a primary attribute of mass and hence not further explicable:[37] this shift has in the previous section been construed as a change in the aesthetic canons of metaphysical acceptability, a construal which explains Leibniz's continued opposition to the transition on traditional aesthetic grounds.

A period of normal science is therefore one in which theory-choices based on indicators of truth and those founded on indicators of beauty coincide and hence there does not arise the dilemma of choosing between the aesthetic appeal of some theories and the observational success of others. The indicators of beauty then prevailing will have been constructed as explained above by induction over the aesthetic features of past theories which have enjoyed empirical success and are therefore reputed to possess great indicators of truth. The resolution of what Kuhn terms 'puzzles' will be achieved within these dominant aesthetic canons: as hinted above and increasingly acknowledged by historians, the Copernican planetary model and the theory of special relativity were solutions to just such puzzles and so did not on this account constitute true revolutions. Normal science will thereby witness a stability of theoretical morphogenesis and spawn a lineage of theories united by aesthetic resemblance; 'anomalies' will conversely accrue when problems are attributed solutions which prove impossible to couch within the reigning aesthetic conventions, i.e., when the induction to indicators of beauty fails to maintain pace with the progression of theories in truthlikeness and therefore canons of beauty begin to lag behind the truths of the hour. A revolution will precipitate when evaluations of theories based on the indicators of beauty of the paradigm have so far deviated from simultaneous judgements founded on indicators of truth that it becomes impossible for scientists involved in theory-choice to recompose or overlook the conflicts. Theoretical morphogenesis then becomes unstable and controversial, and two factions will emerge. Conservative scientists will persist in adhering to the aesthetic norms characteristic of the paradigm in which they have intellectual investment and execute theory-choice under the guidance of its indicators of beauty, even though such a policy will generally cause them to pursue theories which are empirically less successful (i.e., display lesser indicators of truth) than their rivals. This is the faction joined by Leibniz against Newtonian mechanics, Mach against atomism, Planck and Einstein against quantum mechanics. The acts of similar factions illustrate Kuhn's and Lakatos's belief in opposition to Popper that scientists are not invariably hypercritical towards their own theories. Such behaviour will be dismissed as desperate resistance to innovation by the other, more progressive party of which the members will suspend and override the induction to indicators of beauty, repudiate the aesthetic canons of their erstwhile paradigm and conduct theory-choice on the exclusive basis of indicators of truth, a course which – relaxing the extra-empirical constraints on theory-construction – will permit them to adopt theories more empirically successful than those of their conservative adversaries. The aesthetic features of these new theories will in time come to constitute the indicators of beauty of the nascent paradigm. An analogy is thereby suggested between aesthetic progress in science and in artistic endeavours like industrial design or architecture: as in the latter domains a technological innovation of sufficient moment will render suddenly inappropriate the aesthetic conventions peculiar to previous techniques and simultaneously define its own canons of beauty, so empirical advance in science at times occasions a discontinuous exchange of aesthetic norms.[38]

This image of scientific revolution as iconoclasm reinterprets in an aesthetic key Kuhn's controversial view of revolutions as switches of *Gestalt*, explaining how J. H. Wheeler could aptly extend to contemporary physics what Gertrude Stein said of modern art: "It looks strange and it looks strange and it looks very strange; and then suddenly it doesn't look strange at all and you can't understand what made it look strange in the first place."[39] By 'a strange look' one readily intends, in science as in art, a violation of the dominant aesthetic canons of a time; a work of art or a theory cease to look strange when they convert aesthetic incomprehension to consensus. On this construal of revolutions, however, the incompatibility between paradigms is wholly aesthetic and not epistemic, hence preserving the continuity of rationality. After the revolution, aesthetic constraints on theory-choice will tend to crystallize until fresh tensions and ultimately a further revolution supervene. Science periodically enters ruts defined by aesthetic canons: a revolution represents the rationally guided exchange of one rut for another. The hope that indicators of beauty will defeat the threat of underdetermination is incidentally revealed illusory: any decision on aesthetic grounds between empirically equivalent theories will in general be perceived as valid only within the paradigm then current and cannot hence be considered definitive.

Hereby is offered an explication of Kuhn's intuition that whereas in normal science there is widespread agreement within the community on what constitutes solutions to the problems in hand, during revolutionary crises there is no similar consensus among scientists over the principles of theory-choice that ought to be applied: while one faction confers privilege on indicators of truth, the other favours the indicators of beauty then current. This view does not, however, vindicate Kuhn's stronger claim that theories embedded in rival paradigms cannot be compared since, as he believes, there are no paradigm-neutral principles relative to which this comparison could be executed: the transparadigmatic continuity of science is assured by its indicators of truth, even despite the periodic failures to adhere to them by aesthetically conservative factions. It is therefore definitely untrue that "the normal-scientific tradition that emerges from a scientific revolution is not only incompatible but often actually incommensurable with that which has gone before":[40] scientists of all paradigms share the conception of verisimilitude defined by indicators of truth. Also rejected by this approach is Kuhn's view of revolutions as irreducibly irrational transitions for which there is no logic but only a psychology. On the contrary, a revolution is occasioned by the eminently rational decision by certain scientists to pursue indicators of truth in disregard of beauty; the conservative faction in a revolutionary transition is guilty of irrationality in adhering to aesthetic conventions which impose arbitrary extraneous constraints on theory-generation. It is philosophically considerably more appealing to conceive of new paradigms and therefore new directions in science as springing from acts of rational deliberation rather than, as does Kuhn's account, from alogical delusion.

The manifold differences between the revolutions envisaged by Kuhn and those delineated here may thus be summarized by noting that while the former are non-rational (in being prompted by extra-cognitive concerns) and non-realist (because they erode the notion of objective truth), revolutions interpreted as changes in aesthetic canons are on the contrary rational in envisaging a continued allegiance to indicators of truth by the progressive factions, and realist in preserving verisimilitude as the goal of science.

Important repercussions at once arise for historiography. The identification of revolutions with discontinuities in indicators of beauty vindicates Kuhn's warning that the reconstruction of instances of theory-choice in paradigms previous to our own is problematic, for we no longer acknowledge the indicators of beauty which defined those paradigms but rather have constructed our own aesthetic canons by induction over the developments in science to this day. For example, we cannot credit as justified Copernicus's predilection for the circle as the geometrical form of planetary orbits because we do not number his doctrine of Pythagorean simplicity among our current indicators of beauty; we dismiss as unwarranted Einstein's opposition to quantum mechanics because we no longer count determinism among our metaphysical commitments. Nonetheless the reconstruction of past theory-preference is not hereby rendered impossible, for we share the indicators of truth proper to Copernicus and Einstein no less than to their more progressive successors in view of science's extratemporal constitutive goal of truth. The chief task for the historian of scientific revolutions is therefore that of identifying the indicators of beauty of a paradigm in pre-revolutionary times and of charting the theory-choices performed in accordance with those indicators which depressed the observational success of the theories of that paradigm and ultimately led to its demise.

Kuhn's imagery strongly evoked analogies between revolution in science and in society:[41] like social formations, theories succeed one another often not by gradual transition but by discontinuous substitution. The interpretation of scientific revolutions as fractures in inductively-constructed aesthetic canons enables the isomorphism to be deepened with the Marxist theory of economic revolution. That theory locates the driving force of social progress in technical developments within an economic substructure which engenders, consolidates, is gradually hampered by, and ultimately overthrows and replaces a superstructure composed of relations of production and other ideological baggage. One may, in science, analogously conceive empirical progress constituted by increased theoretical verisimilitude as the substructural motor which accommodates successive superstructures consisting of aesthetic canons. As empirical progress is achieved, the prevailing indicators of beauty will be first strengthened, later undermined and ultimately destroyed by rising tensions between them and indicators of truth. The periodic overthrow of successive indicators of beauty is due to the fact that immediately upon formulation they switch to a conservative evaluative tack and in time inevitably begin to hamper scientific progress, exactly as state institutions once erected crystallize a fleeting order and thus tend to hinder continued social evolution. History of science consists essentially of the growth of truthlikeness or empirical success, and aesthetic canons rise or fall as they facilitate or impede that growth.

Thus are met the two challenges to the rationalist image of science which were adumbrated at the outset and of which the close connections have by now been made clear. There exists no nomological correlation between indicators of truth and of beauty, so conflicts may indeed arise between them, albeit minimized by the inductive associations which are erected between truth and beauty by scientists. Epochs of normal science are defined by the temporary success of such correlations while revolutions are presaged by their breakdown. The construal of scientific revolutions as the discontinuous exchange of one set of indicators of beauty for another permits the history of science to be unified in its pursuit of verisimilitude whilst nonetheless undergoing variance in norms of theory-choice: hence revolutions do not necessarily jeopardize the rationality of science. Simultaneously the capacity of revolutions to displace outdated indicators of beauty guarantees that theory-choice will not permanently be diverted from objectivist, truth-seeking criteria by mere aesthetic appeal: the approach of a revolution will relieve scientists of the requirement of allegiance to past indicators of beauty. Although indicators of beauty therefore occupy an autonomous role in theory-choice and may overrule indicators of truth in the eyes of conservative scientists in revolutionary times, progressive science nonetheless maintains its quest for verisimilitude. Rationalism thus weathers the twin challenge of radical standard variance and of theory-choice on aesthetic criteria if these are viewed as two strands of the same model of scientific progress.

NOTES

[1] An earlier version of this paper was presented in March 1987 to a seminar at the Department of History of the Université de Montréal, the participants of which I thank for their discussion. For valuable suggestions I am grateful also to Professor J. R. Brown of the University of Toronto and to a referee of this journal.

[2] Galilei (1638, pp. 66–68).

[3] Hardy (1940, p. 85); emphasis in the original. It would not be pertinent to object to the relevance of this quotation on the grounds that mathematics cannot be counted amongst the sciences in view of the mathematical structure of modern physical theory, which tends to conflate the notions of mathematical and scientific aesthetics.

[4] Dirac (1963, p. 47).

[5] Whitrow (ed., 1967, p. 19). This character-sketch is corroborated by H. Bondi: "As soon as an equation seemed to him to be ugly, he really rather lost interest in it [. . .]. He was quite convinced that beauty was a guiding principle in the search for important results in theoretical physics" (Whitrow, p. 82). For further indications of the importance attached by scientists to aesthetic criteria of theory-assessment see Poincaré (1905, p. 8), and Duhem (1906, p. 24).

[6] Lorentz (1920, p. 23).

[7] Einstein (1949, p. 21).

[8] Einstein (1949, p. 21–23).

[9] Einstein (1949, p. 27).

[10] Einstein (1949, p. 23).

[11] Dirac (1963, pp. 46–47).

[12] For a fuller discussion of underdetermination see Newton-Smith (1978).

[13] Swinburne (1968, p. 21); the property to which Swinburne entrusts this task is simplicity.

[14] Notable exceptions to the general neglect of the aesthetic properties of theories are

constituted by Wechsler (ed.) (1978) and Zee (1986) *passim*; Wisan (1981, pp. 311–15) suggests in connection with Galileo an analysis of history of science in terms of the kindred notion of 'scientific style' reminiscent of Fleck (1935).
[15] Rosen (ed.), (1939, pp. 57–58). Stressing symmetry rather than as here simplicity Gingerich concludes: "Copernicus' radical cosmology [. . .] was, like Einstein's revolution four centuries later, motivated by the passionate search for symmetries and an aesthetic structure of the universe. Only afterward the facts, and even the crisis, are marshalled in support of the new world view" (1975, p. 90). I concur with Gingerich's assessment of the motivations of Copernicus and Einstein; unlike him I shall thence infer in the last section of this paper that neither Copernicanism nor special relativity constituted revolutionary innovations. Gingerich's views on both the aesthetic motivations and the revolutionary nature of Copernicus are shared by Neyman (1974, p. 9).
[16] See Greenaway (1966, pp. 132–34).
[17] Mach (1883, p. 586); emphasis in the original.
[18] Quoted in Holton (1973, p. 236); further on the role of simplicity in Einstein's methodology see Hesse (1974, pp. 223–57), and Elkana (1982).
[19] Holton (1978, p. 299, note 8); emphasis in the original.
[20] Lakatos (1971, p. 131, note 106); emphasis in the original.
[21] See Sober (1975, pp. 161–75). Of course truth is defined largely in terms of simplicity by conventionalism, but that is motivated by its foundation upon a theory of truth as coherence rather than correspondence. Further on the disjunction between simplicity and truth see Bunge (1963, pp. 85–98).
[22] Quoted in Holton (1973, pp. 362–63); further on Einstein's concern for symmetry see Holton, pp. 362–67.
[23] Cassidy (1962, p. 57).
[24] Hesse (1966, p. 4).
[25] Quoted in Thompson (1910, Vol. 2, p. 835).
[26] For fuller details see Miller (1984, pp. 125–83), on which the following account draws.
[27] Quoted in Miller, p. 143.
[28] Einstein (1936, p. 378).
[29] Newton-Smith (1981, pp. 224–25) asserts to the contrary that all criteria of theory-choice – including those here termed indicators of truth – are inductive; on the other hand, he minimizes their rate of inductive change when he avers that "there does seem to be considerable consistency in what the scientific community in different cultures and different ages holds to be the good-making qualities of a theory" (Newton-Smith, p. 112). I concur with the latter proposition in regard to indicators of truth alone: the evidence of the historical mutability of indicators of beauty presented in the previous section appears categorically to refute it.
[30] Huxley (1894, p. 244).
[31] On this account therefore both Copernicanism and the theory of special relativity were less innovatory than is at times supposed, since they maintained aesthetic – including substantial metaphysical – solidarity with anteceding physical doctrine. On the non-revolutionary character of Copernicanism see Hanson (1961); of special relativity see Holton (1986, pp. 101–103). According to the next section by contrast true revolutions were constituted by Keplerian astronomy and indeterministic quantum physics, both of which infringed extant aesthetic canons.

[32] Bachelard (1934, esp. pp. 50–55); Fleck (1935, esp. pp. 125–45).
[33] Kuhn (1962, p. 106). Successive paradigms are in Kuhn's original view separated also by a 'radical meaning variance' of the terms which they employ, but this variance would not itself endanger the continuity of canons of rationality and hence will not be addressed here. In any event Kuhn has withdrawn from this extreme position to allow for communication between proponents of different paradigms: see Kuhn, pp. 198–99.
[34] Kuhn (1977, pp. 321–22).
[35] Kuhn, pp. 322–25.
[36] Newton-Smith's list of 'the good-making features of theories' (1981, pp. 226–32) similarly conflates indicators of truth like 'track record' and internal consistency with indicators of beauty such as 'compatibility with well-grounded metaphysical beliefs' and simplicity, although he elsewhere voices doubts that simplicity is indeed an indicator of truth (Newton-Smith, pp. 114–15, and 1978, p. 77). Of course Kuhn unlike Newton-Smith would not construe his criteria as diagnostic of truthlikeness.
[37] Kuhn (1962, pp. 105–106).
[38] This parallel between the evolution of indicators of beauty in science and the aesthetic development of industrial design or architecture supports the present treatment's construal of indicators of beauty as aesthetic in nature.
[39] Wheeler (1983, p. 185).
[40] Kuhn (1962, p. 103).
[41] Kuhn (1977, e.g. pp. 92–94).

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