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Facts-well-Put

DAVIS BAIRD AND ALFRED NORDMANN

ABSTRACT

In this paper we elucidate a particular type of instrument. Striking-phenomenon instruments assume their striking profile against the shifting backdrop of theoretical uncertainties. While technologically stable, the phenomena produced by these instruments are linguistically fuzzy, subject to a variety of conceptual representations. But in virtue of their technological stability alone, they can provide a foundation for further technological as well as conceptual development. Sometimes, as in the case of the pulse glass, the phenomenon is taken to confirm conflicting theoretical views; sometimes, as in the case of the Lichtenberg-figures, it holds out the false promise of crucial theoretical importance; sometimes, as in the case of the airpump in the 18th century, it emphatically short-circuits theory and human ingenuity, giving a voice to nature herself; and sometimes, finally, as in the case of the quincunx, the phenomenon stands in for theoretical accounts. We propose and develop the salient features of these instruments demonstrating their importance to our understanding of science.

> ***Professor Marcus:*** *And, if I may say so, you have a very curious and charming house. Such pretty windows. I always think that the windows are the eyes of the house, and didn't someone say the eyes are the windows of the soul?*
> ***Mrs. Wilberforce:*** *I don't really know but, oh, such a charming thought, I do hope someone expressed it.* *(Ladykillers)*

1 INTRODUCTION

Like all good jokes, this one skirts a profound insight. To be sure, Mrs. Wilberforce's rejoinder appears a bit foolish. After all, Alec Guiness alias Professor Marcus, had just expressed this beautiful thought right then and there—what a queer request, thus, that someone should express it! And yet, Mrs. Wilberforce knows that it takes more to express a thought than the mere ability to mention or cite it, to rattle down its content. A charming thought needs to be expressed well. It needs to be appropriately framed. The aphorism, for instance, is one way of appropriately framing a thought: 'The eyes are the windows of the soul' or 'An aphorism, like an artwork, must stand apart from the world which surrounds it, self sustaining in its own perfection—like a hedgehog'. (Schlegel in Grenzmann [1976], p. 197). A thought well put.

As with thoughts, so with facts or natural phenomena. In the words of Charles Sanders Peirce:

> When an experimentalist speaks of a *phenomenon*, such as 'Hall's phenomenon', 'Zeeman's phenomenon' and its modification 'Michelson's phenomenon', or 'the chessboard phenomenon', he does not mean any particular event that did happen to somebody in the dead past, but what *surely will* happen to everybody in the living future who shall fulfill certain conditions. The phenomenon consists in the fact that when an experimenter shall come to *act* according to a certain scheme that he has in mind, then will something else happen, and shatter the doubts of skeptics, like the celestial fire upon the altar of Elijah. ([1934], 5.425)

Ideally a phenomenon has the striking and persuasive quality of the divine blaze by which Elijah embarrassed the 450 prophets of Baal, but it must also be constant and reliable, a permanent fixture of the living future.

Phenomena are often framed by experimental apparatus, indeed, only technological ingenuity may be able to create certain phenomena. There may thus be a type of scientific instrument which serves the purpose of putting facts well. We want to elucidate this type of instrument.[1] And to elucidate *one* type of instrument is, perhaps, to suggest a larger, more comprehensive typology of instruments which, however, we are not providing. After all, typology and the identification of types is, Max Weber tells us, not to be confused with classification and the delimitation of classes: the point is not to establish a neat grid of slots into which any given instrument is conveniently and mechanically fitted. The identification of types serves a heuristic purpose, serves the purpose of identifying, perhaps (in the Weberian sense) idealizing, but certainly preparing and isolating for further scrutiny, a feature of interest, whether or not that feature cleanly demarcates one instrument from another (Weber [1949], pp. 90ff.).

The identification of the striking-phenomenon instrument is central to our more general research interests on the nature of 'instrumental' scientific knowledge on the one hand, and a theory of meaning in scientific practice on the other. While our construction of this type of instrument idealizes features of interest to us, its relevance is not limited to our particular research agendas. For instance, striking-phenomenon instruments challenge any purely methodological account of scientific experimentation and any purely theory-oriented attempt at the rational reconstruction of scientific activity. They also promise possibilities for a new form of *instrumental* scientific realism (Baird [1988]; Brown [1990)]; Ihde [1991]), and they provide a fresh variant to the long-standing concern with the historical and epistemological primacy of technology over theoretical science (compare *e.g.*, Heidegger [1976]). Perhaps most important, our construction of this type of instrument is one step toward a better understanding of the rôle of instruments in science, and an antidote to the idea that all scientific instruments are measuring instruments.

We develop and articulate the type, gradually building the case for its importance to theories of knowledge and meaning in science, by considering four striking-phenomenon instruments. We tell the stories of their initial development and subsequent fate,

(1) highlighting the salient features, which make them striking rather than, for example, merely clever, impressive, or ingenious; *i.e.* highlighting what renders them appealing as toys or lastingly effective as demonstration devices;

[1] As such this study moves in the footsteps of, *e.g.*, Peter Galison's explorations of detection devices in his [1985], [1987]; Galison and Assmus [1988].

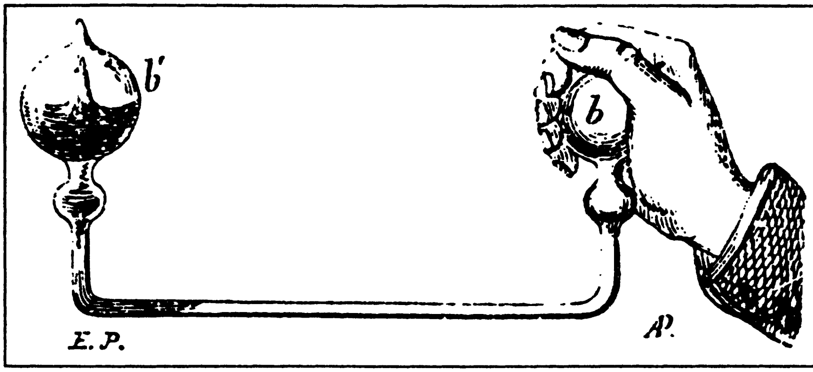

FIGURE 1 Pulse glass. *From*: Turner [1983], p. 114.

(2) showing how each of the four instruments underwent a unique development in relation to theory and methodology, thus substantiating the claim that their history in the theoretical realm is at least somewhat independent of their history in the instrumental realm, *qua* striking phenomena (the relative autonomy *vis-à-vis* theoretical developments); and finally,
(3) suggesting that in each of these instruments intersected various trajectories of meaning, that they served as focal point of interests and activities which extend beyond science.

2 SALIENT FEATURES: THE PULSE GLASS

2.1 *What It Is*

A pulse glass consists of a narrow tube bent at right angles at either end, with two larger spheres on the ends. The tube is roughly $\frac{1}{3}$ to $\frac{1}{2}$ filled with water or alcohol, evacuated and sealed (Figure 1). Because of the vacuum, the liquid in the glass can be brought to boil by holding it in one's hand. Several toys are now made from pulse glasses. The 'fever meter' and the 'drinking duck' are two such toys. By holding the lower sphere of the fever meter in one's hand, one can cause violent boiling in the upper sphere. By appropriately suspending the duck, it will rock back and forth 'drinking' from a cup of water virtually indefinitely.

The pulse glass was brought to the attention of the scientific world by Benjamin Franklin in a 2 July 1768 letter to John Winthrop ([1972], v. 15, p. 170; see also his [1941]). Franklin learned of the pulse glass while travelling in Germany, almost certainly from Johann Friedrich Hartmann (Walz [1962], p. 62). While the original development of the pulse glass in Germany remains somewhat of a mystery (Baird [1991b]), we know that William Hyde

Wollaston is responsible for its ultimate arrival as a standard demonstration instrument in the 19th century. Under its new name 'cryophorus' (Wollaston [1812], [1813]), the instrument was discussed in virtually every textbook for chemistry up to the end of the 19th century.

2.2 *A Fact Well Put*

The first and probably most important feature of the pulse glass is that it embodies a phenomenon so compellingly. Franklin clearly was taken with the pulse glass:

> I bored a very small hole through the wainscot in the seat of my window, through which a little cold air constantly entered, while the air in the room was kept warmer by fires daily made in it, being winter time. I placed one of his[2] [pulse] glasses with the elevated end against this hole, and the bubbles from the other end, which was in a warmer situation, were continually passing day and night, to the no small surprise of philosophical spectators. Each bubble discharged is larger than that from which it proceeds, and yet that is not diminished; and by adding itself to the bubble at the other end, that bubble is not increased, which seems very paradoxical ([1972], v. 15, p. 170).

Franklin *enjoyed* the phenomenon and the effects of its display. In the appended notes to his poem, *The Botanic Garden*, Erasums Darwin echoes Franklin's delight:

> The quick evaporation occasioned in vacuo by a small degree of heat is agreeably seen in what is termed a pulse glass, [...] (Darwin [1978], vol. 1, Additional Notes p. 67).

The phenomenon is *agreeably* seen, the instrument engages us immediately. And while it may arouse our curiosity, the phenomenon needs no further explanation to be appreciated.

Here we have the first salient feature of the striking-phenomenon instrument: instrument and phenomenon are perfectly integrated, *i.e.* the technology utilized for the exhibition of the phenomenon serves no other purpose than to sustain just this phenomenon. The instrumental compactness of the phenomenon also makes for an ideal philosophical toy: at all times ready for the instantaneous recall of a phenomenon, the drinking duck provides the pocket-edition of a natural fact.

2.3 *Theoretical Context*

Even long after the pulse glass was recognized as a technologically certified

[2] He refers to Edward Nairne, a well-known commercial instrument maker in London at the time. Franklin frequented his shop and commissioned several instruments—including several pulse glasses. Nairne suggested several experiments which Franklin describes with the pulse glass.

striking phenomenon, its theoretical context remained unclear. The striking-phenomenon instrument shares this with natural phenomena that its description and explanation depend on theoretical interests while *it* persists through theoretical change. This relative autonomy of the fact-well-put *vis-à-vis* theory is the second salient feature of the striking-phenomenon instrument, setting it apart from apparatus devised and employed for the experimental test of particular hypotheses.

Benjamin Franklin's previously cited account of the pulse glass reveals that he appreciates the phenomenon under at least two descriptions: (1) bubbles 'were continually passing day and night', *i.e.* the phenomenon involves a sort of perpetual motion; (2) the discharged bubbles get larger without diminishing the air from which they spring, *i.e.* something appears to emanate from nothing. He also notes—(3)—that,

> [T]he instant it begins to boil a sudden coldness is felt in the ball held; a curious experiment [. . .] similar to the old observation, I think of Aristotle, that the bottom of the boiling pot is not warm; and may help to explain that fact, if indeed it is a fact ([1972], v. 15, p. 171).

Franklin's readiness to associate (3) with the rather implausible 'fact' reported by Aristotle testifies to the striking power of the pulse glass: it introduced cognitive dissonance, leading Franklin to question what otherwise would have remained unquestioned common knowledge. Moreover, while Franklin observes that—(4)—the liquid in the pulse glass begins to 'boil', Erasmus Darwin spoke of—(5)—'the quick evaporation [. . .] *in vacuo*'. While descriptions (4) and (5) are today considered equivalent, one can imagine a theoretical context where it is at least a question whether (4) and (5) designate the same fact.

If Franklin's interest in Aristotle's strange fact reveals the extent of his sheer puzzlement, James Watt provides a description of the pulse glass from an entirely different point of view. Writing as if he was perfectly able to explain the phenomenon, he notes in his editorial comments on John Robison's *System of Mechanical Philosophy*:

> The invention of the pulse glass is ascribed to Dr. Franklin, its date uncertain, probably subsequent to my improvement of the Steam Engine, at least certainly not known to me at that time. The boiling in vacuo was known long before the pulse glass was invented ([1822], v. II, p. 14).

Why should Watt care whether the pulse glass was invented before or after his improvement on the steam engine? As Watt would put it, steam engines derive their motive power from the elasticity of steam. Watt believed that the pressure at which the steam was generated affected its ability to produce power. According to Watt, then, the pulse glass—(6)—demonstrates that the boiling of water and the generation of power depend on pressure. Indeed, he thinks the pulse glass demonstrates this so strikingly that it threatens to diminish his originality as inventor of the steam engine.

The list of descriptions does not end here. Since Watt's views on the relationship between heat, work, pressure, and the elasticity of steam are now considered obsolete (Baird [1989]), it would have to include contemporary theoretical jargon—(7)—that the pulse glass represents a reversible isothermal transformation. Finally, Wollaston saw that—(8)—the pulse glass demonstrates the transmission of cold, and A. P. Saunders (see below) pointed out—(9)—that it illustrates the nature of thermal equilibria ([1908], p. 279).

All the while, the pulse glass remained technologically stable. The resilience and dependability of the phenomenon represent the unchallenged technological certainty that—(10)—the pulse glass exhibits an instance of natural agency. Moreover, even though a complete and uncontested theoretical account of the pulse glass is available today, the fascination of the pulse glass remains. The striking phenomenon cannot be diminished by or reduced to a theoretical explanation. And all of this testifies to the relative autonomy of the fact-well-put as a salient feature of the striking-phenomenon instrument, it renders (10) a point of instrumental certainty in a sea of linguistic and theoretical confusion.

2.4 *Instrumental Developments*

The pulse glass never assumed theoretical prominence. Even while Franklin and Watt struggled for an understanding of the phenomenon, scientists did not make this a priority, and the ultimate explanation emerged as a byproduct of the independent theoretical development of the ideal gas laws. In the meantime, though the pulse glass remained ill understood and did not further theoretical developments, it was perfectly capable of promoting the further instrumental development of science. This is a third salient feature of the striking-phenomenon instrument.

The first instrumental development was William Hyde Wollaston's 'cryophorus'. Wollaston used the cryophorus to show how cold could be transmitted: by immersing one bulb of the pulse glass in ice water, the water in the other bulb—at a distance of three feet or more—could be frozen.

Wollaston's cryophorus became the basis for J. F. Daniell's dew point hygrometer. Daniell built a thermometer inside one of the arms of the cryophorus. The bulb on the end of this arm was partially filled with water. The other—dry—bulb was covered with silk. By pouring ether on the silk cover, the temperature in this bulb would decrease. This, in turn, would cause the water in the water-filled bulb to evaporate and cool the water-filled bulb. One could then note the temperature of the water in the water-filled bulb with the included thermometer just when dew began to form on the bulb (Daniell

[1820a] and [b]; [1823]; see also Reid [1839], p. 699 and Middleton [1969], pp. 115–7).

Through the 1800s the cryophorus was commonly used to demonstrate the effect of pressure on evaporation, and simultaneously the heat loss suffered in evaporation (Comstock [1845], p. 20; Graham [1842], p. 63; Turner [1847], p. 46). As late as 1908 A. P. Saunders used the cryophorus to explore thermal equilibria with a substance in its three different states. Though Saunders speaks of the 'experiment of the cryophorus' ([1908], p. 279), his 'experiments' require unattainably efficient means to isolate the instrument energetically and ideally efficient means to keep the temperature of the bulbs constant. Wollaston's glass-and-water cryophorus has become, for Saunders, a 'thought instrument' or rhetorical device.

The pulse glass thus contributed to science a compact instrumentally framed fact, a relative technological certainty in a sea of theoretical confusion, and the foundation for further instrumental development. And it is primarily for these three salient features that we choose to call it a striking-phenomenon instrument.

3 FRAMING THE PHENOMENON: ELECTROPHORE AND LICHTENBERG-FIGURES

3.1 *Instrument and Experiment*

Our second case study moves beyond the identification of salient features by detailing the process through which a striking phenomenon is carefully and deliberately crafted. As with the pulse glass, the Lichtenberg-figures provide an autonomous technological certainty in a sea of linguistic confusion. Also, the Lichtenberg-figures gave rise to further instrumental developments. But as opposed to the pulse glass, with the Lichtenberg-figures we have the use of a particular instrument (the electrophore) for the production of a striking phenomenon, rather than the development of the instrument exclusively as a frame for that phenomenon.

One might insist on a distinction between a striking-phenomenon *experiment* and a striking-phenomenon *instrument*. For from the time of its invention by Alessandro Volta (and perhaps independently by Wilcke), the electrophore promised broad space for new experimental opportunities. Indeed, Lichtenberg himself first describes the electrophore in 1768 as providing an open and as of yet undetermined space for experimental opportunities:

> Overall, this instrument has to be regarded as remarkable: partly because of the phenomena which it exhibits, and partly because of the zeal and ardor possessing once again the physicists themselves in their endeavor to investigate the wonderful properties of electricity ([1956], p. 18).

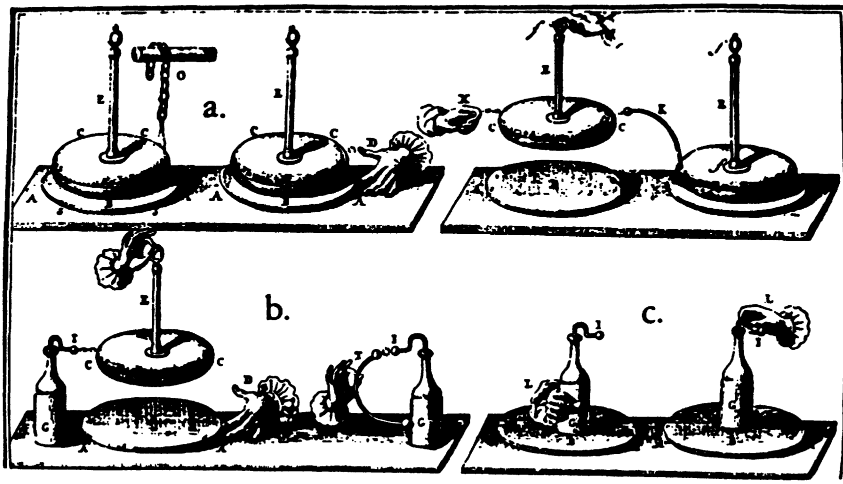

FIGURE 2 Electrophore. *From*: Volta [1918–1929], vol. 3, p. 101.

This sounds programmatic rather than specific since it was not clear at the time what the electrophore had to offer besides being a powerful alternative to the electrical machine.

It is here where deliberate crafting stepped in, carefully adapting the (already striking) characteristics of the electrophore so that they could serve as an effective frame for a particular phenomenon. With this second case study we see the gradual transformation of the electrophore into a device particularly suited for the production and display of Lichtenberg-figures. This striking phenomenon thus appropriated the space of experimental possibility provided by the electrophore.

3.2 *A Perpetual Engine*

The electrophore provided a new and apparently inexhaustible means for building electrical charge, and, for this reason, like the electrical machine, it served as an auxiliary instrument for charging a Leyden Jar. It has two parts. The bottom part consists of a 'cake', usually made of resin, sitting in a grounded metal dish. The top part consists of a lid made of tin-foil wrapped around wood with an insulated handle (Figure 2). As one rubs the resin cake with cat's fur, negative charge accumulates on the non-conducting resin, thus (since opposite charges attract one another) inducing the metal dish to become positively charged which, in turn, maintains the negative charge in the cake. The lid is now placed on the cake. Repelled by the negative charge of the cake, negative charge accumulates on the top of the lid, while the bottom of the lid becomes positively charged. Merely by holding a charge the resin cake thus serves to separate out positive and negative charges in the lid. Moreover, if one now touches and grounds the top of the lid, its negative charge is dispelled into the earth, and when taken off, the lid remains positively charged. That positive charge can now be discharged into a Leyden jar. The process can be repeated any number of times: placing the lid on the still negatively charged cake, transferring more and more positive charge from the lid into a Leyden jar, the cake forever retaining its negative charge. Volta called it *elettroforo perpetuo*, and it was called 'the most surprising machine hitherto invented' in the third edition of the *Encyclopaedia Britannica* (quoted in Heilbron, p. 416).

3.3 *An Inverted Microscope*

While the electrophore quickly became a source for building charge, it remained uncertain whether it exhibited new electrical phenomena. This concern stands at the beginning of Lichtenberg's first report concerning the dust-figures:

> And when I saw that an instrument with a diameter of 18 inches produces effects such as one can hardly expect from a costly ordinary electrical machine, I resolved to build an electrophore of considerable size. In that I was especially motivated by the seeming aberrancies from the phenomena as hitherto observed: these I believed, and I guess justifiably so, to be eliminable by using a larger instrument. For, executing experiments with larger instruments is tantamount to observing the exhibited phenomena under a microscope: what went unnoticed beforehand to the most acute eye even with greatest scrutiny, can no longer remain forever unnoticed even by the sloppiest and most inconsiderate observer with the dullest sense once it is enlarged in this manner ([1956], pp. 18ff.).

In order to accentuate the phenomena, to amplify and exhibit them strikingly even to the casual observer, Lichtenberg thus built an electrophore with a diameter of 80 inches from which he was able to draw sparks 15·5 to 17 inches long which corresponds to a charge of about 200 kV (Zimmermann [1988], p. 158; compare Finn [1971]). The enlarged electrophore was to 'render the latent sensible' as such becoming an exemplary scientific instrument:

> The enlargement of experiments. That not only renders matters more forcefully, but also displays the component parts. As witnessed quite splendidly with the electrophore (Lichtenberg [1968–74], vol. 1, p. 522; compare vol. 2, p. 458 and Fischer [1982]).

3.4 *Lichtenberg-Figures*

Lichtenberg's transformation of the electrophore into a more sensitive device for the detection and display of new phenomena paid off very quickly. In 1768,

FIGURE 3 Lichtenberg powder figure produced by C. F. Carlson. *From*: Carlson [1965], p. 16.

he observed how dust (from polishing the resin cake) settled on the cake in a peculiar and delightful pattern. The dust did not settle on the cake evenly,

> but to my greatest joy at particular places only, configured to little stars. At first they were barely discernible but when I purposely added more dust they became very distinct and beautiful and often resembled a sublime work. Almost uncountable stars, milky ways, and greater suns would occasionally form. The arcs were dull at their concave edge, and at their convex edge adorned with multifarious rays. Splendid little branches originated, not unlike those brought forth by the frost on window-panes; small clouds in multifarious forms and shades, and finally many figures of particular shapes ([1956], p. 21).

The dust-figures were first identified as a striking phenomenon by noting their apparently exhilarating qualities which had to be expressed in terms of the beautiful and the sublime (Figure 3) (see Stern [1959], pp. 41ff.). However, to recommend the dust-figures as a striking phenomenon there was more than the aesthetic response to their delightful shapes. Lichtenberg's first observation of the figures also demonstrated the peculiar capacity of the electrophore to maintain its charge indefinitely.

> But a most pleasurable spectacle exhibited itself to me when I saw that these figures were virtually indestructible. After carefully wiping the dust away with a feather or a hare's paw I still could not prevent the figures which had just been destroyed from forming anew and even more splendidly (Lichtenberg [1956], p. 22).

The formation and re-formation of the suns, stars, and milky-ways had now taken on the theatrical dimension of an on-going spectacle, moving forward as quickly as the enthusiasm and scrutiny of the experimenter would allow:

> I therefore spread an adhesive substance on a sheet of black paper, laid it on the

> figures and pressed slightly. Thus I succeeded in making some prints of the figures. [. . .] This new method of printing was most welcome to me in order to advance quickly; for I had neither the desire nor the time to either draw or destroy all the figures (Lichtenberg [1956], p. 22).

At this point, a major obstacle still stood in the way of perfecting the electrophore as a striking-phenomenon instrument:

> All the figures on the electrophore that were mentioned so far had been produced by accident; the mode of their creation was hitherto completely unknown at least to me (Lichtenberg [1956], p. 22).

Lichtenberg removed this obstacle by establishing that the shapes represented a pocket of positive charge within the either neutral or negatively charged cake, a pocket created by discharges from the lid into the cake. He thus reconfigured the electrophore by utilizing it no longer to build charges which he would then save in a Leyden Jar, instead directing the discharges from the lid back onto the cake. The dust merely renders visible, it records or traces these underlying pockets of positive charge within the resin cake.

Having discovered the figures and their mode of creation, Lichtenberg devoted himself to the technical improvement of the experiment. He produced figures on a smaller electrophore, in a vacuum. He invented the 'double-electrophore', a development which led to numerous further technical improvements (Przibram [1927], pp. 391ff.). One innovation stands out, namely a simple device to direct the discharge, *i.e.* the course of electrical motion. By increasing the charge he applied to the cake and by conducting the discharge along a chain laid out on the cake, he was able to draw figures, even print letters (Lichtenberg [1956], p. 27). He describes a gift to his former teacher and fellow electrician:

> I gave Kästner his name, namely just the initial K, written with a border in electricity, all behind glass in a golden frame. He was quite beside himself about it (Lichtenberg [1983–5], vol. 1, p. 794).

And he compares his experimental production of the letters GR (Georgius Rex–George III of England) with Franklin's 'even more childish' political experiment to eliminate that King. Surely Franklin would respect *his* 'GR' (Lichtenberg [1983–5], vol. 1, pp. 783 and 793).

At this point, the figures' standing for the purposes of demonstration, contemplation and play is virtually insured.

> [T]hough these experiments may not belong to the class of shiny ones, they can nevertheless compete with them, and I do not doubt that my apparatus will at some point be assigned a place in the repertoire of the virtuosi (which is, indeed, no small honor) (Lichtenberg [1956], pp. 20ff.).

Lichtenberg's prediction was to come true. In 1781 he reports that

> in various parts of Germany, so I am told, a small apparatus is offered for sale. It bears the strange title: an instrument for explaining frost on window-panes according to Professor Lichtenberg. [. . .] The artisans were presumably seduced by a metaphor I used when comparing some of the figures with the little trees on frosted window-panes (Lichtenberg [1956], p. 51).

This completes the development of a philosophical toy just like the pulse glass. This small apparatus has only one purpose, it is designed exclusively as a frame for the Lichtenberg-figures, instrument and phenomenon are perfectly integrated.

3.5 *Theoretical Promises*

The initial process of crafting and framing the dust-figures as a phenomenon changed the character of the electrophore, transformed it into a striking-phenomenon instrument. In the course of this process, various further instrumental developments took place and the integration of experiment and phenomenon was accomplished. However, Lichtenberg managed to bring out yet another striking characteristic of his dust-figures. Convinced that these figures would prove to be theoretically relevant, he further modified his apparatus to produce pockets of negative charge within a now neutral or positively charged cake (Figure 4). He noticed different 'inverted' figures by 'writing' with negative, instead of positive, electricity:

> [T]he figures become negative, so to speak, namely dark on the background of dust, while the others consist of dust on a dark background (Kästner in Lichtenberg [1956], p. 17).

Accordingly, Lichtenberg attempted to show just how his experiment provided a 'New Method to Investigate the Nature and Motion of Electrical Matter'. He hoped that his method might resolve the controversy concerning the number and nature of electrical fluids, *i.e.* the debate between unitarians or Franklinists and dualists or Symmerians. The unitarians posited just one electrical fluid, normally in a neutral state, a surplus or deficit of which making for positive or negative electricity. The dualists hypothesized two electrical fluids, two kinds of electricity, each a positive force which balances the other out in the neutral state. Without attempting to confirm or refute any of the current views, without proposing a new theory of his own, Lichtenberg wished to recommend his method as a means to settle the dispute insofar as it recorded the different motions of electrical matter.

Ironically, however, the Lichtenberg-figures ended up making theoretical contributions of a different kind entirely. Instead of providing a means to decide between competing theories, they served to render the entire debate undecided and obsolete (Nordmann [1991]). In order to recommend his method to both parties, Lichtenberg introduced a terminological convention which 'the

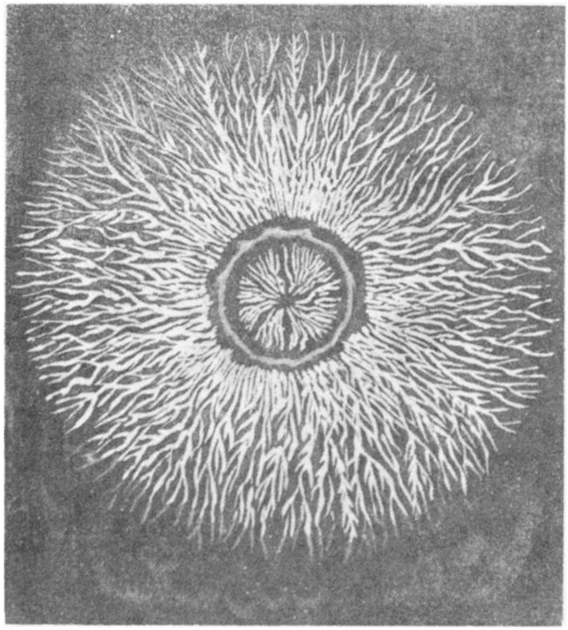

FIGURE 4A Positive Lichtenberg figure. *From*: Lichtenberg [1968–1974], vol. 3.

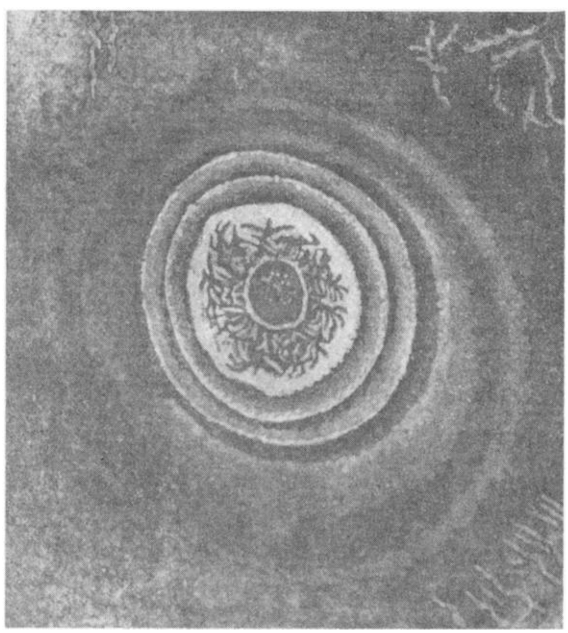

FIGURE 4B Negative Lichtenberg figure. *From*: Lichtenberg [1968–1974], vol. 3.

investigators of this or that school can use without danger of damage or controversy' (Lichtenberg [1956], p. 35). He recognized that the Franklinian quasi-algebraic talk of 'positive' and 'negative' electricity is 'especially fitting' to the Symmerian conception of fluids which exert opposite forces that cancel each other out (Lichtenberg [1983–5], vol. 2, p. 843). He therefore suggested that the designation +E and −E would capture the shared conviction 'that there are two electricities or two modifications of a single matter which cancel each other out according to the rules of positive and negative magnitudes' (Lichtenberg [1956], p. 34). Aside from providing common ground, this semantic innovation constituted yet another important step towards the quantification of electricity which characterized electrical theory of the 19th century but which 'did not, however, resolve all or perhaps even the chief qualitative difficulties that had worried' the unitarians and dualists (Heilbro, p. 490).

3.6 *Reverberations*

Lichtenberg's linguistic contrivance to recommend his striking phenomenon for theoretical consideration had removed the necessity to do so (see Fierz [1950–51]). And along with the theoretical issue, the Lichtenberg-figures fell by the wayside. They never again assumed theoretical centrality. By the same token, having introduced a relatively autonomous and irreducible element of cognitive dissonance, the Lichtenberg-figures still persist as a touch-stone for theoretical and instrumental developments. A physical explanation of the figures did not emerge until well into this century (in terms of the ionization of the atmosphere, see Przibram [1927]). And just recently, Lichtenberg's production of the figures in a vacuum has been reconsidered in light of research on high-energy electrical phenomena (Anders [1989]). And his comparison of the figures to ice flowers is now taken seriously by chaos-researchers (for their striking resemblance to Mandelbrot fractals, see Zimmermann [1988], p. 161). And most consequential perhaps were the Lichtenberg-figures as a new method of writing and printing. Chester F. Carlson, the inventor of xerography, traces his invention back to Lichtenberg as discoverer of 'the first electrostatic recording process' (Carlson [1965], p. 16).

A phenomenon, according to Ian Hacking, is 'public, regular, possibly law-like, but perhaps exceptional' ([1983], p. 222). To produce a phenomenon is to stabilize an observed occurrence, to prepare it for public scrutiny, to enable its display in a regular, law-like fashion. And as Hacking or Peirce would insist, the 'mere' production of phenomena is a particular contribution to science in its own right. As we saw in Lichtenberg's case, the development of a striking-phenomenon instrument shows the kind of work that needs to be done to accomplish that task. And as we will see in the remaining two case studies, this work firmly roots the phenomenon within the overall lived experience of scientists who deal with it. Accordingly, knowledge of what the phenomenon is and of what it takes to produce it proves to be a radically different kind of scientific knowledge than knowing that or why the phenomenon is observed. And the striking phenomenon itself carries a residuum of meaning that reaches well beyond its scientific meaning as attributed from theoretical and methodological contexts.

4 STRIKING, INGENIOUS, AND CRUDE PHENOMENA: EXPERIMENTS WITH THE AIRPUMP

It was argued that the electrophore promised space for new experimental opportunities, a space which was subsequently occupied by a particular type of experiment. On first sight, our third case involves a similar story. Robert Boyle's airpump or pneumatical engine drove a great number and a great variety of experiments. From among this variety, one dominated the latter part of the 17th century, another one the 18th century. So here again we will see a striking phenomenon appropriating a broader space for experimental opportunities.

However, this case takes us one step further. Since the airpump served as a host for very different experiments, it allows us to contrast striking phenomena with ingeniously contrived, theoretically relevant phenomena. Additionally, we can contrast our striking pheneomenon with an equivalent experimental procedure that is crude rather than striking. These comparisons will press the issue: What makes striking phenomena striking, and what kind of scientific accomplishment do striking-phenomenon instruments represent?

4.1 *An Ingenious Experiment*

For the purposes of British science, Robert Boyle invented the airpump in 1660. He presented it in a book entitled *New Experiments Physico-Mechanicall, Touching The Spring of the Air, and its Effects, (Made, for the most part, in a New Pneumatical Engine)*. In 1948, the first of two important historical studies concerned with Boyle's work was published. James Bryant Conant's *Robert Boyle's Experiments in Pneumatics* presents Boyle as providing ingenious experimental proof of the spring of air and of the vacuum.

The experiment in question was the *vacuum-in-vacuo* or void-in-the-void experiment. It explored the nature of the void which appears in a barometer as the column falls. What is in the empty space above the column? Opinions were divided, some arguing that there was literally nothing, a vacuum, others that there had to be something there, an ethereal fluid maybe. Boyle placed the barometer into the receiver of an airpump. He set out to show that the height of the column and the volume of empty space above it depended proportionally on the degree by which he exhausted the receiver: the more air he pumped out, the lower the column fell, suggesting that if he succeeded to completely evacuate the receiver, the column would fall entirely and the space above the column would merge with and prove identical to the content of the exhausted receiver: mere absence of air, a vacuum. The strict proportionality of this was to show that no other physical processes were at work, ruling out the physical reality of a spreading ethereal fluid. Boyle thus made an experimental statement about the relation between the so-called Torricellian vacuum in the barometer and the Boylean vacuum in the exhausted receiver of the airpump.

Conant's account was supplemented and revised in 1985 by Steven Shapin and Simon Schaffer's *Leviathan and the Air-Pump: Hobbes, Boyle, and the Experimental Life*. They insist that there was no such thing as a simple experimental proof presented by the airpump. Experimental proof was to be had only under the supposition that one can infer from the actual working of an imperfect instrument what a perfectly working machine would show. Also, experimental proof required the adoption of certain methodological norms, standards of proof intimately tied to the experimental life. Shapin and Schaffer show that all these suppositions were contested by Hobbes, rendering the *vacuum-in-vacuo* experiment a philosophical *cause celebre* in the late 17th century. They show that in the end, and for reasons not at all obvious, Boyle and the experimental life prevailed. And only within the experimental life did it become possible to say, as Conant does, that the *vacuum-in-vacuo* experiment represents experimental proof of the vacuum.

On both accounts, Boyle's production of experimental proof took considerable ingenuity. Conant emphasizes Boyle's clever contrivance of a theoretically crucial experiment, while Shapin and Schaffer highlight the rhetorical effectiveness of his experimental methodology. But once Boyle's ingenuity had accomplished its goal, once the experiment was accepted as a form of proof, what was the further fate of this experiment, how did the void-in-the-void fare in the 18th century? For those who had understood the proof, the experiment became a 'mere' gauge: once the relation between the Torricellian and Boylean vacuum was agreed upon, the height of the barometric column could be used to measure the quality of the airpump, the degree to which the receiver could be evacuated. Here, then, is the demise of an ingenious experiment from theoretical *cause celebre* to pedestrian gauge.

4.2 *A Striking Phenomenon*

The transformation from ingenious experiment to pedestrian gauge occurred only for the informed members of Boyle's community of experimental scientists. For those who had not yet understood the proof and remained uninitiated, the void-in-the-void could still serve as a demonstration experiment, an introduction to the theory of the day. As such, it may have invited a

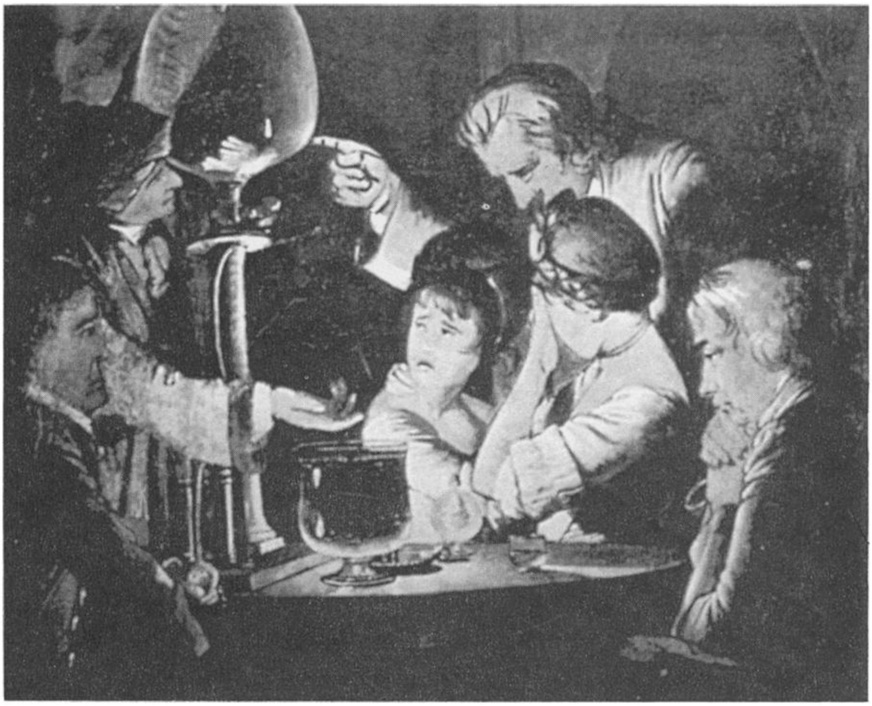

FIGURE 5 Sketch for *Experiment with the Airpump*, Joseph Wright of Derby [1768].

discourse of the kind displayed in the sketch by Joseph Wright of Derby (Figure 5). The sketch depicts a gathering around a lecturer who shows, explains, and instructs. Instrument and experiment are subsidiary to human ingenuity which contrives experiments such as the void-in-the-void and which contrives instruments like the orrery as the mechanical equivalent to our theoretical models of the solar system.

But the experiment in this sketch is not the void-in-the-void experiment. While also performed by Boyle already, this experiment with a bird in the evacuated receiver of the airpump engages its audience in a radically different kind of discourse, as suggested in the following passage by Joseph Priestley:

> All true history has a capital advantage over every work of fiction. Works of fiction resemble those machines which we contrive to illustrate the principles of philosophy, such as globes or orreries, the use of which extend no further than the views of human ingenuity; whereas real history resembles the experiments with the airpump, condensing engine and electrical machine, which exhibit the operations of nature, and the nature of God himself ([1817–31], pp. 27f.).

In order perhaps to do justice to this categorical difference between experi-

FIGURE 6 *Experiment with the Airpump*, Joseph Wright of Derby [1768].

ments for demonstration or instruction and the striking experiment with the bird in the airpump, Joseph Wright revised his sketch to produce this final version (See Figure 6). As depicted now, the experiment is not subsidiary to, but carries further than the views of human ingenuity. The experimenter's gaze transports it outwards, we see here a direct transmission or exhibition of the operations of nature. Nothing appears to intervene between experiment, experimenter, and the viewers of the painting (Busch [1986]; Nordmann [1994]).

Priestley's and Wright's views of the airpump do not rest on the *vacuum-in-vacuo* experiment which provided clever experimental proof. Their view exploits the power exerted over the imagination by experiments like the one with a bird flapping helplessly in the evacuated receiver. And as the painting suggests, an eery and haunting experiment it is. A bird is suffocating from lack of air, right in front of our eyes and yet deprived of something that surrounds us all. The space under the belljar is a stage for the performance of novelty and difference, hermetically sealed off against the world of spectators, yet perfectly transparent to them. However, not through our visual but through our auditory sense do we experience the commencement of action. We hear the cranking of the pump, a noise dramatically similar perhaps to the winding of a clockwork mechanism: the mystery will unravel as soon as the spring is tightened. While these grinding sounds contribute effectively to the gradually mounting suspense, the phenomenon itself unfolds in eery silence. Since sound-waves do not travel in the vacuum, the pitiful reactions of the suffocating bird, while immediately present to our visual sense, remain distant and aloof to our auditory sense. If only to re-enforce these ambiguities of proximity and remove, the bird itself suffers in three distinct ways under the condition of the vacuum: it is suffocating, it is unable to make itself heard, and it is limp, its flapping wings do not enounter the resistance of air.

Against this spectacle pales the void-in-the-void experiment with its slow and always imperfect diminishment of a barometric column. However, there is nothing ingenious about putting animals in the receiver of an airpump and just watching what happens. No theories are refuted or rejected, only theoretically long-familiar physical features of the vacuum and of animal organisms confirmed. As the experiment with the bird appropriated the experimental space of the vacuum under the receiver, there arose a changed conception of the airpump: the airpump has become the host for striking-phenomenon experiments.[3] Functioning as a stage on which nature exhibits her operations, the pneumatic engine is now an instrument that simply drives the ceaseless production of phenomena. Indeed, as if to confirm the lack of methodological standing for the experiment of the bird in the airpump, Joseph Wright's painting depicts an entire series of experiments that lacks a common theoretical denominator. Aside from the experiment with the bird, there will be one involving some tissue now in a jar, another one utilizing Guericke-spheres, yet others employing a watch suspended in the vacuum or the barometer.

4.3 *A Crude Experiment*

No matter how evocative our descriptions of striking phenomena, these descriptions cannot substitute for an analysis of just what makes some experiments striking and others 'merely' ingenious. If Boyle performed both experiments, if the methodologically ingenious experiment had soon completed its well-defined persuasive task, what accounts for the unbroken vigor of a theoretically uninteresting experiment? What is so spectacular about the spectacle of a bird that is deprived of air? Or, posing the question in Priestley's terms: why is it that this experiment resembles not fiction but real history?

An obvious answer suggests itself. The experiment with the bird involves issues of life and death, the fate of the bird simply is much more important than the relative height of a barometric column, it appeals more directly to human concerns. Moreover, in respect to this general and profound concern, we may

[3] At this juncture, our discussions of the electrophore and the airpump tie in with social constructivist interpretations of technology. Compare, for example, Wiebe Bijker's article on changing social and technological conceptions of 'the bicycle' (Bijker in Bijker *et al.* [1989]).

have overlooked so far the, if ever so limited, theoretical or methodological importance of the experiment.

Indeed, a case can be made for this. As noted above, one of the experiments waiting to be performed in Joseph Wright's painting involves a watch suspended in the vacuum. Presently, however, the watch is held by the person immediately to the left of the airpump. He appears to be timing just how long it takes for the bird to suffocate. In other words, data are collected and these data may figure into a larger context. Already in 1670, Robert Boyle describes such a context in his 'New Pneumatical Experiments about Respiration' including 'A Comparison of the Times wherein Animals may be killed by Drowning, or withdrawing of the Air':

> To help myself and others to judge better of some difficulties concerning respiration, I thought it might be useful, that we compared together the times, wherein animals may be killed by that want of respiration which in those that are drowned is caused by the water that suffocates them, and that other want which proceeds from withdrawing the ambient air. [. . .] A greenfinch, having his legs and wings tied to a weight, was gently let down into a glass body filled with water; the time of its total immersion being marked: at the end of a half a minute after that time the strugglings of the bird seeming finished, he was nimbly drawn up again, but found quite dead ([1809], pp. 486ff.).

Boyle's experiment with the greenfinch is precisely equivalent to the one depicted in Joseph Wright's painting, indeed, it is its exact complement in the comparison of death by drowning and death by evacuation. And it equally addresses human concerns with life and death. Thus, for all our interpretive attempts, the two experiments have identical meaning, they are methodologically and thematically indistinguishable, representing the exact same contribution to scientific knowledge. And yet, there is nothing striking about drowning a greenfinch in a jar of water. On the contrary, Boyle's second experiment well deserves the labels 'crude,' 'insipid' or 'lackluster', it does not represent an achievement of experimental technique, it strikes no one as either suspenseful or sublime redeeming its pedestrian and somewhat distasteful, if not outright revolting character.

4.4 *The Agency of Nature*

When we ask about the striking character of certain experiments and phenomena, we are asking about the qualitative difference between these two perfectly symmetrical experiments. By the same token, we are asking about a dimension of scientific knowledge and meaning that eludes the framework of theoretical relevance and methodological rôle. In this spirit we have to confront again the question suggested by Priestley: What is it about the experiment with the airpump that makes it resemble not fiction but real history? To quote Priestley again:

> By the help of these machines, we are able to put an endless variety of things into an endless variety of situations, which nature herself is the agent that shows the result ([1775], vol. 1, p. xii.).

John Robison, one of the first historians of 18th century chemistry, explains in 1803 what is so special about 'nature herself' being 'the agent that shows the result'. After Joseph Black's first discovery of a gas, namely 'fixed air',

> arose a new species of chemistry, chiefly conversant with aerial fluids, having an apparatus altogether peculiar to itself, and so unlike all that we are hitherto acquainted with [. . .] It is no longer confined to the study of those properties of bodies [like the spring of air] which make them the subject of human art, by which they are worked up for our purposes. We are now admitted into the laboratory of nature herself, and instructed into some of those great processes by which the author of this fair world makes it a habitable place ([1803], p. lvi).

With the striking phenomenon in Wright's painting we are admitted into the laboratory of nature herself. While we are not guided by human theorizing, the variety of experiments without common denominator testifies to that, it does take technological ingenuity to unlock this laboratory where nature herself can be the agent that shows the result. For the specific aim of keeping the greenfinch submerged in water, Boyle adopted a straightforward method of physical restraint. In contrast, exhausting the receiver of the airpump merely sets the stage on which an infinite series of phenomena can proceed. And exhibiting herself on this stage, nature shows us different things: in the case of the suffocating bird, for example, the processes by which the author of this fair world makes it a habitable place. The experiment engages the human family in a sublime experience of the conditions of life and death, with the experimenter himself a God-like authority, perhaps about to turn the valve and revitalize the bird.

4.5 *Literary Resonances*

Priestley's conception of the airpump as a host for striking-phenomenon experiments thus agrees with a conception of science according to which scientists unlock natural agency. The airpump resembles real history because it provides a controlled environment in which nature has the freedom to make history, showing herself in novel ways to unsuspecting minds.

And this in itself may render some experiments with the airpump striking. By putting nature on our evacuated stage, we treat it as a free agent, successfully coaxing it to reveal more and more from its infinite repertory. At the same time, we have some measure of experimental control over this free agent as we make nature perform and repeat tricks for us. With the airpump, science is taming nature: 'It is here that we see the human understanding [. . .] grasping at the noblest objects, increasing its own powers, by acquiring to itself the powers of nature' (Priestley [1775], p. iv).[4]

There may yet be more specific ways, however, by which specific experiments appear striking. As we evacuate the receiver we become witnesses to sublime events, but where, precisely, lies their sublimity? Two 18th century poets illustrate two very different ways of being struck by experiments with the airpump. The first response comes from Erasmus Darwin who celebrates this new laboratory of nature as he becomes witness to the primeval moment of creation. As 'in brazen pumps the pistons move' and as the receiver becomes exhausted, the bird deprived of air flaps its wings noiselessly:

> Rare and more rare expands the fluid thin,
> And Silence dwells with Vacancy within.
> So in the mighty Void with grim delight
> Primeval Silence reign'd with ancient Night ([1978], vol. 1, p. 172).

The other poet is Christopher Smart whose *Jubilate Agno* was written in an insane asylum in the 1760s. Instead of exhilaration, we find here an expression of anxiety. If air, as the condition of life, is sucked out of the receiver, that what remains behind shall not, must not be mere nothingness. There must be a sense in which life remains behind once all the air is sucked out.

> For the AIR-PUMP weakens and dispirits but cannot wholly exhaust.
> For SUCKTION is the withdrawing of the life, but life will follow as far as it can.
> For there is infinite provision to keep up the life in all the parts of Creation.
> For the AIR is contaminated by curses and evil language ([1954], p. 77).

The theoretical demise of the void-in-the-void experiment was accompanied by the rise in the imagination of the bird-in-the-vacuum experiment. This is not to imply, of course, that the airpump lost scientific significance while rising in the popular imagination. On the contrary, it assumed a new kind of scientific significance by engaging the imagination of scientists. Joseph Priestley writes this about the popular appeal of striking phenomena:

> So far are philosophers from laughing at the astonishment of the vulgar at these experiments, that they cannot help viewing them with equal, if not greater astonishment themselves ([1775], vol. 2, pp. 134–7).

Instead of leaving the striking phenomena to the general public, they define for Priestley and Robison not only the potential of the airpump but the core of pneumatic chemistry itself.

[4] For a somewhat more detailed discussion of Priestley's metaphysics and epistemology in relation to the airpump see Nordmann [1994].

5 INTERLUDE AND TRANSITION: THE MEANINGS OF STRIKING PHENOMENA

5.1 *Representing Phenomena*

As Shapin and Schaffer point out, Robert Boyle had to persuade the natural philosophers of his day that the airpump could make a meaningful contribution to scientific discourse through the void-in-the-void experiment. Indeed, according to Bruno Latour's poignant extension of their argument, the void-in-the-void experiment constituted experimental proof only insofar as the airpump was given the right to represent the voice of brute matter on issues of natural philosophy. Boyle thus established a particular non-trivial form of political representation for nature (Latour [1991]). As we saw already, the contribution of the void-in-the-void experiment was highly constrained: it was allowed to vote on a single pre-formulated question and was then retired to the position of gauge. Against Boyle's precedent, the 18th century experiments with the airpump gave nature a far less constrained voice. The airpump exhibited the real history of nature, now representing nature as a free agent. As we argued above, this alone provided for a striking encounter of the scientific mind with the divine mind as expressed through natural processes.

But insofar as nature speaks freely through the airpump, answering perhaps some pre-formulated questions but extending significantly beyond them, the meaning of nature's striking exhibitions cannot be fully captured in the scientific language of the day. To be sure, the experiment with the bird in the receiver yields data for a comparison of death by drowning and death by evacuation, and these are meaningful data which give the striking phenomenon definite methodological standing. But while the language and methodology of science can circumscribe particular dimensions of meaning, the controlled fate of the bird also instills a sense of scientific wonder, mastery of nature, technological accomplishment, and morbid fascination. Joseph Wright's painting, Darwin's and Smart's poetic responses all help capture this excess of scientific meaning.

5.2 *Sources of Meaning*

We started, innocently enough, by claiming for the pulse glass that it presents a technological certainty in a sea of linguistic confusion, by claiming for the pulse glass and the Lichtenberg-figures that they present cases of cognitive dissonance which remain relatively autonomous as against varying descriptions or conceptualizations. As such, striking-phenomenon instruments present enduring scientific achievements. In order to make our case, we rehearsed scientific accounts of the phenomena and then limited ourselves to the modest claim that the technological reality of the phenomenon displays a stability and compactness of its own. We did not speculate about the content of our fascination with the pulse glass, not dwelling, for example, on the fact that it appears to represent a form of perpetual motion or the production of something out of nothing (see page 42, above).

Under the guidance of Priestley and Joseph Wright we begin to tread more difficult ground. Recognizing that the relative autonomy of striking phenomena includes a positive dimension of meaning, we here explore the nature and content of the instrumental and technological knowledge of striking phenomena. Before we continue this exploration with our fourth and last case study, we should ask just what makes this pursuit more difficult.

The phenomena studied and created by scientists have many aspects. While we resist the idea that phenomena are *identical* to some construal of 'texts',[5] it remains the case that one aspect of phenomena is that they can be '*read*' for the particular information they provide concerning some particular theoretical issue. A phenomenon may provide a measured value for a predefined variable; a phenomenon may provide evidence to support or refute a particular proposition.

This matter of reading phenomena, however, delimits their meaning. As far as scientific discourse is concerned, there is no means of recognizing or articulating the meaning of phenomena other than in their methodologically defined relation to hypotheses and beliefs. To articulate what makes a striking phenomenon striking we must explore other aspects of the phenomenon's meaning.

However, in attempting to articulate this pervasive and important dimension of meaning we enter an area where the specifically theoretical and methodological language of science maintains a systematic silence. We are trying to articulate an aspect of meaning which scientists may rightly judge to be inarticulable, incommunicable, unfit as a subject for science. Indeed, the very possibility of theoretical science may require a coralling of the phenomena to make them speak in a highly specific, directed, and strictly delimited manner. But if, aside from knowledge *that* something is or should be the case and from knowing *how* to manipulate certain instruments, there is also an instrumental knowledge of *what* the phenomenon is, we can only learn very little about this knowledge by looking at the texts scientists produce when they write about striking phenomena. To discover this kind of knowledge we must rely instead on residual hints, turns of phrase which reveal more than a detached and passing interest in a phenomenon. And this reliance produces an interpretation of that phenomenon which the linguistic practice of science appears to deny, if only by excluding this interpretation for the purposes of maintaining a well-defined universe of rational discourse.

[5] We agree with Hacking's urging that to do so is an unhelpful semantic ascent, obscuring rather than clarifying scientific work ([1983], ch. 9).

Since we have to rely on an integral though unofficial undercurrent of scientific discourse, we come, as in the case of Priestley and his contemporaries, upon a language that is saturated with the philosophical predilections of a particular scientific culture. Priestley and Boyle speak in an easily intelligible scientific language when they consider the bird in the receiver in terms of comparative lengths of time of suffocation. But languages and cultural sensibilities begin to diverge when we see that for scientists like Priestley the experiments with the airpump are striking insofar as in them 'nature as a free agent is tamed and controlled, providing an encounter between the divine mind as expressed in nature and the unsuspecting mind of the scientist'. And they diverge even more and even within Priestley's own culture when we see that these kinds of controlled encounters invite very specific, perhaps fairly personal interpretive responses concerning the presence of God in nature.

Our last case provides an easier encounter with these difficulties. Since it is taken from the late 19th century, we have a more contemporary and intuitive—to our 20th century sensibilities—presentation of the striking experience of having experimental control over a phenomenon. And as we consider the ways in which this striking phenomenon resonates rather more idiosyncratically with the cultural sensibilities of a given scientist, we have to self-consciously embark upon careful speculation. If the striking phenomenon itself possesses a continuous spectrum of meaning which ranges from the well-defined data-point to high metaphor, our reconstruction of scientific ways of knowing this phenomenon must encompass the same spectrum.

6 MEANING IN EXCESS: GALTON'S QUINCUNX

6.1 *The Quincunx*

Like the airpump, our fourth and last striking-phenomenon instrument allows the experimenter 'to put an endless variety of things into an endless variety of situations'. But while the airpump served as a stage for the immediate exhibition of nature herself, Galton's quincunx functioned as a physical model of statistical reality. It could stand in for the theoretical models even in the function of explanation, allowing certain variables to be fixed, others changed, and conceptual implications observed.[6] As such, the quincunx helped guide the future conceptual development of statistics. By the same token, the very existence of a physical analogue to a statistical concept proved the living reality of the concept, enabling scientists to experience it and incorporate it into their working knowledge of nature.

Sometime prior to 1874 Francis Galton had a device built to help him

[6] John Smeaton's model waterwheels provide another example of an artifact working analogously to theoretical models, see Baird [1991].

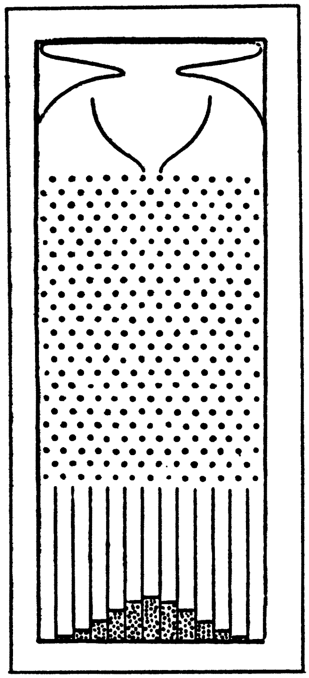

FIGURE 7 Galton's quincunx. *From*: Galton [1889], p. 63.

understand phenomena associated with what was then called the 'law of error', and what we now call the 'Normal' probability distribution. Galton's device consists of a series of rows of pins attached to a board in a repeated series of patterns of a die's five-face—a 'quincunx' pattern. Shot is poured down through the pins and collected in bins at the bottom. When built correctly, the instrument produces a bell-shaped pile—a Normal distribution—of shot in the bins at the bottom (Figure 7). Here was a striking mechanical instantiation of a statistical distribution. It helped Galton and his immediate successors as they slowly came to grips with a statistical way of thinking. Galton's device provided a physical analogue to what had previously only been seen as a mathematical pattern in large collections of data. By studying the operation of the quincunx and by building a series of 'quincunx variants', Galton came to better understand regression to the mean and its application in the biological theory of evolution (Stigler [1986], pp. 275–80; Pearson [1930], pp. 9–10).

6.2 *A Striking Phenomenon*

The operation of the quincunx is striking indeed. Galton's 1889 description of its operation cannot be bettered:

> When the frame is held topsy-turvy, all the shot runs to the upper end; then, when it is turned back into its working position, the desired action commences. . . . The shot passes through the funnel and issuing from its narrow end, scampers deviously down through the pins in a curious and interesting way; each of them darting a step to the right or left, as the case may be, every time it strikes a pin. The pins are disposed in a quincunx fashion, so that every descending shot strikes against a pin in each successive row. The cascade issuing from the funnel broadens as it descends, and, at length, every shot finds itself caught in a compartment immediately after freeing itself from the last row of pins. The outline of the columns of shot that accumulate in the successive compartments approximates to the Curve of Frequency [of error], and is closely of the same shape however often the experiment is repeated (p. 64).

The shot *scampers* down in a *curious and interesting way*. The operation of the quincunx is fun to watch and the constancy of the shape of the pile at the bottom on repeated uses exemplifies in an immediately revealing way the fact that chance is not simply chaotic. Chance produces regular predictable results when viewed in the right way.

The quincunx is a marvelous demonstration piece. Galton used it to advantage in several of his lectures before the Royal Society ([1877], p. 493). And some of his fellow inquirers into the emerging science of statistics borrowed Galton's quincunx for their own lecture-demonstrations (Stigler [1986], p. 316). It still makes for good demonstrations. Many science museums have large floor-to-ceiling quincunxes illustrating the 'operation of chance' and the emergence of 'order in apparent chaos', thus illustrating a central *topos* of our current age.

6.3 *Explaining Statistical Phenomena*

While the quincunx makes for a marvelous demonstration of a cultural and statistical *topos*, while it enlivened what can be a dreary subject, and while Galton was tickled by his invention, Galton used the quincunx as a means of discovery and proof, 'a surrogate for his rudimentary mathematics' (Stigler [1986], p. 276). Galton built the device to imitate in a controlled setting the production of a Normal distribution, providing an explanation by producing a physical analogue.

A typical story goes like this. Consider tulip heights. Each of the rows of pins represents some source of deviation from the average tulip height—*e.g.*, exposure to sunlight; variations in the mineral content of the soil, soil drainage, etc. In some cases an individual tulip plant will benefit from a series of sources of deviations all of which tend to make the plant taller. In the great majority of cases, an individual tulip plant will receive a 'boost' from some of the sources of deviation and be held back by other sources of deviation. The net effect is an average-size tulip plant. The story explains by analogy, as such is a fantasy of sorts. After all, tulip plants do not tumble down bouncing hither, thither and yon off wooden pins. Whatever the causes are that effect tulip height, they need not be supposed to operate independently; sunlight may affect the drainage and mineral content of the soil. Finally, there is no theoretical reason to suppose that the final height of a tulip plant is the additive effect of a series of such small causes.

On the other hand, the central fact which drives the plausibility of thinking about tulip heights in terms of the operation of the quincunx is the fact that the quincunx proves that there are physical human-made—'mechanical'—instantiations of the production of a Normal distribution. It then becomes a matter of physical interpretation to determine the extent to which the tulips share other relevant features with the quincunx. If the net effect is a Normal distribution of outcomes in either case, we may perhaps infer that a similar causal story obtains. Importantly, independent of whatever underlying story is finally agreed on—if any—the quincunx allows for an examination of the phenomena that accompany statistical distributions.

Galton, thus, used the quincunx to conjecture 'the reason why mediocrity is so common':

> [M]ost of the shot finds its way into the compartments that are situated near to a perpendicular line drawn from the outlet of the funnel, and the Frequency with which shots stray to different distances to the right or left of that line diminishes in much faster ratio than those distances increase. This illustrates and explains the reason why mediocrity is so common (Galton [1889], p. 64–5).

Here a wood-and-glass instrument serves a function usually seen exclusively as a function of theory.[7] Herein is one reason to think of an instrument as an element of knowledge *sui generis*. Perhaps more important in the current context is the autonomy of statistical 'law' presupposed in its use in explanation. The story of the 'little causes' is not necessary to appreciate the operation of the quincunx. It is the behaviour of the statistical distribution itself that serves to explain, not some underlying background story of how the distribution was itself produced.[8]

6.4 *Exploring Statistical Phenomena*

Thus the quincunx served as a model, an intellectual tool aiding and constraining the further conceptual development. As such, it assumed a well-defined role in conceptual and instrumental work. Indeed, the instrument proved adaptable to a variety of questions. With his quincunx Galton explained a statistical feature of heredity that had puzzled him for some time. It

[7] And, indeed note the above use of the Lichtenberg figures to explain frost on window-panes, see Lichtenberg as quoted on p. 49 above.

[8] This feature is explored at some length in Hacking's discussion of Galton [1990], ch. 21.

was widely understood that the children of tall parents tended to be tall, but, generally, not as tall. Yet—and herein lies the puzzle—the distribution of heights remained roughly the same generation to generation. If there is regression, why does the distribution of heights stay the same? With his quincunx Galton showed how a Normal distribution of heights—of parents—would produce a Normal distribution of heights of offspring. Despite the fact that there was regression to the mean, the overall distribution was reproduced.

The height of each child could be considered as a single pellet in the quincunx. We can suppose that instead of each pellet starting in the center, each starts its journey to the left or to the right of center depending on parental height—tall parents 'on the right', short 'on the left'. It is as if the shot in a single quincunx were intercepted half way to the bottom—in a Normal distribution—and then let go to finish their trip to the bottom. Galton built just such a two-stage quincunx to demonstrate the fact that a Normal distribution still emerges at the bottom. A proof of this fact was beyond Galton's mathematical talents, but the physical instantiation of the fact came quite easily from experiments with the quincunx. A form of proof can be seen in his illustration of the quincunx (Figure 8). With another quincunx variant, Galton studied the operation of natural selection. He constructed a quincunx where, like the variant above, the shot was intercepted at an intermediate stage (Figure 9). Shot with extremely large deviations above and below the mean were 'selected against' and kept from continuing the descent through the remainder of the pins. The result was a Normal distribution with a smaller amount of variation:

> ... Galton ... illustrates his idea by a second ingenious Quincunx, in which the middle stage is formed by a vertical normal-curve diaphragm which cuts off from the descending pellets, uniformly distributed over the horizontal bases of their compartments in the top stage, the 'selected pellets', which again are on the removal of the sliding floor allowed to run down into the third stage compartments where they form a normal distribution of much reduced variability (Pearson [1930], p. 11).

Karl Pearson also built a variant quincunx to help him understand non-Normal distributions. Until the end of the century, it was widely believed that the only natural statistical distribution was the law of error, the Normal distribution. If other distributions were found, that was evidence that the populations underlying these non-Normal distributions were not natural. During the 1890s, in an effort to widen the understanding of possible statistical distributions, Karl Pearson began playing with the pin placement in Galton's quincunx. He wanted to produce a mechanical demonstration of other—non-Normal—distributions (Figure 10). This would indeed have provided a compelling argument that non-Normal distributions could come from 'natural' causes. But Pearson's efforts failed. All his modified quincunxes

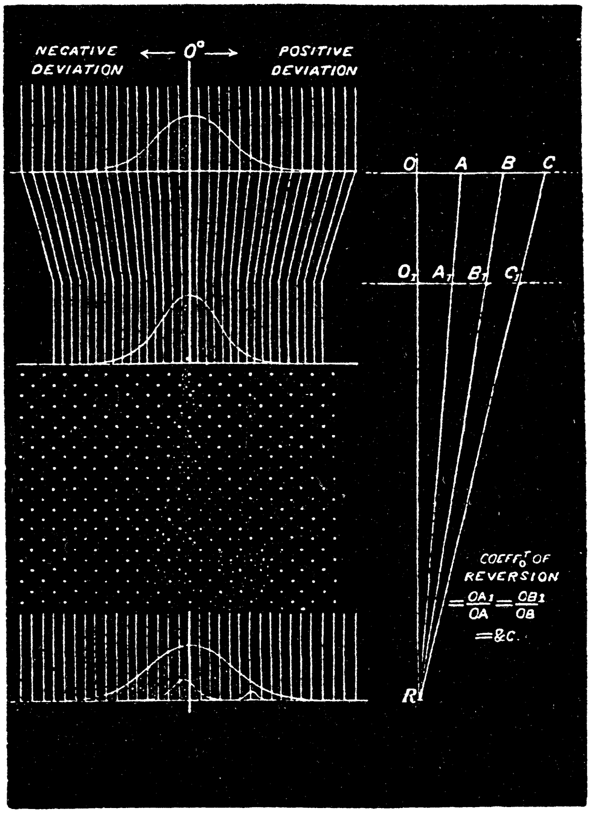

FIGURE 8 Galton's Quincunx illustrating the nature of Regression. *From*: Karl Pearson [1930], page 9.

produced Normal distributions. Pearson did manage eventually to move statistics beyond the law of error with a mixture of 19th century positivism and an abundance of non-Normal data (Baird [1983]).

While Pearson was not able to use Galton's quincunx to learn about non-Normal distributions, the quincunx still holds a place of central importance in the development of statistics. Stephen Stigler acknowledges as much in the conclusion to his history of 19th century statistics:

> How could the known diversity of causes be reconciled with this always present order? How could the normal distribution Quetelet had found be disassembled to allow a study of causes? Galton's quincunx had led to the answers to these questions, by suggesting a new role for conditional probability. In the theory of errors, conditional probability had permitted inference about constants of astronomer's theories. In regression analysis, conditional probability made

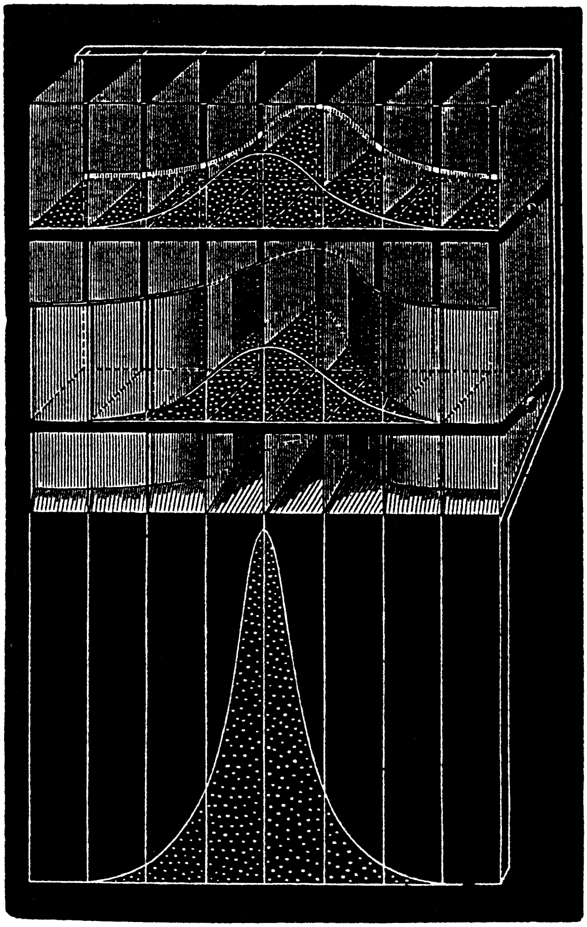

FIGURE 9 Galton's Quincunx illustrating the nature of Natural Selection. *From*: Karl Pearson [1930], page 10.

> possible the very definition of the quantities about which the statistician was interested in making inferences (p. 360).

Unlike any of the other striking-phenomenon instruments investigated here, the quincunx directly promoted subsequent theoretical developments. But as with the other striking-phenomenon instruments, the physical production of the phenomenon was more dependable and in an important sense better understood than the causal story behind it. Pearson did not know that his modifications of Galton's quincunx would produce Normal distributions. And

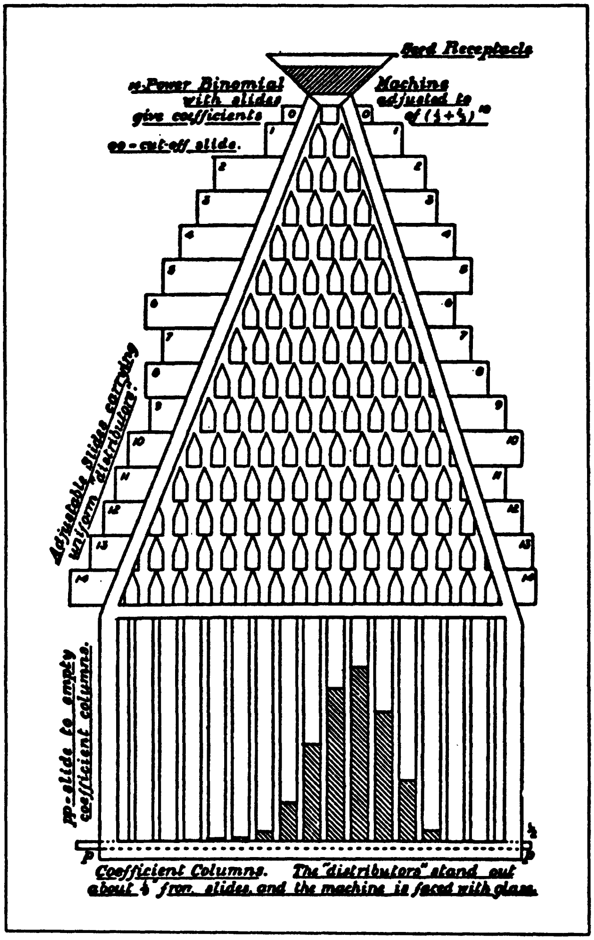

FIGURE 10 Karl Pearson's adjustable quincunx. *From*: E. S. Pearson [1956], *Karl Pearson's Early Statistical Papers* (Cambridge University Press: Cambridge), Plate 1.

Galton could not analytically prove his statistical results. Both learned from tinkering with the quincunx, *i.e.* by treating it as a tool for thought allowing for conceptual implications to be traced as certain physical variables were changed. Thus, beyond providing a fact-well-put the quincunx constituted a physical space for the observation of statistical phenomena under varying conditions.

6.5 *Metaphor for the Modern Age*

Thus far we have dealt with the contribution of Galton's quincunx to the understanding and development of statistics. In this circumscribed, although hardly trivial rôle, the significance of the quincunx is not controversial. But, as in the case of the airpump the quincunx might have fulfilled that rôle even if its operation were not 'fun to watch'. This theoretical contribution of the quincunx cannot, then, exhaust its striking character. The quincunx points to a new unexplored world of phenomena, a corner of our universe which had previously seemed beyond control. As such the quincunx then became a metaphor for the statistical conception of the world. The quincunx points to the vast 'empire of chance' (Gigerenzer *et al.* [1989]).

With the quincunx we can observe the interplay of chance and control. Watching the operation of the quincunx one is always held in suspense as the pellets tumble down: Will they *really* produce a Normal distribution *this* time? After all, any distribution would be logically possible. The uniformity with which the quincunx inevitably produces order from manifest chaos, is hard to believe; it is almost magical. And the suspense one feels as the pellets tumble down enacts the tension between logical and real possibility. We experience suspense and then gratification as this wildness is resolved and tamed before our very eyes. By embracing chance we find not less but more order, more control. Hacking writes:

> There is a seeming paradox: the more indeterminism, the more the control. This is obvious in the physical sciences. Quantum physics takes for granted that nature is at bottom irreducibly stochastic. Precisely that discovery has immeasurably enhanced our ability to interfere with and alter the course of nature ([1990], p. 2).

The title for Hacking's book, *The Taming of Chance*, is apt. Instead of turning our backs on the blooming buzzing confusion that is the appearance of our world and supposing that this confusion is 'really' ordered by some collection of unknown but deterministic laws, we embrace the confusion by understanding regularities in populations. While the individuals may be unpredictable, the population behaves according to statistical law.

This powerful experience of control over chance ties the quincunx to our modern experience of a statistical world. Just after describing the operation of the quincunx, Galton, with characteristic eloquence, continued with an interpretation of statistical law:

> I know of scarcely anything so apt to impress the imagination as the wonderful form of cosmic order expressed by the 'Law of the Frequency of Errors'. The law would have been personified by the Greeks and deified, if they had known of it. It reigns with serenity and in complete self-effacement amidst the wildest confusion. The huger the mob, and the greater the apparent anarchy, the more perfect is its sway. It is the supreme Law of Unreason ([1889], p. 66).

The quincunx did not simply provide a data point or a means to investigate statistics empirically. It resonated with a fundamental motif that characterizes the modern world.

Galton's supreme Law of Unreason should be appreciated not simply, or even primarily, as the foundation for quantum physics. It is also, as Galton saw, a law of *human* populations. While individuals may be unique and may lead their own unique lives, the population is uniform—Normal—like the curve of pellets produced by the quincunx. To be sure, this attempt to relate the quincunx to the modern world leaves room for divergent evaluations. While Galton used the law of regression as a plea for genius reflecting his abhorrence of mediocrity, others might see in it a defense of democratic ideals. Hacking continues the passage quoted above:

> A moment's reflection shows that a similar statement may be attempted in connection with people. The parallel was noticed quite early. Wilhelm Wundt, one of the founding fathers of quantitative psychology, wrote as early as 1862: 'It is statistics that first demonstrated that love follows psychological laws' ([1990], p. 2).

We no longer think of each of our lives—our fate—as simply our own. When diagnosed with cancer one doesn't simply seek the treatment which seems the best and hope for a cure. One is placed in a group from which the 'odds' of survival can be determined. These odds cannot predict a cure in an individual case, but they do tell how 'dire' the illness is, as if a death from an illness with a 5% survival rate is different from a death from an illness with a 95% survival rate.

So the quincunx provides a metaphor to open up the universe of chance. We have the paradox of gaining control by embracing chance. We also have a new conceptual space within which to think of humans: we are all members of populations describable by statistical laws.

7 CONCLUSIONS

7.1 *Technologically Expressed Scientific Knowledge*

One of the earlier attempts to explore the rôle of instruments in science was Maurice Daumas's 1961 paper 'Precision of Measurement and Physical and Chemical Research in the Eighteenth Century'. In it, he formulates what he takes to be a puzzling feature about the 18th century. He notes the incredible advance in the design and execution of instruments, allowing in many cases for the first time a considerable degree of precision. But curiously, scientists did not take immediate advantage of these instrumental capabilities; they did not use them to venture into quantitative science. He suggests, here revealing pre-Kuhnian biases, that scientists were held back by a kind of drawing-room mentality so that 'despite appearances, for the first six or seven decades, physics remained in a moribund state'.

> Faced by the great number of phenomena revealed to them, they seem to have shown a naive satisfaction, or a disturbing confusion of mind (p. 428).

Three of our four striking-phenomenon instruments come from the 18th century. Our discussion of them suggests a way of resolving Daumas's puzzle—along a line suggested by Daumas himself:

> [O]ne may ask oneself who was responsible for the evolution of instruments to this stage: was it the physicists or the instrument-makers? The writings of scientists containing the results of measurement usually simply give the results, without pointing out that a greater degree of accuracy would advance their field of study. On the other hand, as a profession, the instrument-makers were more concerned to make a better job of their work; thus they put at the disposal of the observers progressively more effective apparatus (p. 427).

To make more effective apparatus, to make the phenomena more pronounced, to draw out their contours, to let them stand out better, to purify and amplify them, to render them ever more striking and thus stabilize them technologically for public scrutiny, this may have been the chief concern of 18th-century scientists and instrument-makers alike, especially in the British tradition. The point was to further the production of new phenomena, not to promote precise measurement. That such instruments afford greater precision of measurement and thus facilitate a greater degree of quantification would now appear as a windfall.

While today instruments are often judged in terms of the precision they allow and their ability to satisfy strictures of theory and methodology, this 18th century undercurrent is still present, sometimes subterraneously, sometimes overtly. This is surely one of the reasons Galton's quincunx was so striking and compelling in the 19th century; statistical phenomena were new and ready to be well-framed by a striking-phenomenon instrument. In our own day, consider, for instance, the variety of toys, now popular, which demonstrate chaotic behavior. While many instruments do promote precise measurement, they also produce phenomena, and this production may be equally important, especially in the early stages of our acquaintance with a new phenomenal realm as they allow us to see and experience the new phenomena.

Here then we come across different dimensions of meaning in a methodological norm just as we previously encountered such different dimensions in the striking phenomenon. In respect to strictures of theory and methodology, precision is a virtue insofar as it enables a more well-defined, a more definite reading of the phenomenon as a text. But in respect to our fascination with control and the phenomenon itself, it serves as an instrumental and experimental norm. It represents the goal of rendering the phenomenon distinct and striking.

A similar case can be made for the methodological and instrumental norm 'replicability'. Methodologically it is to ensure the universality of the experimental experience. As an instrumental norm it specifies a technical criterion for what it takes to tame the phenomenon.

7.2 *The Ideal Type*

Striking-phenomenon instruments assume their striking profile against the shifting backdrop of theoretical uncertainties. While technologically stable, the phenomena produced by these instruments are linguistically fuzzy, subject to a variety of conceptual representations. But in virtue of their technological stability alone, they can provide a foundation for further technological as well as conceptual development. Sometimes, as in the case of the pulse glass, the phenomenon is taken to confirm conflicting theoretical views; sometimes, as in the case of the Lichtenberg-figures, it holds out the false promise of crucial theoretical importance; sometimes, as in the case of the airpump in the 18th century, it emphatically short-circuits theory and human ingenuity, giving a voice to nature herself; and sometimes, finally, as in the case of the quincunx, the phenomenon stands in for theoretical accounts. But in all cases the instruments themselves delight and engage, exhibit a permanent fixture in the living future, allow us to *experience* the phenomena in their larger cultural context, and, in one way or another, have to be contended with.

In summary then this is how we determine the features of interest of striking-phenomenon instruments.

(1) The instrument and the phenomenon are completely integrated, in this way the instrument provides a compact presentation of a phenomenon.
(2) Even if the phenomenon is ill-understood theoretically, the reliability of the phenomenon presented in the instrument provides for further instrumental developments.
(3) While the description and explanation of the phenomenon presented may depend on theoretical interests, and while these theories and the interests which underlie them may change, the phenomenon remains an accepted item, possibly requiring explanation.

The result is a fact-well-put, a striking-phenomenon instrument.

Of these three features, the last required most work to spell out. The striking-phenomenon instrument is the product of our ability to tame a phenomenon. It is the product which constitutes our knowledge of the phenomenon. As this knowledge is not of the standard propositional sort, not in the standard frame of knowledge, we had to go to some lengths to specify what this knowledge actually consists in and what the meaning of the striking phenomenon is. Toward this end we noted several points:

(1) The striking-instrument phenomenon presents a point of instrumental certainty in a sea of linguistic confusion.
(2) A 'meaning' for a striking phenomenon can be fixed by its being tied to particular theoretical or methodological interests. Still the phenomenon may serve many different interests and so have many 'meanings'. Furthermore, when treated this way the striking phenomenon is indistinguishable from ingenious or crude, naturally found or experimentally produced phenomena. Its 'striking' character eludes such a description.
(3) The striking-phenomenon instrument provides an ability to tame a particular phenomenon, to render it compact. This perhaps unlikely or otherwise extraordinary achievement is a central aspect of the meaning of striking phenomenon instruments.
(4) The particular phenomena presented in striking-phenomenon instruments invite metaphorical readings which reflect the idiosyncrasies of the scientific culture in which they are developed and employed.

The striking-phenomenon instrument thus is a receptacle for a vast spectrum of meanings. It is technologically/instrumentally relatively autonomous, presenting, as it does, the striking achievement of instrumental certainty and control over natural agency. At the same time it is relatively open to a variety of theoretical appropriations. And, by the same token, it is relatively open to cultural interpretations.

This concludes our identification of the ideal type. As we carry this feature to other instruments and experiments, we may find it increasingly difficult to distinguish between mere contrivances for experimental purposes and genuine striking-phenomenon instruments. However, this difficulty does not call into question our identification of this type of instrument, it rather alerts us to a feature of interest in the instrument that occasions the difficulty: there is obviously more to it than meets the experimentally and methodologically trained eye, a dimension of meaning and achievement which remains inarticulate in the experimentally and methodologically bound language of science, an achievement, nonetheless, which represents the other of two ways of knowing nature:

> In nature there is just complexity, which we are remarkably able to analyse. We do so by distinguishing, in the mind, numerous different laws. We also do so, by presenting, in the laboratory, pure, isolated, phenomena (Hacking [1983], p. 226).

Department of Philosophy,
University of South Carolina, Colombia,
South Carolina 29208, USA

REFERENCES

ANDERS, A. [1989]: 'Lichtenberg-Figuren im Vakuum—ein Hochdruckphänomen', in Ulrich Joost and Wolfgang Promies (*eds.*) *Lichtenberg-Jahrbuch 1988*. Ober-Ramstadt: Lichtenberg Gesellschaft, pp. 200–6.

BAIRD, DAVIS [1983]: 'Conceptions of Scientific Law and Progress in Science', in N. Rescher (*ed.*) *The Limits of Lawfulness*. Lanham, MD: University Press of America, pp. 33–41.

BAIRD, DAVIS [1988]: 'Five Theses on Instrumental Realism', in A. Fine and J. Leplin (*eds.*), *PSA 1988*, **1**, pp. 165–73.

BAIRD, DAVIS [1989]: 'Instruments on the Cusp of Science and Technology: The Indicator Diagram'. *Knowledge and Society: Studies in the Sociology of Science Past and Present*, **8**, pp. 107–22.

BAIRD, DAVIS [1991a]: 'Scientific Instruments as Elements of Scientific Knowledge: John Smeaton's Model Waterwheel and Benjamin Franklin's Pulse Glass'. Unpublished manuscript.

BAIRD, DAVIS [1991b]: 'Conceptual Puzzles with the History of an Instrument: Benjamin Franklin's Pulse Glass'. Unpublished manuscript.

BAIRD, DAVIS and FAUST, THOMAS [1990]: 'Scientific Instruments, Scientific Progress and the Cyclotron'. *British Journal for the Philosophy of Science*, **41**, pp. 147–75.

BOYLE, ROBERT [1809]: 'New Pneumatical Experiments about Respiration', in C. Hutton, G. Shaw and R. Pearson (*eds.*), abridged edition of *The Philosophical Transactions of the Royal Society*. London: Baldwin, **1**, pp. 473–89.

BROWN, HAROLD [1990]: 'Prospective Realism'. *Studies in the History and Philosophy of Science*, **21**, pp. 211–42.

BIJKER, WIEBE, HUGHES, THOMAS and PINCH, TREVOR (*eds*) [1989]: *The Social Construction of Technological Systems*. Cambridge, MA: The MIT Press.

BUSCH, WERNER [1986]: *Joseph Wright of Derby: Das Experiment mit der Luftpumpe*. Frankfurt: Fischer.

CARLSON, CHESTER F. [1965]: 'History of Electrostatic Recording', in John Dessauer and Harold Clark (*eds.*), *Xerography and Related Processes*. London: Focal Press, pp. 15–49.

COMSTOCK, J. L. [1845]: *Elements of Chemistry*. New York: Pratt, Woodford & Co.

CONANT, JAMES BRYANT [1950]: *Robert Boyle's Experiments in Pneumatics*. Cambridge, MA: Harvard University Press.

DANIELL, J. F. [1820a]: *Quarterly Journal of Science*, **8**, pp. 298–336.

DANIELL, J. F. [1820b]: *Quarterly Journal of Science*, **9**, pp. 128–37.

DANIELL, J. F. [1823]: *Meteorological Essays*. London.

DARWIN, ERASMUS [1978]: *The Botanic Garden*, in Donald Reiman (*ed.*), New York: Garland Publications. First ed., [1791].

DAUMAS, MAURICE [1961]: 'Precision of Measurement and Physical and Chemical Research in the Eighteenth Century', in A. C. Crombie (*ed.*), *Scientific Change*. New York: Basic Books, pp. 418–30.

FIERZ, MARKUS [1950–51]: *Die Entwicklung der Elektrizitätslehre als Beispiel der physikalischen Theorienbildung*. Basel: Rektoratsprogramm der Universität.

FINN, BERNARD [1971]: 'The Influence of Experimental Apparatus on 18th Century Electrical Theory'. *Proceedings of the International Congress of the History of Science, Paris 1968*, **10A**, pp. 51–5.

FISCHER, GERTRUD [1982]: *Lichtenbergische Denkfiguren: Aspekte des Experimentellen.* Heidelberg: Carl Winter.

FRANKLIN, BENJAMIN [1941]: *Benjamin Franklin's Experiments: A New Edition of Franklin's Experiments and Observations on Electricity,* I. Bernard Cohen (*ed.*) Cambridge, MA: Harvard University Press. This is a reprint of the fifth edition of Franklin's *Experiments,* [1774].

FRANKLIN, BENJAMIN [1972]: *The Papers of Benjamin Franklin,* in William Willcox (*ed.*) New Haven: Yale University Press.

GALISON, PETER [1985]: 'Bubble Chambers and the Experimental Workplace', in Peter Achinstein and Owen Hannaway, *Observation, Experiment and Hypothesis in Modern Physical Science.* Cambridge, MA: The MIT Press, pp. 309–73.

GALISON, PETER [1987]: *How Experiments End.* Chicago: University of Chicago Press.

GALISON, PETER and ASSMUS, ELEXI [1988]: 'Artificial Clouds, Real Particles', in D. Gooding, T. Pinch and S. Schaffer (*eds.*), *The Uses of Experiment.* Cambridge, England: Cambridge University Press, pp. 225–74.

GALTON, FRANCIS [1877]: 'Typical Laws of Heredity', *Nature.* **15**, pp. 492–5; 512–4; 532–3.

GALTON, FRANCIS [1889]: *Natural Inheritance.* London: Richard Clay and Sons.

GIGERENZER, G. *et al.* [1989]: *The Empire of Chance: How Probability Changed Science and Everyday Life.* Cambridge, England: Cambridge University Press.

GRAHAM, T. [1842]: *Elements of Chemistry.* London: Hippolyte Bailliere.

GRENZMANN, WILHELM [1976]: 'Probleme des Aphorismus', in Gerhard Neumann (*ed.*) *Der Aphorismus: Zur Geschichte, zu den Formen und Möglichkeiten einer literarischen Gattung.* Darmstadt: Wissenschaftliche Buchgesellschaft, pp. 177–208.

HACKING, IAN [1983]: *Representing and Intervening.* Cambridge, England: Cambridge University Press.

HACKING, IAN [1990]: *The Taming of Chance.* Cambridge, England: Cambridge University Press.

HEIDEGGER, MARTIN [1976]. 'The Question Concerning Technology', in D. Krell (*ed.*) *Martin Heidegger: Basic Writings.* New York: Harper & Row.

HEILBRON, JOHN [1979]: *Electricity in the 17th and 18th Centuries: A Study of Early Modern Physics.* Berkeley: University of California Press.

IHDE, DON [1991]: *Instrumental Realism.* Evanston: Northwestern University Press.

LATOUR, BRUNO [1991]: 'The Impact of Science Studies on Political Philosophy'. *Science, Technology and Human Values,* **16**(1), pp. 3–19.

LICHTENBERG, GEORG CHRISTOPH [1956]: *Über eine neue Methode, die Natur und die Bewegung der elektrischen Materie zu erforschen.* Leipzig: Akademische Verlagsanstalt, pp. 17–28; also in Lichtenberg [1968–74], 3, pp. 24–34.

LICHTENBERG, GEORG CHRISTOPH [1968–74]: *Schriften und Briefe.* Wolfgang Promies, ed. München: Hanser.

LICHTENBERG, GEORG CHRISTOPH [1983–5]: *Briefwechsel.* Ulrich Joost and Albrecht Schöne (*eds.*) München: Beck.

MIDDLETON, W. E. KNOWLES [1969]: *Invention of the Meteorological Instruments.* Baltimore: The Johns Hopkins Press.

NORDMANN, ALFRED [1991]: 'Prudence and Polarity: Electricity, Mathematics and Eighteenth Century Conceptions of the Self'. Unpublished manuscript.

NORDMANN, ALFRED [1994]: 'Der Wissenschaftler als Medium der Natur' in Karin Orchard and Jörg Zimmermann (*eds.*) *Die Erfindung der Natur*. Freiburg: Rombach.

PEARSON, KARL [1930]: *The Life, Letters and Labours of Francis Galton, Volume IIIA: Correlation, Personal Identification and Eugenics*. Cambridge, England: Cambridge University Press.

PEIRCE, CHARLES SANDERS [1934]: *The Collected Papers of Charles Sanders Peirce*. Cambridge, MA: Harvard University Press, **5** (cited by volume and paragraph-number).

PRIESTLEY, JOSEPH [1775]: *The History and Present State of Electricity, with Original Experiments*. London: Bathurst.

PRIESTLEY, JOSEPH [1817–31]: 'Lectures on History and General Policy', in *The Theological and Miscellaneous Works of Joseph Priestley*, London, **24**.

PRZIBRAM, KARL [1927]: 'Die elettrischen Figuren', in H. Geiger and Karl Scheel (*eds.*) *Handbuch der Physik*. Berlin: Julius Springer, **14**, pp. 392–404.

REID, D.B. [1839]: *Elements of Chemistry*. Edinburgh: Machlachlan, Stewart & Co.

ROBISON, JOHN [1803]: 'Preface', in Joseph Black. *Lectures on the Elements of Chemistry*. John Robison (*ed.*) Edinburgh: Mundell, **1**.

ROBISON, JOHN [1822]: *A System of Mechanical Philosophy*, David Brewster (*ed.*) Edinburgh: J. Murray.

SAUNDERS, A. P. [1908]: 'A Note on the Experiment of the Cryophorus'. *The Journal of Chemistry*, **12**, pp. 279–82.

SHAPIN, STEVEN and SCHAFFER, SIMON [1985]: *Leviathan and the Air-Pump*. Princeton; Princeton University Press.

SMART, CHRISTOPHER [1954]: *Jubilate Agno*, in W. H. Bond (*ed.*) Cambridge, MA: Harvard University Press.

STERN, JOSEPH PETER [1959]: *Lichtenberg: A Doctrine of Scattered Occasions*. Bloomington: Indiana University Press.

STIGLER, STEPHEN [1986]: *The History of Statistics: The Measurement of Uncertainty before 1900*. Cambridge, MA: Harvard University Press.

TURNER, E. [1847]: *Elements of Chemistry*, Eighth ed. London: Taylor and Walton.

VOLTA, A. [1918–1929]: *Le Opere*. Milan.

WALZ, H. [1962]: 'Benjamin Franklin in Hannover 1766'. *Hannoversche Geschichtsblätter* **21** *(Neue Folge)*, pp. 59–65.

WEBER, MAX [1949]: ' "Objectivity" in Social Science and Social Policy', in Edward Shils and Henry Finch (*eds.*) *The Methodology of the Social Sciences*. New York: Free Press, pp. 50–112.

WOLLASTON, WILLIAM HYDE [1812]: 'On a Method of Freezing at a Distance'. *Philosophical Transactions of the Royal Society*, pp. 71–4.

WOLLASTON, WILLIAM HYDE [1813]: 'On a Method of Freezing at a Distance'. *Annals of Philosophy*, **2**, p. 230.

ZIMMERMANN, JÖRG ed. [1988]: *Lichtenberg: Streifzüge der Phantasie*. Hamburg: Dölling und Galitz.