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Induction and the scientific method

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Abstract. The role of induction, or reasoning from particulars to generals, was carefully delimited by Newton in his statement of the scientific method. Some of his constraints seem overly stringent to conform the current scientific practice.

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The emergence of the scientific method is a momentaneous event in history. It attained preeminence after a long-drawn conflict that climaxed in the seventeenth century, with Francis Bacon, Descartes and above all Galileo being asociated with the most famous battles. It was the role of Newton to seal the victory by overwhelming the opposition with a dazzling display of success based on this approach for the study of nature.

To be sure, there was scientific knowledge before Galileo and Newton, but the lack of a strict definition of the scientific domain entangled it with wider metaphysical issues. This gave rise to recurrent arguments, all too frequently settled with an appeal to authority, and left room for superstition and magic in the interaction with our surroundings.

The scientific method has come to represent for many the only safe road to truth. It was born in the physical sciences, and so it is understandable that younger bodies of knowledge in process of structuring themselves in a scientific way should look at the former for guidance. This is true in our day about the social sciences: anthropology, sociology, linguistics, economics and others. But which attributes of the physical sciences are to be imitated? It is a subtle problem, and requires a clear idea of their method.

Another reason why a precise definition is relevant has to do with important changes in outlook that have taken place since the time of Newton, who gave the method its canonical form. Quantum mechanics brought about a deep revision of our concept of causality. Darwin's theory of evolution has permeated all fields of knowledge, and opened the possibility that even our laws of nature, so painstakingly

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discovered, are themselves changing in time. Lagrange called Newton a lucky man, for there was but one set of laws of the universe, and he had discovered them. Further research has proved Lagrange wrong on this point, although one must add that Newton himself saw no contradiction in the possible existence of other worlds, subject to different laws.

Yet another reason for having a faithful statement of the scientific method concerns the persistent phenomenon of anticipation of major scientific discoveries, often happening more than half a century before their acknowledged birthdate, at a time when available experimental evidence seemed insufficient to grant such speculations to the vast majority of the scientific community. It is our aim to show that, to conform to this fact, the traditional constraints imposed on the inductive aspect of the method need to be relaxed.

The scientific method, as it emerged from the work of Galileo, Descartes, Bacon and others is based upon:

1. Isolating limited manifestations of reality for experimental and theoretical study.

Hence when the fall of bodies is our subject of study, we diminish as much as possible the effect of air friction and geometric shape. When detecting neutrinos from a supernova, extraneous events are filtered out. Such isolation of relevant variables was systematically practiced by Aristotle, and can be contrasted with a holistic attitude usually associated with the name of Plato, but advocated in a much stronger way by oriental schools of thought that strive for total knowledge, to be found in every element of the world. *'In a grain of sand one hundred thousand Buddhas'*, according to an oft-quoted statement that captures the essence of their approach.

2. Accepting empirical testing as the ultimate criterion of truth.

This represents a most important break of the scientific method with former ones. It at once confronted the problem of personality and authority that still plagues other activities, and made revelation, enlightment and similar individualistic experiences foreign to scientific discourse.

Ipse dixit —He himself said it— was a favorite dogmatic phrase of the scholastics to start and end discussion about almost any subject, their sources of truth being Aristotle and Scripture. The chinese classics took an even stronger hold on the minds of the descendants of Confucius and Lao-Tzu. The element of tradition reigned supreme. *The Master says* is the oriental counterpart to the european *ipse dixit*. Statements like 'At twenty five his hair was gray from studying the classics' are frequent compliments awarded chinese scholars who lived a millenium or two after their great mentors. Indian classics like the *Mahabharata* were tampered with throughout subsequent centuries to their appearance, but no new projects of similar magnitude were undertaken.

3. Making general inferences based on experimental results about specific phenomena, and then applying these inferences to new phenomena to determine their domain of validity.

This, the inductive aspect of the scientific method, is not without historical antecedents, exemplified by Hippocrates' celebrated approach to medicine as 'rational practice'. Nevertheless, before the seventeenth century 'practice' was frequently oriented, and even distorted, to legitimize or conform to preconceptions orienginating in the 'rational' element. Galileo's efforts can be interpreted as an attempt to reverse this procedure in the natural sciences.

Induction received a great deal of attention from Newton, who gave several non strictly equivalent versions of it in the *Principia* and his *Opticks*. The above statement is a condensation of one to be found in *Query # 31* of the latter book.

The last part of the scientific method, and the most controversial one, has to do with the nature and bounds of the inductive activity. The traditional limits on inference-making were set down by Newton in the *Principia*, so we can do no better than quote him [1];

4. We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances.

5. In experimental philosophy we are to look upon propositions collected by general induction from phenomena as accurate or very nearly true, notwithstanding any contrary hypotheses that may be imagined, till such time as other phenomena occur, by which they may either be made more accurate, or liable to exceptions.

Such brake on reckless inference-making is understandable, for Newton's was an age of transition from the older quest for *final* to one for *efficient causes* of phenomena. He was bombarded with demands for the cause of gravity to make it acceptable as the basis for a system of the world, and he could provide none. Exasperation with such requests led to his famous *'hypotheses non fingo'* statement against assumptions insufficiently warranted by experimental information.

How accurately does the scientific method thus defined describe research activity as it has been practiced since the time of Newton? About the first three rules there is no disagreement among scientists. It is around the character of its inductive part, as set down by Newton in the last two, that most controversies have centered.

To begin with, rules 4 and 5 do not faithfully eflect Newton's own work, as proved by the famous *'Queries'* at the end of his *Opticks*, where, after warning the reader that his statements are based on insufficient experimental information, he ponders with amazing instinct about the bending of light rays by massive objects, reciprocal transmutation of light and matter, the existence of powerful short range forces to explain chemical phenomena, the nature of magnetism, the origin of gravity and similar wondrous subjects.

They are not very accurate in describing the work of Newton's succesors, either. When Lagrange created his *Mécanique Analytique* the starting body of experimental data and intended realm of applicability were the same as in Newton's theory, so one could consider him to be at fault with respect to the same two rules: he introduced new concepts and laws (action, and its minimal principle) where they were not strictly necessary. Yet it was his version of mechanics and not Newton's that could be generalized to encompass field theories and quantum mechanics. In fact the motivation to write his classic text might have had little to do with available experimental evidence, as one is led to suspect reading in the introductory part of

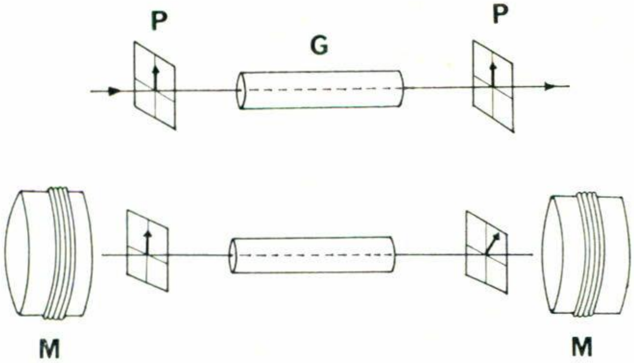

FIGURE 1. Farady effect. A rod of glass (G) leaves intact the state of linear polalrization (thick arrow in polarimeter P) of light going through it (top figure). But when placed between the poles of a powerful magnet (M), it rotates the direction of polarization by an angle that depends on the length of glass traversed and the strength of the applied field. Faraday discovered this phenomenon in 1845. In his words: "That which is magnetic in the forces of matter has been affected, and in turn has affected that which is truly magnetic in the forces of light."

the work his proud warning that the reader will find no diagrams in it, but a rational statement of mechanics.

In the course of his mathematical investigations on non-Euclidean geometry during the first half of last century, Gauss was led to the hypothesis that we live in curved space, and tested it constructing a large triangle with its vertices at the tops of three mountains in Germany, looking for a possible deviation of the sum of its internal angles from 180 degrees, which would have signaled the presence of curved space. He obtained a null result, not because the effect was not there, but because his experimental equipment was not precise enough to detect it. His pupil Bernhard Riemann considered again the same problem, and proposed that the metric of our space was determined by its material content. All this was more than half a century before Einstein's theory of general relativity. That the experimental information for such work was scant is proved by the fact that it was not taken up by any sizable fraction of the scientific community: it was too far 'ahead of its time'.

During his ingenious attempts to unify mechanics and optics, William Rowan Hamilton introduced in the 1830's certain waves in the mathematical space employed to study the motion of material particles. Under certain approximations, he obtained for these waves an equation identical with a basic one in optics. Again due to lack of sufficient experimental motivation, his work languished for almost a century, until it was revived by Schrödinger, who took it in the mid 1920's as the starting point in his search of an equation for the matter waves recently proposed by DeBroglie.

Almost contemporary with Hamilton's work was Faraday's attempt to prove the unity of all fundamental interactions. After his observation that variable magnetic fields produced electric effects, he discovered that a magnetic field was capable of making glass and other substances optically active, that is, able to rotate the plane of polarization of light going through them (Fig. 1). This convinced him that not only was light related to the electromagnetic field, but that similar effects should connect light with gravitation, and gavitation with electromagnetism. He spent many years looking for such phenomena, without success. A few decades later his work inspired Maxwell in the identification of light as a vibrating electromagnetic field. Again, Faraday's project anticipated by almost a century our present attempts to unify all basic interactions, initiated by Einstein around 1920.

How faithful are rules 1–5 in their description of present scientific activity? Let us examine two open contemporary problems, one from a mature science: the search for a theory of fundamental interactions based on superstrings; and one from a younger science: the reason to exist of introns, large segments of the DNA molecule that do not code for proteins and seem to play no other role in the cell.

Superstrings are extended one-dimensional mathematical constructs that evolve in space-time according to certain equations invariant under so-called supersymmetry operation [2], that interchange symbols used to describe fermions with those that represent bosons (Fig. 2). At present they are the only candidates to describe quantum gravity and all other known interactions in an unified way. Their promise stems from partial proofs of mathematical consistency, and from their ability to reproduce in the low energy limit the highly successful 'standard model' of the strong and electroweak interactions [3].

The outstanding problems in superstring theories are the following:

a) Mathematical consistency. It must be proved that all resulting scattering amplitudes, charges and masses are finite and have the right signs. Then there is the question of uniqueness: a truly unified theory of all known interactions is a theory of *everything*, so one would expect it to be unique, that is, no other theoretical possibilities must remain after satisfying the requirement of consistency.

b) Contact with experiment. The value of fundamental parameters in the standard model must be calculable in the correct superstring theory in terms of just one basic quantity, related to the tension of the strings. These parameters include the masses and all other features of leptons, quarks and elementary bosons appearing in that model.

Needless to say such vast and enormously difficult problem has only been carried out to a limited extent. Most of the effort has concentrated to date on part (a), initially yielding a partial proof of mathematical consistency for strings moving in a space-time of 10 or 26 dimensions. A source of embarrassment when the first string theories were proposed about fifteen years ago, the dimensions beyond the four directly observed by us now play an essential role in the unification of the known interactions. Their absence from ordinary experience is attributed to their having a very small lenght, so short that it cannot be directly explored with present day

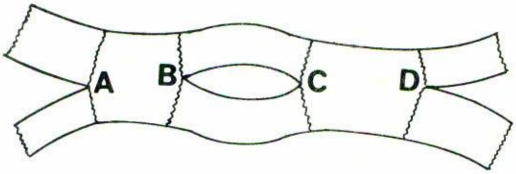

FIGURE 2. Two superstrings (wavy lines) join their end points at A, becoming a single one, that splits at B, rejoins at C and splits again at D. All known interactions: gravitational, electroweak and strong, are assumed to be low energy manifestations of such basic string behavior. Superstring theory involves the study of surfaces like this one, generated in space-time by moving strings.

accelerators. More recently promising superstring theories have been constructed in four space-time dimensions, but at the price of losing the remarkable degree of uniqueness achieved with the ones in 10 and 26 dimensions.

With respect to the phenomenological part, point (b), the record of superstring theories is much poorer. There is to date no single clearcut experimental prediction that one can associate with them. To go beyond the standard model one should be able to calculate quantities like the electron mass, or get confirmation for the correct string theory from very high energy phenomena. The problem now is that these energies are truly huge, of the order of 10^{19} GeV per individual event, so they will probably never be directly accessible to experiment.

Only in the past three years have there been attempts to make the dimensionality of space-time amenable to experimentation. One proceeds by looking for irreducible errors in the most precisely measured quantities of physical interest. Such unavoidable discrepancies between theory and experiment would presumably have originated in applying a 4-dimensional theory (*i.e.* the standard model or general relativity), to analize phenomena really taking place in D dimensions. To date the anomalous magnetic moment of the electron, the advance of Mercury's perihelion and the Lamb shift in the hydrogen atom have been employed as probes, yielding [4] $|D-4| < 10^{-11}$ as a limit on low energy manifestations of extra dimensions.

The technical tools employed in theoretical work on superstrings are extremely sophisticated, to the extent that articles on this subject tend to be close in language and content to purely mathematical ones. The excess of freedom from experimental guidance has led to a rather peculiar situation, indistinguishable at a distance from a

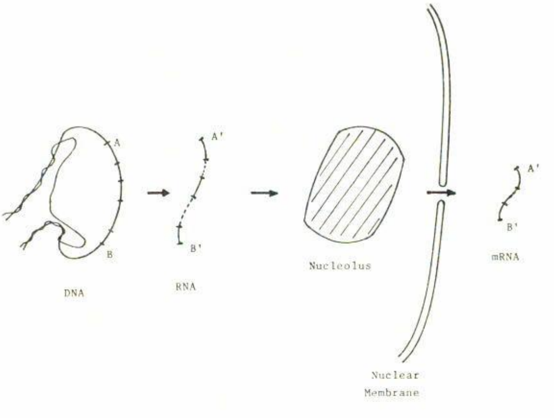

FIGURE 3. Introns in a DNA segment (AB) produce introns in its RNA transcription (broken line sectors), that are removed in the nucleolus before it can pass through the pores of the nuclear membrane as mRNA, to direct protein synthesis in the cytoplasm.

random run of many after the latest flare of mathematical virtuosity by the leaders of the field. This has given rise to some voices of concern about laxity in the adherence of the whole exercise to the scientific method. The feeling is perhaps best conveyed by the title of one of these articles of criticism: *Is physics becoming trivial?*

Introns are segments of the DNA molecule in eukaryotes that do not code for proteins and seem to have no other function in the physiology of the cell (Fig. 3). Discovered in 1977, their existence came as a great surprise. Outstanding experimental facts about them are [5]:

a) They comprise up to 90% of the fraction of the DNA molecule that gets transcribed into RNA. After processing in the nucleolus, only the meaningful 10% of the latter molecule abandons the nucleus as mRNA and is translated into proteins in the cytoplasm. Introns are subsequently degraded within the nucleus.

Exceptions to their apparent physiological irrelevance are very few:

b) Introns divide an RNA transcript into separate coding intervals, that can be spliced in various ways to produce several different proteins from a single DNA segment. The resulting advantage when small genomes are involved as of use to some viruses.

c) Lymphocites are able to change a certain intron into a coding sequence by moving a stop signal, thus transforming the corresponding protein from a hydrophobic into a hydrophilic one. The resulting antibody can then be released into the bloodstream, instead of staying anchored to the cell membrane.

d) In *Tetrahymena thermopila*, a protozoon, an RNA segment resulting from an intron becomes an enzyme when excised, a most remarkable one, as prior to its discovery all enzymes were supposed to be proteins.

Introns represent an apparently senseless investment of cell resources: an excessively long DNA molecule is synthesized, and only about 10% of its transcribed segments go into the production of proteins. So the problem of consistency of such level of waste with the darwinian requirement of natural selection of the fittest is a rather serious one.

Conjectures about them include the following:

i) They are just parasites in the DNA molecule, gradually acquired through the harmless intrusion of viruses and similar pieces of genetic material, whose presence gets amplified by the natural process of gene repetition.

ii) They are useful because mutations can accumulate in them without danger to the cell, until a future time when some will be expressed in the form of new or modified proteins.

iii) They are useful because they break a coding sequence into several pieces, increasing the probability of mutation by permutation, repetition or translocation of DNA segments.

None of these statements is satisfactory, if only due to their lack of predictive power. But, in spite of the serious conceptual difficulty they represent, most research publications about introns describe experimental discoveries and are almost devoid of theoretical analysis of their consequences. This neglect of the inferential part of the scientific method has aroused criticism from some molecular biologists. In a recent article one of them regrets the fascination of his latter day colleagues with experimental technique, to a point where research is degenerating into mere data accumulation [6]. A harsher critic calls them *zombies,* after voicing a similar complaint.

The above examples show that in mature sciences like fundamental physics the inductive element of the scientific method is emphasized, sometimes to the detriment of its empirical aspect. In sciences still in the process of self-definition, on the contrary, a situation can arise where the empirical aspect becomes dominant, affecting the health of the scientific enterprise through neglect of inferential activity.

But the contrast between these two extremes in scientific practice illustrates a difference of degree, a matter of emphasis on its diverse aspects, and does not seriously call into question the accuracy of our former definition of its method. One can understand the divergences found as originating in our contemporary, sharp division of scientists into theoretical and experimental ones. The ideal of the *natural philosopher* represented by Galileo and Newton, who combined theoretical and experimental work in their activity, is one rarely found today, especially in a mature science.

Nonetheless the traditional definition of the scientific method does require modification when viewed from another perspective. We have already mentioned the recurrent phenomenon of anticipation of major discoveries, going back to conditions where experimental information on the subject appeared insufficient to the majority of scientists to justify such inferences. To clarify this point further let us consider in some detail a very clear instance of work 'ahead of its time': the search of Louis Pasteur for a fundamental left-right asymmetry in the basic interactions known to him, electromagnetic and gravitational [7].

He is famous for his microbial theory of disease, the proof against spontaneous generation of life, the pasteurization process, the rabbies vaccine, his dramatic rescue of the wine and silkworm industries, and many other accomplishments. Less well known is his early research on optically active substances, an enterprise on which he invested no small amount of time and resources: the first of seven volumes comprising his collected works is entirely dedicated to this subject and his related hypothesis of a fundamental connection between optical activity and life.

Pasteur's starting evidence was a certain handedness observed in the behavior of tartaric acid, a substance he came across with during his studies on wine fermentation, around the middle of last century. Solutions of tartaric acid are of two kinds, that rotate in opposite directions the plane of polarized light going through them. Their mixture shows a degree of optical activity proportional to their imbalance in concentration. The sodium-amonium salt of tartaric acid produces two types of crystals, which are mirror images of each other. Following then current belief, he assumed their molecular building blocks to have the same mirror image relationship to each other as the macroscopic crystals, so he inferred that crystal-forming interactions were fundamentally non symmetric. From Faraday's discovery of optical activity induced in normal substances by a strong magnetic field, he concluded that the magnetic interaction was asymmetric, and inferred that similar ones shared this feature. These included in his time the electric and gravitational fields. From his own observation that microorganisms metabolized only one component of the optically active ammonium salt of tartaric acid, he came to consider life as an asymmetric phenomenon, whose handedness reflected that in the basic fields.

This breathtaking chain of inferences led him to look for possible sources of handedness in our surroundings, and to explore their effects on living systems. He considered the earth's rotation a candidate, for its mirror image would turn in the opposite sense. Such feature he connected with the proposed handedness of electric and magnetic fields, because they were supposed in his day to propagate through the aether, which was dragged along by massive objects like the earth. Solar light he saw as another source of asymmetry, because at any given moment it hits the earth at an angle that gets inverted in a mirror image.

To study the influence of such agents on biological substances he tried to amplify their effects growing plants in strong magnetic fields, or counter them with ingenious combinations of clockwork mechanisms and mirrors (Fig. 4). He could never detect any variation of handedness produced this way, and even conceded at some point to have been a bit crazy to try such experiments. But his conviction about the asymmetric character of the basic interactions never faltered, and towards the end of his scientific career he regretted having abandoned this search in favor of more practical endeavours.

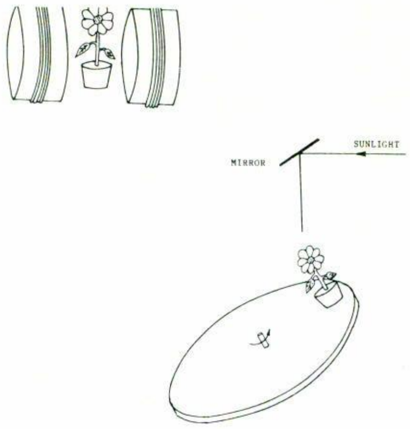

FIGURE 4. Pasteur's experiments on the origin of molecular asymmetry in living matter included growing plants in strong magnetic fields, and modifying the angle of incidence of sunlight with combinations of mirrors and clockwork mechanisms. In his words: "These asymmetric actions, perhaps of cosmic origin —are they luminous, electric, magnetic or calorific? Are they related to the earth's rotation or the current giving rise to its magnetism?" He could never produce a detecable change of molecular handedness with these and similar experiments, but the conviction behind his question never abated.

Today we know that his conjectures was right: the interaction giving rise to atoms and molecules and crystals is indeed 'chiral' (Greek *cheir*, hand), *i.e.*, endowed with a basic handedness. But experimental confirmation of this result didn't come until the late 1950's, from careful analysis of nuclear disintegrations. At the atomic level considered by Pasteur, the effects are even subtler, and it is only in the past decade that they have been unequivocally identified. The sole divergence from his expectations is that handedness in inherent to the *electroweak* interaction, which gives a more faithful description of reality than the separate weak and electromagnetic ones proposed in the past.

Chirality is an example of *symmetry breaking*, or the approximate fulfilment of symmetries in nature. Symmetry breaking is at the root of all modern theories on the structure of matter, and can be contrasted with an older view that sought unity in the unfolding of higher and higher exact symmetries. But this gradual change in outlook has only taken place in the last thirty years, after the work of T.D. Lee and C.N. Yang on parity non conservation in nuclear decays. This is one whole century after Pasteur's search for asymmetries based on a similar conviction.

Induction is a fascinating subject. While conceding that arguing from particular experiments and observations to general conclusions constituted no demonstration of them, Newton judged this "the best way of arguing that the nature of things admits of". It represents not only our widest avenue to new scientific knowledge, but in a sense our only one, for human experiences are necessarily finite in number, and without our power to connect and generalize them our pace of development would be exceedingly slow. Besides, deductive knowledge presuposes a set of basic rules or axioms, themselves a result of induction.

It has proved a difficult concept for philosophical analysis, the ensuing frustration being all too evident in a statement by the philosopher C.D. Broad: "Induction is the triumph of natural science and the disgrace of philosophy". The epistemologist Karl Popper chose instead to deny its existence. Newton's preocupation with it is attested to by the rules he gave for its proper use, and by his numerous warnings against "feigning hypotheses". For him a hypothesis was any statement not granted or required by available evidence. This introduced an unavoidable subjective element, through the decision about what was to be considered sufficient or insufficient evidence to make a given assumption into a hypothesis or an inference.

The inductive process involves our powers of imagination at a subtler level than the deductive aspect of theoretical work. In the latter, one has a sufficient conceptual and phenomenological basis to construct either the solution of the problem at hand, or a range of possible solutions, together with their probabilities of occurrence, as in the case of quantum mechanics. Induction, on the other hand, implies making choices based on incomplete information; so incomplete, in fact, that our ignorance cannot be quantified in statistical terms. It becomes at times indistinguishable from what Pauli once called 'instinct' referring to Dirac's uncanny ability to stick to the right path in his treatment of the negative solutions to his relativistic equation for the electron, a trail that would eventually lead to the discovery of antimatter.

Hence imagination plays a more profound role in induction than in the rest of the scientific method. But imagination transcends our scientific approach to the world. Artistic, philosophical and religious answers to the problems arising from our interaction with the universe all depend on imagination to a very high degree. It will thus come as no surprise that such a potent agent of knowledge also wields a tremendous power to mislead the mind when improperly handled. We can re-interpret Newton's oft-repeated constraints on induction as so many warnings against irresponsible use of the imagination. Our point in this article is that in his zeal to keep it under control, he ended up confining it within bounds too narrow to allow full realization of its potential.

The need remains to define the correct role of imagination in scientific practice. There is of course a final arbier on its performance, for as an instruments of learning it has survival value, a point forcefully emphasized in Konrad Lorenz's theory of "evolutionary epistemology" [8]. Hence, the wrong solution to a given scientific problem will sooner or later be abandoned, as failure to do so entails the risk of punishment by the environment. A piece of art or a philosophical system wholly out of tune with its cultural milieu is destined to fall into oblivion.

But our human condition shows little inclination to submit to such a relentless judge. So a more immediate and less definitive one must be devised, in the form of certain rules of thought that will keep imagination within profitable limits. We will leave the identification of such rules as an open problem, and limit ourselves to venturing a suggestion on a way to relax the traditional curbs on induction, as a preliminary step towards a similar treatment of the wider issue of imagination.

Newton's contraints on induction were entirely justified in his time and circumstance, and their overall effect on scientific activity has been healthy: the greatest spirits have not been hindered in their research by them, and lesser ones have been helped focus attention on fruitful questions. Nevertheless, to bring our description of the scientific method into closer accord with actual practice, we might entirely dispense with Newton's rules 4 and 5, leaving the first three as our contemporary definition. In this way a statement would result consistent with the occurrence of scientific anticipation. Such fertil guides in research as the expectation of beauty and harmony in natural laws would take their rightful place in scientific research, as inferences on inferences. Imagination would thus be awarded center stage, empirical work becoming the provider of anchors to keep inference-making from drifting into fantasy.

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Resumen. El papel de la inducción, o razonamiento de casos particulares a ideas generales, fue cuidadosamente delimitado por Newton en su definición del método científico. Algunas de las reglas que fijó para su empleo son demasiado restrictivas, y no corresponden a prácticas aceptadas en el quehacer científico contemporáneo.