Data, Phenomena, and Theory: How Clarifying the Concepts Can Illuminate the Nature of Science

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Learning about the Nature of Science (NOS) has been an item in most science curricula reforms for the past few decades.[1] It has been given special prominence in recent U.S. science reform projects such as the National Science Teacher Association's (NSTA) *Scope Sequence and Coordination*;[2] American Association for the Advancement of Science's (AAAS) *The Liberal Art of Science,*[3] *Project 2061*[4] and *Benchmarks for Science Literacy;*[5] the U.S. National Academy of Science's *National Science Education Standards*,[6] and their subsequent publication *Inquiry and the National Science Education Standards: A Guide for Teaching and Learning*.[7]

Elsewhere I have advocated a "softly, softly" approach to teaching NOS, an approach whereby one concentrates on case studies, drawing out their significant features as the occasion, students, and circumstances allow; this case study method is tantamount to an inductive approach to NOS.[8] A softly, softly approach is not without its problems — such as identifying and justifying the criteria for selecting cases, and deciding how directive we should be in seeing that the proper methodological lessons are learned.

I want here to continue the "softly, softly" approach and investigate a tripartite distinction between data, phenomena and theory (DPT).[9] The investigation sheds some light on NOS matters, and perhaps some light on research in science education.

DATA, PHENOMENA, AND THEORY IN EDUCATION DOCUMENTS

The DPT constellation is commonly mentioned in science education documents. For instance, *Science for All Americans* in its chapter on NOS notes that:

> Sooner or later, the validity of scientific claims is settled by referring to observations of phenomena. Hence scientists concentrate on getting accurate data. Such evidence is obtained by observations and measurements taken in situations that range from natural settings (such as a forest) to completely contrived ones (such as the laboratory)....Scientists do not work only with data and well-developed theories. Often, they have only tentative hypotheses about the way things may be....Scientists strive to make sense of observations of phenomena by inventing explanations for them that use, or are consistent with, currently accepted scientific principles. Such explanations — theories — may be either sweeping or restricted.[10]

NSTA's blueprint for reform, *Scope, Sequence, and Coordination,* notes that:

> Empirical law is a generalization of a relationship that has, through observation or measurement, been established among the phenomena represented by two or more concepts...but which rely on no theory or model for its expression or utilization....A theory is used to explain facts, observations, phenomena, and empirical laws....A model is a mental picture or representative physical system of a phenomenon.[11]

These statements contain the terms: "theory," "evidence," "phenomena," "observation," "data," "measurement," "hypothesis," "model," and "explanation." The statements suggest that the terms are grouped as follows: *Data* — Evidence about phenomena obtained by observation or instrumentation; *Phenomena* — The name given to what is observed or measured; and *Theory* — Serves as explanation of the phenomena, or properties of it, that are identified.

THE CENTRALITY OF DPT IN EPISTEMOLOGY

The DPT triplet has featured whenever the epistemology of science (or, earlier, natural philosophy) has been discussed. Since Aristotle, the routine methodological question for philosophers has been "How does theory relate to evidence? Or, given certain evidence, how justified are our theories (knowledge claims) about that evidence?" Empiricists, inspired by Aristotle's commitment to the sensory foundation of knowledge ("nothing in the mind that is not first in the senses"), have given certain answers to how theory and data are related (various forms of both inductivism and of deductivism). Rationalists, inspired by Plato's commitment to knowledge transcending the limits of sense ("we see through the eye, not with the eye"), have given a variety of other answers to how theory relates to evidence.

The traditional methodological debates have assumed that data (evidence) was, or could be made, secure and uncontroversial. The engaging philosophical issue was how discrete, limited and particular evidence could support universal knowledge claims such as are typically found in scientific theories and law statements. But Russell Hanson and Thomas Kuhn's work on the theory dependence of observation has drawn attention to the problematic status of evidence itself.[12] The "D" term in DPT has become as contentious as the "T" term. But it has been widely assumed that, if data (D) could be secured (with or without theory dependence), then the phenomena (P) was consequently secured or fixed. That is, it seems widely held that the phenomenon is no less, but no more, problematic than the observation of it. But delineating phenomena is not quite so simple; there is a gain in NOS understanding if the three DPT concepts are separated.

SOCIAL SCIENCE

In social science it is notoriously hard to identify the phenomena, even when data is uncontroversial. Data from IQ testing (Stanford-Binet scores, or any other test score) is consistent with phenomena of low intelligence, low motivation, low reading ability, test anxiety and so on. In this case, just what is the phenomena that theory has to explain, is up for grabs, or up for ideological contest. Are we to explain an individual's low intelligence, low motivation, low reading ability, or nonacademic home situation? What we theorize about and how we conduct research depends on what phenomenon we take the IQ test data as revealing.

Likewise for numerous other examples in social science: Is the phenomenon to be explained in the Gulf War, defence of democracy or defence of petroleum interests? Is the phenomenon of British arrival in *Terra Australis* to be identified as settlement or invasion? Is a child's behavior manifesting the phenomenon of Attention Deficit Disorder or Spoilt Brat Syndrome? In Israel do we have the phenomenon of one country defending its legitimate right to exist, or the phenomenon of illegal occupation and theft of another people's land? Was the USSR a Russian Empire or a Union of Soviet Republics? Were the Japanese liberating or invading South-East Asia in 1941? Is a woman exercising her right to choose or is she killing an infant? And so on.

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The theoretical explanations will differ depending on how the phenomenon is described and conceptualized. The road from data to phenomena is rocky, and strewn with methodological, theoretical, ideological, and cultural obstacles.

NEWTON ON PHENOMENA

A brief examination of Newton's usage of the terms "observation," "phenomena" and "hypothesis" is sufficient to suggest that the explication of the DPT concepts is not as straightforward as often assumed. In a celebrated passage at the end of Book III of the *Principia*, Newton writes:

> I have not been able to discover the cause of those properties of gravity from phenomena, and I frame no hypotheses; for whatever is not deduced from the phenomena is to be called an hypothesis; and hypotheses, whether metaphysical or physical, whether of occult qualities or mechanical, have no place in experimental philosophy.[13]

In a draft of the *Principia* Newton writes:

> Phenomena I call *whatever can be seen and is perceptible* whatever things can be perceived, either things external which become known by the five senses, or things internal which we contemplate in our minds by thinking…but those things are *properly called* phenomena which can be seen.[14]

However in Book II of his *Principia*, after laying out his Rules of Reasoning in Philosophy (our science), Newton has a section on Phenomena, where among six phenomena that he believes his System of the World has to account for, are listed:

> That the fixed stars being at rest, the periodic times of the five primary planets, and (whether of the sun about the earth, or) of the earth about the sun, are as the 3/2th power of their mean distances from the sun.…That the moon, by a radius drawn to the earth's centre, describes an area proportional to the time of description.[15]

Now these are manifestly not observational statements; they cannot to be phenomena in the terms that Newton had earlier laid down. They are statements of the phenomena to be explained. As Newton acknowledged, these phenomena come from the work of the giants on whose shoulders he stood: Galileo, Kepler, and Brahe.

Indeed to speak of planetary orbits as phenomena is itself indicative of the large, but usually unnoticed, gulf between observation and phenomena. Orbits are simply not observed. What are observed are planetary movements against the fixed stars. It was Plato who introduced the phenomena of orbits when he postulated that the observed planetary movements were indeed part of a closed loop, an orbit. He superimposed the notion of orbit onto chaotic observations, including retrograde loops, that simply did not, and could not, manifest or display orbits. For Plato, the "thing" that astronomers had to explain was the planetary orbit that he took to be circular. Circular orbits were then the phenomena for which astronomical science needed to provide explanations.

Kepler's "elliptical planetary paths" were, in turn, phenomena separate from, and not necessarily implied by his astronomical observations, data, and measurements. As William Whewell noted in the nineteenth century in his critique of Mill's inductivist account of science, the concept of an elliptical path was supplied by Kepler's mind, not by his data. There is usually no univocal inference from data to phenomena. Phenomena is underdetermined by data, just as theory is underdetermined

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by evidence. In the above case, the data is probably consistent with periodic times of 5/4th power of mean distance.

FROM DATA TO PHENOMENA

"Phenomenon" has its origin in Greek language and philosophy where it meant "that which shows itself." In the Aristotelian, direct realist tradition, the move from observation to phenomenon was thus straightforward: what was observed was that which was revealing itself. Bacon did, in the early seventeenth century, famously warn against the influence of the "Idols" on how things were seen; he wanted a cautious or reflective kind of direct realism. With Kant, the immediate connection between observation and phenomenon was broken. The mind, Understanding, or forms of intuition, contributed something to what was observed; observation was no longer objective, and so also the phenomenon was no longer purely objective. Kant called the world-as-it-is the *noumenon*, but to this we have no unmediated access.

In the natural and social sciences, real objects (processes, events, occurrences, states) are observed either in natural settings (Aristotle's preference) or experimental settings (Galileo's, and subsequent Western science's, preference). The observation can be immediate (with eyes, microscopes) or inferred (meter readings, instrument displays). The observations are then verbalized, described, written, or tabulated (or "re-presented," as some prefer). This has to be done in a language (including mathematics), and according to some theoretical standpoint. This is all done in the realm of discourse. These descriptions are characteristically sifted, sorted, and selected — lots of readings and descriptions are simply thrown away, or ignored. The result is scientific data. These then are the raw representations of real objects (processes, events, occurrences, states). This step is clearly theory dependent. A range of falling red apples, or swinging weights on a string are, in physics, represented as points on a graph, as printouts on a tickertape, as lines on a screen. These representations are not meant to mirror, or copy, the real. They are precisely meant to represent the real, and representations vary with our purposes. Economists, artists, dieticians, and farmers, for instance, have different ways of representing apples. Adequacy of representation simply does not mean correspondence of representation, in the sense of the representation mirroring the object.

Scientific representations can change. Leonardo represented the pendulum pictorially, Galileo and Huygens represented it in geometric form, Newton represented it algebraically. The variously theorized pendulums are not meant to correspond to real objects: What does it mean for a sentence to correspond to a real object? For a point to correspond to a falling stone? Likewise the idea of a group's average age may not correspond to anything, in the sense that no one may be the average age. Yet the notion of a group's average age, weight, intelligence, longevity is perfectly respectable and usable, and is the "thing" that social scientific theories have to explain, and are judged against. Representations are in the domain of discourse, and are separate from the domain of the real. Thus they cannot, in any serious sense, mirror or correspond to real states of affairs. Their adequacy and theoretical utility does not depend upon correspondence.

For example, with pendulums, even highly refined experimental apparatus will give a scatter of data points. The laws of pendulum motion are not meant to, and

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cannot, explain these data points. They are too erratic. However in science, from data comes phenomena; and it is the phenomena which is the subject of scientific laws and theories. Often a line of best fit is put through the data points, and the line is then taken to represent the phenomena being investigated. Thereafter it is the phenomena which are discussed and debated, not the data. A line of slightly different fit, would constitute a different phenomenon.

Or, again, any number of individual telescopic observations, when corrected and selected, constitute astronomical data. From this we infer, construct, invent planetary phenomena: circular orbits, elliptical orbits, heliocentric or geocentric orbits. The latter are not seen. They are not observational. But this is no scientific impediment. Once we settle on the phenomena, it becomes the subject matter of our scientific theories. Likewise, a line of best fit is put through a scatter of points, and we declare that PV = constant. This, Boyle's law, is taken as a phenomenon to be explained by scientific theory. Once identified, phenomena are stable. And they can, by the right person in the right circumstances, be identified quickly.

Data is idiosyncratic. Different scientists, using different equipment, test procedures, statistical analyses, will generate different data. But this does not necessarily imply different phenomena. Pooling idiosyncratic data, triangulating, is meant to establish more firmly the relevant phenomena. One of Galileo's major achievements was to "reduce" the observationally different motions of free fall, levers and inclined planes to that of the balance. The balance became a "model of intelligibility" of all these motions. The motions were "seen" as examples of the balance, and of Archimedean balance principles.[16]

Aristotle was the high priest of observational science; he elevated observation to a position of epistemological primacy in natural philosophy from which it has seldom been moved. The British empiricists, with their commitment to tracing back all meaningful statements to sense impressions, continued, under a different name, this Aristotelian orientation. For example, David Hume wrote: "all our simple ideas in their first appearance are deriv'd from simple impressions, which are correspondent to them, and which they exactly represent."[17] The twentieth century positivists and logical empiricists were also Aristotelian as regards the primacy they accorded observation, and observation statements in their logic of science. Ernest Nagel, in his influential *The Structure of Science*, wrote:

> Scientific thought takes its ultimate point of departure from problems suggested by observing things and events encountered in common experience; it aims to understand these observable things by discovering some systematic order in them; and its final test for the laws that serve as instruments of explanation and prediction is their concordance with such observations.[18]

What is underdeveloped in Nagel's statement is that although science takes departure from "observations of things and events" the "final test of laws" is not quite their "concordance with such observation."

Structured Interrelations

Galileo's marvelous mathematical proofs of the pendulum's properties did not receive universal acclaim: on the contrary learned scholars were quick to point out substantial empirical and philosophical problems with them.[19] Guidobaldo Del

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Monte, the foremost mathematician and technologist of the late sixteenth century and patron of Galileo, and others repeatedly pointed out that actual pendula do not behave as Galileo maintained. Galileo never tired of saying that *ideal* pendula would obey the mathematically derived rules.

The empirical problems were examples where the world did not "correspond punctually" to the events demonstrated mathematically by Galileo. In his more candid moments, Galileo acknowledged that events do not always correspond to his theory; that the material world and his so-called "world on paper," the theoretical world, did not correspond. Immediately after mathematically establishing his famous law of parabolic motion of projectiles, he remarks that:

> I grant that these conclusions proved in the abstract will be different when applied in the concrete and will be fallacious to this extent, that neither will the horizontal motion be uniform nor the natural acceleration be in the ratio assumed, nor the path of the projectile a parabola.[20]

One can imagine the reaction of del Monte and other hardworking Aristotelian natural philosophers and mechanicians when presented with such a qualification. When baldly stated, it confounded the basic Aristotelian and empiricist objective of science, namely to tell us about the world in which we live. Consider, for instance, the surprise of Giovanni Renieri, a gunner who attempted to apply Galileo's theory to his craft, who when he complained in 1647 to Torricelli that his guns did not behave according to Galileo's predictions, was told by Torricelli that "his teacher spoke the language of geometry and was not bound by any empirical result."[21]

The law of parabolic motion was supposedly true, but not of the world we experience: this was indeed as difficult to understand for del Monte as it is for present-day students. Furthermore it confounded the Aristotelian methodological principle that the evidence of the senses is, with some qualifications, paramount in ascertaining facts about the world. That is, with a healthy observer, in a normal situation, then what the eye sees is what is the case. The situation might usefully be represented as follows:

Level 1	Fundamental Laws and Mechanisms	eg. Gravitational Attraction Simple Harmonic Motion
Level 2	Phenomena, Scientific Models, Idealizations,	eg. Four Pendulum Laws (mass & amplitude independence; period varies as square root of length; isochronous oscillation)
Level 3	Data	Individual period measurements for different masses, amplitudes, lengths; scattered points on a graph
Level 4	Observation	Perceptual experience of swinging pendulum
Level 5	Objects, Events and Processes in world	eg. Weight swinging on end of cord

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Level Five is constituted by objects, processes, and events in the world; Level Four is constituted by perceptions, observations and psychological states occasioned by events in world; Level Three is constituted by the representation of observations; this is data; Level Two is constituted by phenomena such as "isochronous motion" which can be represented by models, or empirical laws, or equations such as $T=2\pi\sqrt{l}/g$; and Level One is constituted by fundamental scientific laws or high-level theory.

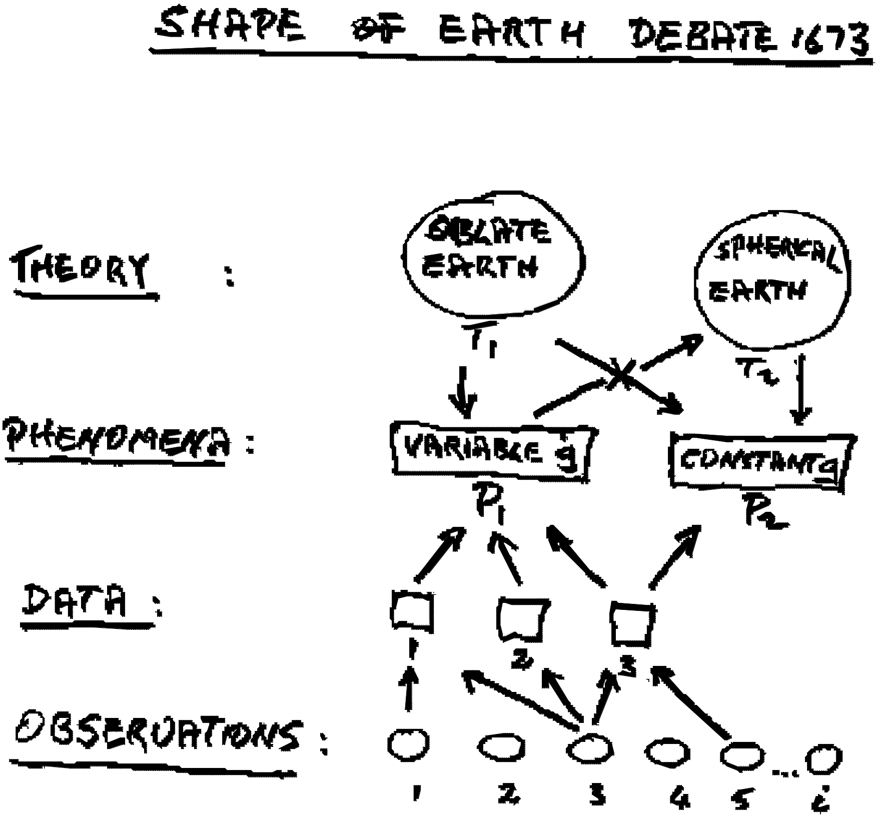
Level One claims are not immediately tested against level Three observations because these latter are too idiosyncratic, particular, and messy. Just as a falling autumn leaf manifests the law of gravitational attraction but does not display it, so to does a swinging pendulum manifest but not display the law of simple harmonic motion (a body's motion is such that the restoring force acting on it is proportional to its displacement from its point of equilibrium). Level One claims are tested against level Two, not against level Three. Getting level Two assertions from level Three data requires "cleaning up," "smoothing out," creating lines of best fit, idealizing. And once all this is done we still need to identify and name the phenomena which is manifest in the cleaned up data. Does the line represent natural motion or forced motion? Does the test data represent cognitive learning or conditioned behavior? Do the points manifest parabolic motion or chaotic motion? Galileo's pendulum laws belong to level Two; they are not meant to correspond to level Three data, and they cannot be induced from such data.

This set of distinctions and structured levels can be seen in Nancy Cartwright's arrestingly titled book *How the Laws of Physics Lie*.[22] Cartwright maintains that we have to choose between fundamental laws that are explanatory and empirically true laws; she says we cannot have both. Her problem is basically the very old one of giving epistemological primacy to level Three dwellers. If this is done, then Galileo's opponents were correct in saying that his pendulum laws lied. But this is to misunderstand what level fundamental laws should be appraised against, they are judged against phenomena and their properties, not against raw data.

One can repeat the above example with the everyday phenomenon of a falling autumn leaf, where: Level Five is the real event of a falling autumn leaf; this might be called *everyday* phenomenon; Level Four is someone's observation of the falling leaf; Level Three is the recorded data in the form of time/displacement graphs, trajectory plots, and so on (this will be completely chaotic); Level Two is the identification of the *scientific phenomenon* being displayed, namely free fall under various influences (gravity, resistance, turbulence, and so on); and Level One is the appropriate theory or mechanism, namely the law of gravitational attraction, to explain level Two.

The chaotically moving autumn leaf "obeys" a number of fundamental causal mechanisms — gravitation, air resistance — but its path (data points) does not illustrate or confirm the appropriate laws. Contrary to Nancy Cartwright's claims, we need not believe that the fundamental laws of physics lie, they might lie about appearances (level Three items above) but if we abandon the long entrenched, Aristotelian-based, conviction that the laws should be about level Three items, then we can maintain their truthfulness. They are true of phenomena, not of data.

Or consider the seventeenth-century debate about the shape of the earth, a debate that was occasioned by data indicating that a seconds pendulum had to be shortened (3mm) at the equator in order to keep beating seconds.



Here,

Observations, O_{1-i} might be the experiences of Jean Richer and other astronomers in the 1670s who were testing the length constancy of the seconds pendulum in different latitudes.

Data, D_1 , D_2 , D_3 might be the representations of the observations as recordings, graphs. Note that O_2 ,O_4 have not given rise to data; the experiences were discounted

Phenomena, P_1 and P_2 are, respectively, the assumption of a variable gravitational strength from pole to equator, and a constant gravitational strength. Historically most of the data, D_1 — D_4 suggested P_1 which was contrary to expectation and contrary to Huygens suppositions. But some of the data D_3 was consistent with P_2.

Theories T_1 and T_2 are respectively the theory of an oblate earth (Newton) and a spherical earth (Huygens). T_1 implies P_1 and negates P_2 ; whereas T_2 negates P_1 and implies P_2 .

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Even when P_1, the phenomenon of variable gravity, was established, natural philosophers could, and did, defend the conservative spherical earth theory T_2. Huygens final appeal was to the effect of centrifugal force at the equator, claiming that it effectively diminished the influence of gravity (the gravitational pull downwards on the body was slightly counteracted by the centrifugal movement away from the centre). This sustained T_2 until Huygens himself worked out mathematically what the precise effect was, and recognized that it did not account for the magnitude of variation. He, and others, then abandoned the spherical earth theory.[23]

Ronald Giere's view is comparable to that argued here. When discussing the laws of pendulum motion he says:

> On my alternative interpretation, the relationship between the equations and the world is *indirect*.…the equations can then be used to construct a vast array of abstract mechanical systems…I call such an abstract system a *model*. By stipulation, the equations of motion describe the behavior of the model with perfect accuracy. We can say that the equations are exemplified by the model or, if we wish, that the equations are *true*, even *necessarily* true, for the model.[24]

CONCLUSION

Real events and processes occur naturally or in experimental situations; both are immediately observed with the senses, or else they are "observed" at one remove via instrument readings; data are the representation (mathematical, graphical, narrative) of these observations; the appropriate *scientific* phenomenon is identified from the data, usually this involves idealization, abstraction, and disregarding "noise" in the data; theories then compete to explain the identified phenomenon. Theory affects data and observation, which is a problem for classical empiricist aspirations. But phenomenon are relatively resistant and stable; once identified, they are to be explained by theory, but they do not change with every adjustment of theory or with choice of alternative theories. Once identified, the phenomena of gravity varying with latitude was fixed; different theories then were generated to account for this phenomena.

Philosophy is not far below the surface in any science classroom. At a most basic level any text or scientific discussion will contain terms such as "law," "model," "explanation," "cause," "truth," "knowledge," "hypothesis," "confirmation," "observation," "evidence," "idealization," "fields," "species" and so on. Among such terms are "data," "phenomena" and "theory." Philosophy begins when students and teachers slow down the science lesson and ask what these terms mean and what the conditions are for their correct use. Thinking through the conceptual connections in DPT is just one route into philosophical thinking that the science classroom provides, but it is an important one whose outcome can generalize into other classrooms and subject matters.

Disentangling the conceptual stratigraphy of DPT allows greater appreciation of the distinct empirical and conceptual issues involved when for instance Galileo's Pendulum Laws, Boyle's Law, Dalton's model, or Darwin's theory is discussed. And, over time, such engagement and thinking promotes a richer and more solidly based understanding of the nature of science.

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1. See Michael R. Matthews, *Time for Science Education: How Teaching the History and Philosophy of Pendulum Motion Can Contribute to Science Literacy* (New York: Kluwer Academic Publishers, 2000); Michael R. Matthews, *Science Teaching: The Role of History and Philosophy of Science* (New York, Routledge 1994), chap. 3; William McComas and Joanne Olson, "The Nature of Science in International Science Education Standards Documents," in *The Nature of Science in Science Education: Rationales and Strategies*, ed. William F. McComas (Dordrecht: Kluwer Academic Publishers), 41-52; and James Donnelly, "Contested Terrain or Unified Project? 'The Nature of Science' in the National Curriculum for England and Wales," *International Journal of Science Education* 23 (2001): 181-95.

2. National Science Teachers Association (NSTA), *Scope, Sequence and Coordination: A Framework for High School Science Education* (Washington DC: NSTA, 1992).

3. American Association for the Advancement of Science (AAAS), *The Liberal Art of Science: Agenda for Action* (Washington DC: AAAS, 1990).

4. American Association for the Advancement of Science, *Project 2061: Science for All Americans* (Washington DC: AAAS, 1989); also published by Oxford University Press (1990).

5. American Association for the Advancement of Science, *Benchmarks for Science Literacy* (New York: Oxford University Press, 1993).

6. National Research Council, *National Science Education Standards* (Washington DC: National Academy Press, 1996).

7. National Research Council, *Inquiry and the National Science Education Standards: A Guide for Teaching and Learning* (Washington DC: National Academy Press, 2000).

8. Michael R. Matthews, "In Defense of Modest Goals for Teaching About the Nature of Science," *Journal of Research in Science Teaching* 35 (1998): 161-74 and Matthews, *Time for Science Education*, chap. 13.

9. The distinctions have been discussed recently by a number of philosophers. See esp. James Bogen and James Woodward, "Saving the Phenomena," *The Philosophical Review* 97, no. 3 (1988): 303-50; Matthias Kaiser, "The Independence of Scientific Phenomena," *Poznan Studies in the Philosophy of the Sciences and the Humanities* 44 (1995): 179-200; and James Woodward, "Data and Phenomena," *Synthese* 79 (1989): 393-472.

10. *Project 2061: Science for All Americans*, 27.

11. *Scope, Sequence, and Coordination: A Framework for High School Science Education*, 188-90

12. Norwood Russell Hanson, *Patterns of Discovery* (Cambridge: Cambridge University Press, 1958) and Thomas S. Kuhn, *The Structure of Scientific Revolutions,* 2d ed. (Chicago: University of Chicago Press, 1970).

13. Isaac Newton, *Mathematical Principles of Mathematical Philosophy* [1729], trans. A. Motte, rev. F. Cajori (Berkeley: University of California Press, 1934), 547.

14. Peter Achinstein, "Newton's Corpuscular Query and Experimental Philosophy," in *Philosophical Perspectives on Newtonian Science*, ed. P. Bricker and R.I.G. Hughes (Cambridge: MIT Press, 1990), 137.

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