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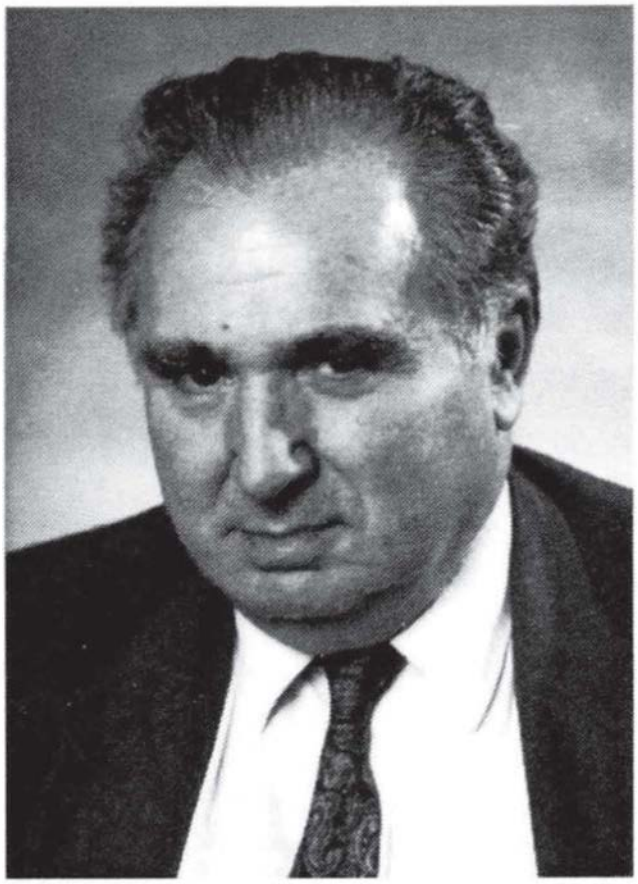

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# Science and Art: Heuristic and Aesthetic Dimensions of Scientific Discovery

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Einstein's epochal 1905 paper, for which he was awarded the 1921 Nobel Prize, is entitled "Concerning a Heuristic Point of View About the Creation and Transformation of Light." In this paper, Einstein proposed, among other things, that the photoelectric effect—in which electrons are emitted from the surface of certain metals illuminated by certain frequencies of visible light or by ultraviolet radiation—can be made more intelligible if the energies of the impinging radiation are conceived of as discrete quanta or photons. What problem was Einstein addressing? And in what sense was his proposed solution the adoption of a "heuristic point of view"? What exactly does "heuristic" mean here? And how does it, in this signal instance, relate to questions of aesthetic form in the actual work of scientific inquiry and in those high moments of scientific discovery?

These are the questions I hope to address in this paper. But to proceed heuristically with my own project, I will begin by telling a story of sorts—in effect, a parable. Like other parables, fables and moral tales, the story is well-known, and I can give only a crude and condensed version of it here. I will point the moral and draw its consequences later. The story concerns (as one might have guessed) Einstein's 1905 paper.

Einstein begins his paper with characteristic clarity, posing the problem succinctly:

> There is a profound formal difference between the theoretical ideas which physicists have formed concerning gases and other ponderable bodies and the Maxwell theory of electromagnetic processes in so-called empty space.[1]

What is at issue here, for Einstein, is the difference between particles and fields, between a physics of bodies moving in space, and a physics of waves or undulations in a medium. As long as matter could be conceived of in terms of discrete, finite quantities specifying the states of the classical mechanical parameters (e.g. position, mass, time); and as long as radiation could be conceived of in terms of the continuous functions of an electromagnetic field, the two universes of physics could be held apart, as matter and radiation. Newton had, of course, proposed a unified view of both matter and of light-radiation at least, conceiving of light as corpuscular, thus constituted of bodies in motion just as matter was. But by the early 19th century, this theory had been replaced by the wave theory of light of Young and Fresnel. Yet, early in the century (1839), Becquerel (senior) had reported that illumination of one of a pair of metal plates immersed in a dilute acid solution effected a change in the electromotive force of the cell. Later, Smith, Hertz, Halbwachs and Lenard investigated aspects of this interaction of radiation and matter in the photoelectric effect; and by 1900, Elster and Geitel formulated the first law of this effect, proposing that the number of electrons emitted by the metal surfaces was directly proportional to the intensity of radiation. And in 1902, Lenard had established that the maximum kinetic energy of an electron emitted under radiation depended only on the frequency of the radiation, and was independent of its intensity.

What was problematic, in the given state of physical theory, was how the kinetic energy of the emitted electron *could* be independent of the intensity of radiation, since in the Maxwell equations, radiant energy varies continuously, and the intensity is fixed by the magnitude of the electrical field. The problem then was to formulate the interaction of matter and radiation in such a way as to explain the dependency of the maximum kinetic energy of the emitted electrons on the frequency of the impinging radiation alone.

Einstein's solution to the problem was as simple as it was ingenious: it was to conceive of radiation as being like matter in its form or structure—i.e. as having a discrete, discontinuous or particulate structure, without, however, being "ponderable", i.e. without having mass. This would then yield a distinct proportionality between such a quantized series of frequencies and the energy absorbed by the emitted electrons in the photoelectric effect. Planck's earlier work on black-body or thermal radiation had in fact yielded such a quantized account of the range of values of a harmonic oscillator. From the earlier work of Kirchoff, Stefan and others on black-body radiation, and from Wien's mathematical equation of the spectrum of such radiation, Planck arrived at a formula which fitted the results of experiment. But in attempting to derive the formula mathematically, he was led to a conclusion, at variance with classical physics. In classical physics, as the wavelength of electromagnetic radiation decreases, the increase in the density of radiant energy should increase in proportion to the square of the frequency. The higher the frequency, the higher the energy, without limit, in a continuous function. But the observed results showed a different distribution of the radiant energy with decrease in wavelength. They exhibit a peak which then falls off rapidly. (This came to be expressed later by the Rayleigh-Jeans law $\frac{(\rho v = 8[\,]v^{2}kT)}{c^{3}}$ where $\rho$ increases without limit as $v$ increases. Jeans could then show an explicit anomaly in the Maxwell theory of electromagnetic radiation, the so-called "ultra-violet catastrophe", but Planck, in 1900, did not have this formulation available as yet.) Planck's conclusion was that the atoms or harmonic oscillators on the surface of the walls of the cavity which emits black-body radiation changed energy—i.e. absorbed or emitted radiation—only in quantized packets of energy.

Einstein drew on this concept to explain the photoelectric effect. In place of thermally induced radiation of the black-body case, the radiant energy in the photoelectric effect comes from illumination by the higher frequencies toward the ultraviolet end of the spectrum. Limiting himself to these higher or ultraviolet light frequencies (for which Wien's law held best) Einstein proposed that the energy of a light quantum or photon was proportional to its frequency, in the discrete numerical proportions that Planck had proposed (i.e. that $e=hv$, where $h$ = Planck's constant, [i.e. an energy of 6.62559 x $1^{-27}$ erg-seconds]. In this way, Lenard's result (that the maximum kinetic energy of emitted electrons was proportional to the frequency of radiation) could be explained by the thesis that this radiation was absorbed or emitted in such quantum amounts; in short, that light radiation was corpuscular and not wavelike in this interaction, and that increasing the intensity of radiation simply delivered more quanta of a given energy, proportional to the frequency. This would account for both the Elster-Geitel law and for Lenard's law.

The conceptual difficulty here was the apparent contradiction between this theory of the nature of light and the highly successful wave theory which lay at the basis of optics and explained the phenomena of diffraction, dispersion and refraction of light. To put it differently, two incompatible mathematical forms confronted each other: the continuous spatial functions of the Maxwell theory, and the discrete numbers and spatial discontinuities which characterized the quantum description. The mystery deepened as the quantum theory later developed, and as the converse proposition—that matter had the structure of waves—was developed by De Broglie and others. The conceptual task was thus posed of making coherent this apparent duality of particles and waves in the structure of both matter and radiation. But in 1905, Einstein writes of his "heuristic" approach thus:

> It appears to me, in fact, that the observations on 'black body radiation,' 'photoluminescence,' the generating of cathode rays with ultraviolet radiation, and other groups of phenomena related to the generation and transformation of light can be understood better on the assumption that the energy in light is distributed discontinuously in space. According to the presently proposed assumption, the energy from a beam of light emanating from a point source is not distributed continuously over larger and larger volumes of space but consists of a finite number of energy quanta, localized at points of space, which move without subdividing and which are absorbed and emitted as units.[2]

So much for the story. What is its moral? How does it bear on the thesis of this paper? The thesis is a familiar one: that considerations of form play a heuristic role in scientific discovery, and that these formal considerations may be characterized as aesthetic. Because the thesis is familiar, it is not my aim to argue here that it is the case—I take that as given—but rather to understand what this claim comes to; and more important, to explore the question of why aesthetic form does indeed play such a powerful heuristic role in scientific thought.

The thesis that aesthetic form is a desideratum in scientific thought is neither new, nor is it especially clear. There is a long tradition in science that links such aesthetic form to scientific thought, and there is a standard and growing list of apt quotations from great scientists bearing witness to the role that considerations of beauty or aesthetic criteria played in their moments of discovery. Kepler, Copernicus, Galileo, Newton, in the classical age of modern science; Boltzmann, Helmholtz, Poincaré, Einstein, Dirac, Heisenberg, Chandrasekhar, Dyson, Wang, Lipscomb, Cyril Smith, Weinberg and many others in more recent times have offered testimonials, sometimes examples, more rarely explanations of the heuristic role of such considerations. In a recent issue of *Science*, a report-article on current developments on supersymmetry and supergravitation in physics waxed eloquent, reporting sentiments among scientists to the effect that theories of such abstract beauty must be true. Indeed, it is initially obvious what the characterizations of these aesthetic components of high theory must include: symmetry, simplicity, economy or elegance, completeness, unity or great systematicity, the comprehension or ordering of great complexity by few principles, the stunning expressions of invariance through transformation—in short, order, proportion, harmony, all of the standard repertoire of those aesthetic properties which mark form in art, as well as in science. It is also fairly obvious what are the psychological features of insight, surprise, delight, satisfaction,—the aesthetic or intellectual emotions which accompany the epistemological recognition of deep structures or relations among what were previously regarded as disparate phenomena.

It is also relatively easy to pick out paradigmatic examples from the history of science and mathematics: from the earliest discoveries of explicitly mathematical form in nature, e.g. in the symmetries discovered by the Pythagorean school in their theory of acoustic proportions, in the geometrical order adduced by Platonic cosmology and in the discovery of the five regular polyhedra, in the development of the symmetry principle in various applications by Archimedes; and thenceforward through the whole history of science, with favorite stops in Copernican astronomy, Newtonian mechanics and optics, hydraulics, chemical theory—(who hasn't heard the story of the empty spaces in the periodic table)—crystallography, quantum electrodynamics, etc. etc. etc.

All of this tells us too much and too little: too much, in that there is an *embarras de richesses* in all of the examples; too little , in that this plenitude of instances is ordered by principles at once too weak and too vague to explain the heuristic force of such aesthetic desiderata. True, there are some sustained thematic studies in the history of science, like Emile Meyerson's *Identity and Reality*, there is Weyl's work on symmetry, there is the work of Hadamard and Polya on heuristics and discovery in mathematics. But the question remains, what exactly is the heuristic character of such approaches? And why do such desiderata as symmetry, unity, economy, etc. play such a role in theory-formation and in problem-solving?

There are several ways to approach these questions. The first may be called *ostensive* or *revelatory*: one simply points to exemplary or paradigmatic cases, and leaves it to be understood by the audience what the role of heuristic form is from the example itself. The supposition here is than aesthetic form and its heuristic role will simply show themselves in the example being pointed to. The audience will be prepared to know it when they see it; they will already have the incipient concepts or background knowledge to recognize what is revealed. Were I to adopt this approach, my paper would now be finished, and all of you would understand the issue from the bare example. You would, in effect, have caught on to the joke without my explaining why it is funny. The second approach may be called *testimonial*: here one simply cites what leading scientific thinkers have said about the role of such aesthetic criteria as beauty, symmetry, simplicity etc., in their own work. One then simply takes it on the authority of these great scientists that the thesis is true. What vindicates such testimonials is that they are themselves heuristic: they suggest that one pay attention to these considerations, and beyond this, also sometimes point to exemplary cases, as in the ostensive approach. These seem to me to be the least satisfactory, albeit the most common approaches to these questions.

A third approach has been characteristic of the philosophy of science. One may call it a *prescriptive-methodological* or *prescriptive-logical* approach. Here, one reconstructs what is taken to be the proper method of scientific thought. The implicit suggestion to the scientist is: "Do it like this". Such a reconstruction usually has proceeded as a *logical reconstruction* of the formal structure of scientific explanation. Such reconstruction has focused on the justification of the beliefs of scientists, rather than on their mode of inquiry or on the process of discovery. The process of discovery itself is set aside here as rationally unreconstructible, and as lying outside the context of justification, which focuses instead on the formal structure of completed scientific theory. Insofar as such logical reconstruction proposes (or claims to reveal) the norms of rationality, of logical coherence and of empirical confirmation or testability, it (usually tacitly) proposes a heuristic for theory-construction and criteria for what is properly scientific. But logical reconstructionists wouldn't be caught dead dealing with question of aesthetic form as part of this methodological heuristic.

A final approach may be called *definitional, explicative* or *interpretive*. Here one defines the terms "heuristic", "aesthetic form", etc. and attempts to make explicit, by the interpretation of examples, how these concepts are concretely embodied in scientific thought, in moments of discovery, and how indeed, such heuristics and aesthetic criteria may develop, or change historically.

In this paper, I will eschew the ostensive, testimonial, and methodological approaches and focus on this last definitional-explicative approach. To this end, I will begin by attempting to tease out what counts as heuristic in scientific and mathematical thought generally, and specifically in the example offered. And then, I hope to show what role if any aesthetic form plays here.

Let me begin by making a distinction between a *heuristic* and an *algorithm*. Both concern ways of proceeding to a given end. Both are therefore also prescriptive: they suggest or recommend how one ought to proceed. An algorithm, however, guarantees success: it is defined relative to a known, finite procedure, in which the end-state is determined by a sequence of prescribed steps. Thus, the operation of addition is algorithmic in arithmetic, in that the end-state—the *sum* of a series of numbers—is defined by the very operation of *addition* itself. Thus, one cannot fail to arrive at the end-state, if one proceeds algorithmically.

The algorithm defines the game, so to speak. The success that an algorithm guarantees is the success of playing the game, but not that of winning it. Thus the algorithm for chess consists of the rules for initially positioning and moving the pieces. If one follows the rules, one is playing chess. There is, however, no algorithm for *winning* a chess game, (as there is, for example for winning at tic-tac-toe, if the second move doesn't occupy the central square). For winning, there are strategies, there are insights, there are serendipitous moves, but all of these constitute the heuristics of chess. They do not guarantee success. Among the rules of art in chess, there are a range of negative and positive heuristics, e.g. keep the center strong, avoid moving knights to the edge in the opening game, get the pieces in the backfile into play quickly, etc. Thus, generally, a heuristic recommends what is preferable, what to avoid, what may be fruitful. An algorithm defines what is permissible and what is forbidden. Its prescriptions are therefore law-like, unlike those of a heuristic.

In the case of Einstein's "heuristic approach", there is the tentative proposal to consider light radiation as quantized, for the sake of explaining the frequency-dependency of the maximum kinetic energy of emitted electrons. Einstein obviously did not rule out in 1905, the wave-models of refraction, diffraction or reflection of light. In fact, the alternative field and particle models continued *as* alternatives, through the remarkable set of conceptual permutations that marked the later development of quantum theory, as matter and radiation took on each other's coloring, so to speak. The success of Einstein's heuristic approach, then, was not that it resolved the issue between (in his words) "The profound formal differences" between particle and wave theories, but rather that it posed the question in a new and different way.

It raised them, moreover, in terms of the formal-mathematical structure of theory; but at the same time, such a formal structure is taken as a *representation* of physical structure, i.e. it has an ontological interpretation. It is not simply that the equations give a better or formally more coherent account of the experimental data, but that light—what the equations are about, what they refer to—has a granular structure. In effect, the mathematics is a model, or is interpreted in a model which is not merely phenomenological, but which makes a putative claim about the structure of the natural world.

For example, in the case of Einstein's heuristic approach, the proposal to reconceive the nature of light in terms of a quantized structure within the space-time of classical physics is at one and the same time a consideration of the symmetry of the mathematical form of expression for the description of both matter and radiation, and therefore, also a proposal for an ontological symmetry between the two fields. Thus, when Einstein writes that the phenomena in question can be "better understood on the assumption that the energy of light is distributed discontinuously in space", the sense of "understanding better", entails the heuristic notion that the mathematical and ontological symmetry of the structure of matter and radiation in the case of the photoelectric phenomena yields a deeper understanding than does the previous postulation of two fundamentally different structures. This criterion may be characterized as one concerning the unity of nature, or correlationally the unity of physical science in its methodology and ontology. At the same time, the proffered resolution of this formal asymmetry, or in the one case (the photoelectric effect, etc.) duality gives rise to a still deeper asymmetry, for it now poses as a problem the remaining field-structures of electromagnetic radiation, and the remaining granular or particulate structures of matter. With the development of quantum-mechanics after 1925, these questions were sharpened, by the introduction of probabilistic characterizations of the classical parameters of the spatial location of the quantized packets of energy, so that the "schizophrenic" conception of the "wave-packet", and the still more exotic notion of its "collapse" in the event of a measurement-operation radically put in question the ontological coherence of the prior (wave/particle) structures, and led to the invention of alternative ontologies (of matter, of energy) as well as to the view that both classical ontologies had to be abandoned, in favor of purely phenomenological-mathematical descriptions, or of an uninterpreted mathematical formalism which simply was predictively successful. "Damn the ontology, full steam ahead", so to speak.

The heuristic approach, then, is at once methodological---concerning a way of proceeding mathematically—and ontological—concerning a model of the real world, i.e. an *interpreted formal system*. Its feature, as an adequate representation, then, is its systematicity as a model: consequences flow from it. It defines a domain which is to be grasped coherently, or understood in terms of, or through the formal representation itself. The conditions on the representation itself, then, are that it yield to such systematic comprehension, i.e. that it is both formally and interpretively or physically coherent, as far as it goes. To put this differently, the model has to be testable in its interpretation: its consequences obtain their physical significance only when the interpretation can be empirically or experimentally confronted. In short, such heuristic models are proposals to see the world in the form of the model; and where such interpreted formal structures radically revise a prevailing world-picture, they invite us to see or comprehend the world differently; they exercise our imaginations in the interests of world revision. They are utopian projects to be realized in the practice of inquiry itself.

But here, it seems to me, is the deepest affinity between discovery, as theory construction and theory revision in science, and discovery as construction and style-revision in the arts. For it is through alternative modes or styles of representation or of construction in the arts that we come to see or comprehend what was beyond our visual, aural or linguistic imagination before. The artist discovers (or creates, invents) alternative world-models, whether of color, of shape, of sound, of imagery, of linguistic meaning in the artifacts which function as artworks. It is the form of the work which makes it graspable, available to comprehension, which orders our visual field in the plastic arts, or the structures and temporal sequences of sound, imagery, feeling or meaning in music, literature, the dramatic arts. The artist, like the scientific theorist, makes available to the mind's-eye and ear of others what has been grasped, discovered, understood, created by his or her own mind's-eye, in the imagination. The artistic creation, like the scientific discovery, explores the possibilities of human conception, of what the mind can construct in the forms which permit these discoveries or insights to be shared, or communicated to others. The constraint here is the language or the symbolic form in which such insights can be represented, and the conditions under which such constructions can be transmitted. No artist, and no scientist invents a new language, but works to revise, reform the conunon language, to extend its range and its reference to include what has been grasped in the act of discovery. Thus theory change in science, and analogously, style change in art are both continuous and discontinuous with what they are changes from: they are history-bound innovations.

Thus, Einstein's heuristic proposal makes sense as a discovery or the creation of an alternative model only against the background of the history of physics, of the prevailing theories of matter and radiation, of the Wien Law, of Planck's 1900 paper on black-body radiation, of the work of Boltzmann, Lenard and others. Einstein's concern for the *formal* incompatibility of the two models is not in itself reason enough for proposing an alternative view of light radiation: there may, in fact, simply be two discrete structures in nature, irreducible to each other. In fact, false unified theories abound in the history of science, and one may counterpose a heuristic of multiple structures – i.e. of complexity – to one of unity or simplicity. Or, it may be that the human mind has evolved two complementary and distinct structures of comprehension, the one marked by the discreteness and atomicity of elements in combination or relation, the other, by continuities. "Particle" and "field" may be, as some have suggested, not features of the physical world but rather the limiting forms of two alternative *a priori*, or evolved structures of comprehensibility of human understanding, both of which are necessary for the dialectic development of our scientific world pic ture. The duality or complementarity of granular and field-theoretic models, *may* be the limiting polarities of our approximations of nature, rather than unity. But then, we have *competing* heuristics. The desideratum of unity, as a merely aesthetic desideratum would not have produced the 1905 paper. Rather, it was the solution of a problem which prompted the heuristic proposal. Yet, the problem could not have been solved, if the stimulation of what were considerations of aesthetic form hadn't suggested a bold move, a change in the angle of vision, a revision of a well-established world-picture .

One may understand Cézanne's innovation against the background of the work of Corot, Courbet, El Greco, Pisarro; yet, when Cézanne made his moves, the desiderata of aesthetic form which moved him to his construction of a new vision of nature, of light, of mass, of the shape and look of things had to be framed in the technical language of painting. They concerned the creation of a new coherent structure of pigment on a surface, a new vocabulary of shapes in order to represent his vision, so that we could come to see the world Cézannishly. So too, in scientific discovery, it is the construction of a representation—an alternative formal structure with a putative physical interpretation—which permits the speakers of a community of practitioners of the common language—in this case physics-—to "catch on" to the heuristic suggestions for a revised vision of the world which the scientist proposes. It is this, in effect, which marks the act of discovery in science as a social act. Its aesthetic dimension is, it seems to me, rooted in those same requirements for comprehensibility,—namely, the desiderata of order, form, beauty —which mark the enjoyment of art. In both cases, the human mind comes to appreciate its own capacity to understand the world, and here, I suggest, lie some of the deepest sources of that pleasure which we characterize as aesthetic, and which Spinoza called "the intellectual love of God", a metaphor to which Einstein's own view is strikingly close.

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## Footnotes

[1] A. Einstein, "On a Heuristic Viewpoint Concerning the Production and Transformation of Light," *Annalen der Physik*, June, 1905.

[2] *Ibid.*