FOCUS: SCIENCE AND VISUAL CULTURE

Making Visible

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ABSTRACT

An overview of some of the main modes of making images of natural objects and processes, as they have appeared in the history of science, leads to two main conclusions. First, the dichotomies that have traditionally distinguished, for example, art from science, museums from laboratories, and geometrical from algebraic methods have produced a poverty of understanding of visualization. It is at the intersections of these dichotomies where much of the creative work of science occurs, and it is into those intersections that this Focus section leads us. Second, the section suggests that we need to understand images as arguments. Generalizing, we need to develop a "materialized epistemology" that reunites sensual with ideational knowing. Recent work in the history of science is already pointing the way and producing a dramatically new historiography.

MUCH OF THE HISTORY OF SCIENCE could be written in terms of making new things visible—or familiar things visible in a new way. Limiting ourselves to the literal sense of things visible to the eye, and leaving aside what the mind's eye may also see, it remains striking that "new worlds" opened up to visual perception occupy so much of the territory of scientific discovery, from mountains and valleys on the surface of the moon, made visible by Galileo's telescope, to the field of a magnet depicted by Michael Faraday's lines of force, to the landscape of the working brain illuminated in PET scans. Even more striking, as the essays collected here observe, is that historians of science traditionally have devoted relatively little of their attention to the means of producing images, to their epistemological significance (except in isolated cases like Faraday's), or to their relation to the wider culture. That situation has been changing over the last thirty years, especially with the emphases on practice, coming originally from the sociology of science, and, more recently, on material culture, coming from the cultural history of science; but there is a long way to go. It may be useful at the outset simply to enumerate some of the generic forms of visualization that have become prominent in modern science.

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METHODS OF MAKING IMAGES

When we think of making new worlds visible, perhaps no figure is more representative than Alexander von Humboldt. Like many others, he regarded precision instruments as a means of extending the senses beyond their normal reach. He meant this not merely in the quantitative sense of smaller or larger but qualitatively, as extending human sensibilities to qualities of nature not previously available even to the most sensitive observer. With the aid of the instruments that accompanied him through South America and Mexico, Humboldt sought to portray the physiognomy of the landscapes he explored in visual images, revealing their physical and biological character to newly opened eyes.[1] The array of methods he employed suggests the range that the subject of visualization needs to encompass: optical instruments, maps, plots, drawings, paintings, mathematical analysis, and more.

Optical Instruments

Paradigmatic for direct visual extension are eyeglasses and their compound forms, the telescopes and microscopes that open very large and very small spaces to direct vision, revealing a vast zoo of new objects from galaxies to microbes. The optical zoo includes also the retinal images from Helmholtz's ophthalmoscope and the products of spectral analysis emanating from Isaac Newton's prisms, Robert Bunsen and Gustav Kirchhoff's spectrometers, and Henry Rowland's concave diffraction gratings, to say nothing of the later electronically mediated versions of these and other devices. Laser interferometers, for example, may one day extend Albert Michelson's original attempt to see the differential motion of light waves through the ether and make gravity waves visible.

Maps

Humboldt would not have been able to see very much of the landscape had he relied only on optical instruments. Instead, he mapped and plotted physical measurements over wide areas so as to see relations of latitude, elevation, climate, vegetation, people, agriculture, mining, and other features. One result was his famous vertical projections of the landscape, to which he tied its other characteristics. Similarly, from plotting his own temperature data and that of many other observers on a world map, he obtained the isothermal lines that became models for other now-familiar maps of magnetic variation and meteorological systems. One of the features that make such maps particularly interesting is the way they have passed from natural history (as description and classification) to natural philosophy (as causal analysis). Maps of geological strata, electromagnetic fields, and gene sequences all exhibit this characteristic. They simultaneously constitute new things and invoke explanations of them.

Museums

But maps remind us first of travel, of changing landscapes and of varieties of things observed and collected. As such, they are closely connected both with cabinets and museums of objects and with their visual proxies: collections of paintings, drawings, and

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[1] Michael Dettelbach, "The Face of Nature: Precise Measurement, Mapping, and Sensibility in the Work of Alexander von Humboldt," *Studies in History and Philosophy of Biological and Biomedical Sciences,* 1999, *30:*473–504.

photographs. Humboldt's voluminous publications again provide an exemplar of the genre; so too do the great volumes of the *Description of Egypt* that collected the plants, animals, minerals, monuments, peoples, and maps recorded by the 150 members of the scientific team that Napoleon took with him for his occupation of Egypt. Jennifer Tucker reminds us here, in "The Historian, the Picture, and the Archive," of the significance of such proxy museums for nineteenth-century photograph collections and atlases. Like other sorts of images, photographs are not only constitutive of the things they bring into view, as scientific things, but reveal a great deal about the scientific view as a cultural expression.

Time and Projection

A rather different aspect of the traveling theme is motion. Makers of images have always wanted to make them move and change in time. Projection on screen began early to serve that function, initially in magic lantern shows using movable slides and light control. Throughout the nineteenth century visitors to the houses specially constructed for 360-degree panoramas experienced cities, exotic lands, and battle scenes with such realism that they suffered vertigo. Movable panoramas and dioramas with variable lighting from front and rear greatly enhanced the audience's sense of travel and the passage of time. And all of these media found ready exploitation by scientists seeking to make manifest to themselves and to the wider public the marvelous processes occurring in the world they inhabited. If their means were often illusionistic, as Iwan Rhys Morus discusses in "Seeing and Believing Science," they were nevertheless realistic illusions meant not to deceive but to capture authentic phenomena of nature. The effects of motion and time were also produced in the planetariums of the later nineteenth century and at institutions of popular science, such as the Urania in Berlin, that continued the genre.[2]

Projection on screen first became a major instrument of scientific investigation with film. In "Microcinematography and the History of Science and Film" Hannah Landecker describes how speeded-up and slowed-down projection became the telescope and the microscope of time, allowing investigators and their publics to witness the dynamics of long-term and short-term processes. She is concerned to point out, however, that, as in visualizing scientific objects in space, visualizing processes in time involves both constituting them as scientific things and constituting the scientific view. Science and the scientist are constantly under revision in this very social process of projecting images.

Graphic Methods

In the historical space between maps and film another genre of image making developed, one that used mechanical instruments to record graphically the invisible processes occurring inside man-made machines and the imagined machines of nature. A primary source was the indicator diagram for steam engines, invented by James Watt and his mechanic

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[2] Wolfgang Schivelbusch, *The Railway Journey: Trains and Travel in the Nineteenth Century,* trans. Anselm Hollo (New York: Urizen, 1979), shows brilliantly how high-speed travel produced a form of "panoramic vision." On panoramas and dioramas see Bernard Comment, *The Panorama* (London: Reaktion, 1999); Stephan Oettermann, *The Panorama: History of a Mass Medium* (New York: Zone, 1997); and Richard D. Altick, *The Shows of London* (Cambridge, Mass.: Harvard Univ. Press, Belknap, 1978). For popular projections in the late nineteenth century see Charlotte Bigg, "Staging the Heavens: Popular Observatory Science in the Late Nineteenth Century," in *The Heavens on Earth: Observatory Techniques in the Nineteenth Century,* ed. David Aubin, Bigg, and H. Otto Sibum (in preparation); and Ole Molvig, "Theatres of Science: On Stage and Behind the Scenes at the Berlin Urania," *ibid.*

John Southern. This directly inspired not only Carnot diagrams for depicting the second law of thermodynamics but Carl Ludwig's pulse-recording kymograph and Helmholtz's myograph for drawing the "curve of energy" of a frog muscle, which famously gave a visual image of the delay time required for propagation of the nerve impulse.[3] Since that canonical achievement, the curves produced by graphic methods have become part of our everyday understanding of the world, from lie detector traces to trends in the stock market. And their means of production have become ever more sophisticated, with statistical analysis and cathode ray tubes reading out the internal workings of systems large and small. Personal computers have made the methods of curve production available to every analyst.

Mathematical Methods

We may not immediately think of mathematics as being about visualization, until perhaps we consider the epicycles and deferents of Ptolemaic astronomy or the diagrams of geometrical optics and then go on to think of geometry more generally. But algebra and the calculus, too, have been full of image making. Fourier analysis extracts harmonic waves from heat diffusion in the earth (important to Joseph Fourier's friend Humboldt) and from quantum states as well as from violin strings. Hermann Minkowski's space-time diagrams make special relativity visible (*anschaulich*) to physicists and the interested lay audience alike. Feynman diagrams make the interactions of elementary particles look as simple as stick-figure drawings. Only recently, however, have historians taken up in depth the knowledge-making role of these diagrams.[4]

Contemporary Developments: Scans, Sequences, and Simulations

It seems probable that, like everyone else, historians have become more conscious of images because we are completely immersed in them and they have become indispensable to our own ability to understand the world and the sciences we study. Film, television, digital cameras, the computer screen, and the Web are of course ubiquitous. But a similar plethora of images inform contemporary science. X-rays, CAT scans, MRI, colonoscopy, and many newer techniques of digital imaging largely define medical diagnosis, while PET scans and functional MRI are the tools of brain research, and the scanning tunneling microscope makes it possible for experimental physicists to see and to manipulate individual atoms. Could we even conceive of current genetics research without images of the double helix of DNA and of gene sequences?

It may be that we are dealing here not with a qualitative change but only with a landslide in the same sort of imaging that we have seen throughout history and that the proliferation alone is responsible for our new assessment of that history. But when we consider the images produced by computer simulations, it becomes apparent that something quite new has appeared in the last thirty years. Yes, there are precedents in earlier physical models and even in the on-screen simulations of panoramas and film. But never before has the capacity existed to couple mathematical modeling with visual representations so that the

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[3] Robert Brain and M. Norton Wise, "Muscles and Engines: Indicator Diagrams in Helmholtz's Physiology," in *Universalgenie Helmholtz: Ruckblick nach 100 Jahren,* ed. Lorenz Krüger (Berlin: Akademie Verlag, 1994), pp. 124–145; rpt. in *The Science Studies Reader,* ed. Mario Biagioli (New York: Routledge, 1999), pp. 51–66.

[4] David Kaiser, *Drawing Theories Apart: The Dispersion of Feynman Diagrams in Postwar Physics* (Chicago: Univ. Chicago Press, 2005).

dynamical behavior of a virtual system can be observed as it runs. And for the (so far) irreducibly complex objects of the recent sciences of complexity, computer simulations offer the only way to understand the dynamics of the system. People working on the structure and folding of proteins, climate models, artificial life, and myriad other topics of contemporary research depend thoroughly on visual representation to comprehend the processes they study.

If the essays collected here do not take up these contemporary topics, they nevertheless reflect the fact that visually constituted knowledge has acquired an altogether new relevance. Coupled with the turn to practice and to material culture, visualization has become a topic of central historical importance.

Drawing and Painting

From this perspective it can be no surprise that historians of science have turned back to drawing and painting for a deeper understanding of their role. Pamela Smith offers an exemplary analysis of what is at stake in “Art, Science, and Visual Culture in Early Modern Europe.” The empirical focus of the Scientific Revolution of the seventeenth century, she persuasively argues, depended crucially on the representation of natural objects, and of the very meaning of the natural, by artist/artisans in interaction with investigators of nature.

FROM DICHOTOMIES TO INTERSECTIONS

Once the subject of making visible in science leaves the domain of mere illustration or mere technology and becomes a matter of making knowledge, then the making acquires much higher status. Makers of images, along with their materials and techniques, must then appear in the same space with writers and readers of verbal ideas. The dichotomies of doing versus thinking, craftsperson versus creator of ideas, and body versus mind (or the senses versus the intellect) must then be transformed into overlapping actions, or intersections, where the “and” of collaboration replaces the “either/or” of intellectual conceit. One might have thought that this lesson had been learned long ago for all forms of scientific practice. But images are a uniquely stubborn case. They have often appeared, on the one hand, as much too powerful, likely to lead to the deceptive excesses of imagination rather than the calm reflections of reason, and, on the other, as much too weak, capable of illuminating only the surface of things rather than their deep structure. These two problems of images, trust and depth, have long infected science and its history with a series of unfortunate dichotomies. All of the essays presented here grapple with the effects.

Art and Science

For Smith, the relevant dichotomy is art versus science, though the terms need to be translated for the seventeenth century into mechanical arts (hand work) versus natural philosophy (head work). Despite the later carping of people like Linnaeus—“Who ever derived a firm argument from a picture”—it is just at the intersection of art and science that Smith finds some of the most effective of the empirical methods of the Scientific Revolution, where naturalistic representation provided the means of investigating, understanding, and knowing. Her thesis could readily be extended to the intersections of art and science in other periods. The prominence that the curve acquired in nineteenth-century

Germany, for example, was closely tied to interactions in the art/science nexus, where both projective geometry and neoclassical aesthetics operated in the overlap.[5]

Science and Culture

These examples immediately raise the related dichotomy, now turned intersection, of science and culture, with which all of the other essays in this section are also concerned. Focusing on the intersection draws into the orbit of science not only materials, techniques, craftsmen, and technicians but also the conventions for making and understanding images that the makers of specifically scientific images partly share with the culture at large, both high and low. The selection process for subjects and context, what to include and exclude, viewpoint, and action is as important for the lantern slides, photographs, and films of science as it is for any others. If they are to be effective, they must correlate with the conventions of the medium. This is most obvious for presentations of science to the public, where viewers have learned already how to see images and to understand the role of the technology employed in producing them. Both Morus and Landecker make the point that, no matter how strong the illusion they produce, the technologies involved can never be invisible. The audience comes to see scientific wonders—but wonders understood as accomplishments on screen. Within the capacities of a culturally formed medium, the presenters of popular science can aim further to enculturate the audience to see what science reveals and what scientists are. But they must always present their images within the culture they inhabit. The same is true for the more esoteric presentations of professional science. Both making and understanding images immediately draw on broad cultural resources.

Algebra and Geometry

Beyond the dichotomies of art/science and science/culture with which the essays here mainly deal, the problems of trust in and depth of images have always involved competing ideals of scientific understanding. A recurring dichotomy of this sort is that between algebra and geometry. From the algebraic side, Joseph Louis Lagrange, writing as a major figure of the rationalist Enlightenment, famously asserted in the preface to his *Mécanique analytique* (1788) that "one will not find any figures in this work." Lagrange held that the limited and deceptive appeal to the senses of Newtonian geometrical intuitions of space and time compromised the rigor and generality of the algebraic theory. Only half a century later, writing within the geometrical tradition that continued in Britain, William Thomson and Peter Guthrie Tait turned Lagrange's mechanics upside down in their *Treatise on Natural Philosophy* (1867).[6] Not only pictures but the machines and engines of the Industrial Revolution would ground their mathematics. The contest has continued through the twentieth century. Richard Feynman's intuitive diagrams for field theory contrasted with Julian Schwinger's exhaustive integrals. Experimental mathematics, pursued visually on a computer, seems unsubstantial and untrustworthy to mathematicians committed to proof. But the lesson of the dichotomies should now be clear: they demand the "and" of intersection. Geometrical intuition never gets far without analytic abstraction, and vice versa.

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[5] David Freedberg, *The Eye of the Lynx: Galileo, His Friends, and the Beginnings of Modern Natural History* (Chicago: Univ. Chicago Press, 2002), p. 413 (quoting Linnaues); and M. Norton Wise, *Bourgeois Berlin and Laboratory Science* (in preparation), Ch. 5: "What's in a Line."

[6] Joseph Louis Lagrange, *Mécanique analytique* (1788), 2nd ed. (Paris, 1811), p. i; and William Thomson and Peter Guthrie Tait, *Treatise on Natural Philosophy* (Oxford: Clarendon, 1867).

Museums and Laboratories

Just as prominent in the history of science has been a dichotomous understanding of the roles of museums and laboratories. Museums, it is often supposed, including the visual proxy museums of drawings and photographs, pursue descriptive natural history by classification, while laboratories pursue causal natural philosophy by experiment. But the actual history is more interesting. Mineralogical museums, for example, began already in the eighteenth century to use chemical analysis for classification. More generally, experimental laboratories typically grew up in the nineteenth century in a complementary role, alongside the museums that preceded them.[7] Emblematic for this relation might be the large collections of machine drawings acquired by every polytechnical institution that experimented on ways to improve machinery. As engineers have always said, drawing is the language of engineering. As such, it is an invaluable source of creative investigation. And of course drawing is also one of the main repositories and generators of knowledge in laboratories of natural science.

MATERIALIZED EPISTEMOLOGY

As these many examples suggest, to make things visible is to make them real, or to try to. The import of visualization in science, therefore, is not illustration but argument. The interference and diffraction patterns of Thomas Young and Augustin Fresnel, for example, made powerful arguments for the wave nature of light in the nineteenth century. On the other hand, the visibility of polarization effects ultimately made problematic the luminiferous ether that would have to carry the light waves: the effects argued for transverse waves that would require an ether much more rigid than glass for waves traveling at the speed of light, and it was hard to see how planets and people could move through it.[8] To generalize: as visual arguments for light waves—including in their electromagnetic form—became ever more convincing through the century, attempts to make images of the ether plausible through mechanical models of its behavior never became compelling, even though it seemed that the ether had somehow to exist since the light waves visibly did.

Few issues in the history of science have had more attention than light waves and ether, but that attention has focused largely on mechanical models, mathematically conceived, rather than more specifically on the senses and visualization. The difference, to return to the dichotomies associated with trust and depth, is between a more intellectualized account and a more material and sensual one. That the two accounts need to be joined historically for such things as Faraday's lines of force in the ether is a point developed by James Clerk Maxwell in a famous 1870 address, where he discussed the feeling generated in the bodies of mathematical physicists, as opposed to abstract mathematicians, by the symbolical expressions they employed to represent physical quantities.

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[7] On eighteenth-century chemical analysis for purposes of classification see Ursula Klein, "Shifting Ontologies, Changing Classifications: Plant Materials from 1700 to 1830," *Studies in History and Philosophy of Science,* 2005, *36:*261–329. On the general relation of museums and laboratories see John Pickstone, *Ways of Knowing: A New History of Science, Technology, and Medicine* (Chicago: Univ. Chicago Press, 2000), pp. 60–105. For specific instances see Martin Guntau, "The Natural History of the Earth," in *Cultures of Natural History,* ed. N. Jardine, J. A. Secord, and E. C. Spary (Cambridge: Cambridge Univ. Press, 1996), pp. 211–229; Martin Rudwick, "Minerals, Strata, and Fossils," *ibid.,* pp. 266–286; and Lynn Nyhart, "Natural History and the 'New' Biology," *ibid.,* pp. 426–443.

[8] Jed Z. Buchwald, *The Rise of the Wave Theory of Light: Optical Theory and Experiment in the Early Nineteenth Century* (Chicago: Univ. Chicago Press, 1989), gives an exhaustive analysis of the wave theory and polarization, making use of numerous drawings.

> They learn at what a rate the planets rush through space, and they experience a delightful feeling of exhilaration. They calculate the forces with which the heavenly bodies pull at one another, and they feel their own muscles straining with the effort. To such men momentum, energy, mass are not mere abstract expressions of the results of scientific inquiry. They are words of power, which stir their souls like the memories of childhood.

Physical sensations, in Maxwell's view, "revealed to the mathematician new forms of quantities which he could never have imagined for himself."[9]

This power of embodied mathematics would apply just as well to visual sensations as to the muscular ones that Maxwell emphasized. A well-known example is the system of vortex elements in the ether that he depicted in the paper announcing the electromagnetic theory of light in 1873. Although unrealistic in detail, it suggested a possible physico-mathematical structure of electromagnetism with great heuristic power. Similar qualities have resided in images as diverse as Georges Cuvier's "recreations" of extinct animals and Friedrich August Kekulé's benzene ring.

Such depictions attain their greatest power for knowledge production, of course, when they become incorporated into the material culture of research, as part of a tradition of thinking and acting within an entire field. It is this sort of "materialized epistemology"—generalizing Pamela Smith's "artisanal epistemology"—to which the essays in this Focus section point the way. Its adequate elaboration requires in-depth studies of the people and practices involved in making particular sorts of images and of the ways in which those images form both what and how we know. Among the rapidly developing body of such works, I would mention two, at opposite ends of the spectrum of natural science. Convinced that we are undergoing a "momentous historical shift toward visualization" and that we need to engage seriously with visual learning, Barbara Stafford in *Body Criticism* examines epistemological aspects of attempts to "image the unseen" in the mutually constitutive relation of practices in art and medicine in the eighteenth century. Peter Galison's *Image and Logic* takes up two different instruments of research in elementary particle physics and shows how they constituted competing "epistemic machines," thereby taking the subject beyond different styles and values to different embodied arguments. Such studies of materialized epistemology are providing fertile ground for both historians and philosophers of science.[10]

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[9] James Clerk Maxwell, "Address to the Mathematical and Physical Sections of the British Association for the Advancement of Science," rpt. in *The Scientific Papers of James Clerk Maxwell,* ed. W. D. Niven, 2 vols. in one (New York: Dover, 1965), pp. 215–229, on pp. 218, 220.

[10] Pamela H. Smith, *The Body of the Artisan: Art and Experience in the Scientific Revolution* (Chicago: Univ. Chicago Press, 2004), Ch. 2; Barbara Maria Stafford, *Body Criticism: Imaging the Unseen in Enlightenment Art and Medicine* (Cambridge, Mass.: MIT Press, 1991); and Peter Galison, *Image and Logic: A Material Culture of Microphysics* (Chicago: Univ. Chicago Press, 1997). See also the papers of H. Otto Sibum on "gestural knowledge," e.g., "Reworking the Mechanical Value of Heat: Instruments of Precision and Gestures of Accuracy in Early Victorian England," *Stud. Hist. Phil. Sci.,* 2005, *26:*73–106; and "Experimentalists in the Republic of Letters," *Science in Context,* 2003, *16:*89–120.