Clocks to Computers: A Machine-Based "Big Picture" of the History of Modern Science

Frans van Lunteren

Abstract: Over the last few decades there have been several calls for a "big picture" of the history of science. There is a general need for a concise overview of the rise of modern science, with a clear structure allowing for a rough division into periods. This essay proposes such a scheme, one that is both elementary and comprehensive. It focuses on four machines, which can be seen to have mediated between science and society during successive periods of time: the clock, the balance, the steam engine, and the computer. Following an extended developmental phase, each of these machines came to play a highly visible role in Western societies, both socially and economically. Each of these machines, moreover, was used as a powerful resource for the understanding of both inorganic and organic nature. More specifically, their metaphorical use helped to construe and refine some key concepts that would play a prominent role in such understanding. In each case the key concept would at some point be considered to represent the ultimate building block of reality. Finally, in a refined form, each of these machines would eventually make its entry in scientific research, thereby strengthening the ties between these machines and nature.

Now that the scholarly ban on "grand narratives" appears to have been weakened, we historians of science face an awkward question: What, in broad outline, is the story that we want to convey? The question is awkward because it forces us to admit that we have no such story. We have no general account of the emergence of modern science during the last four centuries and of the knowledge regimes produced by the institutions involved. We have a myriad of excellent microhistorical case studies and also many studies of much broader scope, but we lack a general overarching scheme.[1]

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[1] This is not to deny the existence of many able or even excellent overviews of the history of modern science, most of which fall in the textbook category. However, they usually defy concise summarizing in terms of a metanarrative or overarching scheme. Exceptions to this rule are Alistair Crombie's three-volume work *Styles of Scientific Thinking in the European Tradition: The History of Argument and Explanation, Especially in the Mathematical and Biomedical Sciences and Arts* (London: Duckworth, 1994); Chunlin Kwa's related *Styles of Knowing: A New History of Science from Ancient Times to the Present* (Pittsburgh: Univ. Pittsburgh Press, 2011); and John Pickstone's schematic *Ways of Knowing: A New History of Science, Technology, and Medicine* (Chicago: Univ. Chicago Press, 2001). So far, none of these schemes seems to have caught on.

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The reasons for this somewhat embarrassing situation are all too familiar. The postwar specialization and professionalization of our field have brought about a gradual fragmentation—and even abandonment—of older narratives. This process has been accelerated by the cultural turn in the humanities, which is marked by a profound distrust of grand narratives. They were viewed as sweeping the complexities of history under the carpet, as ignoring the nitty-gritty of the evidence, and as being in conflict with the results of in-depth case studies. On top of that, they have been exposed as parochial, ideological, and supportive of vested interests.[2] Our historiographical creed is now steeped in the tetrad "culture, context, complexity, and contingency" and, as such, seems hardly compatible with sweeping generalizations. Most of us have learned to live with this condition, and many may even welcome it as a sign of the maturity of our field. After all, we share this predicament with general historians.

But not all of us have resigned ourselves to this situation. Over the past few decades there have been various calls for a "big picture" of the history of science.[3] The lack of a general overview has several drawbacks. The most obvious one concerns pedagogy. For teaching purposes, especially when one aims at novices in the field, it would be convenient to have a concise overview of the rise of modern science, preferably one with a clear structure allowing for a rough division into periods. Such a picture would also be helpful in accommodating wider audiences, who are now mainly served by outsiders in ways not always to our liking. It is no secret that the scholarly literature that we produce has little impact in the public domain. As a result, the story of science as conceived by the interested layperson is a tale of remarkable discoveries made by rare and eccentric geniuses, heroically struggling to overcome the conservatism and superstitions of their times.[4] This may make for good storytelling, but it is not the kind of narrative that we are willing to endorse.

But what is the view of the development of science that we do want to get across to the public? Presumably that the production of knowledge is a collective rather than an individual achievement.[5] Certainly that in understanding such processes we have to be sensitive to place and time—that is, that we have to recognize that new ideas, values, and practices are always at least partly shaped by contextual factors. Nature never speaks for itself. Classifications, analogies, technical vocabularies, and other conceptual tools that enable us to make sense of natural phenomena are as much of our own making as the instruments that we use to interrogate nature. In this sense, "discovery" is a misleading notion.[6] Moreover, in constructing and apply-

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[2] The classic proclamation of the end of all "grand narratives" with regard to knowledge is Jean-François Lyotard's *The Postmodern Condition: A Report on Knowledge*, trans. Geoff Bennington and Brian Massumi (Minneapolis: Univ. Minnesota Press, 1984).

[3] Charles Rosenberg, "*Isis* at Seventy-Five," *Isis*, 1987, 78:514–517; C. Hakfoort, "The Missing Syntheses in the Historiography of Science," *History of Science*, 1991, 29:207–216; James Secord, ed., "The Big Picture," special issue, *British Journal for the History of Science*, 1993, 26(4); Pickstone, *Ways of Knowing* (cit. n. 1); Bernard Lightman, "Editorial," *Isis*, 2004, 95:357–358; Robert E. Kohler, "A Generalist's Vision," *ibid.*, 2005, 96:224–251; Kathryn M. Olesko, "History and the History of Science Redux: A Preface," *Osiris*, 2002, N.S., *17*:vii–x; David Kaiser, "Training and the Generalist's Vision in the History of Science," *Isis*, 2005, 96:244–251; and Olesko and Kohler, "Clio Meets Science: The Challenges of History," *Osiris*, 2012, N.S., 27:1–16.

[4] Steven Shapin, "Hyperprofessionalism and the Crisis of Readership in the History of Science," *Isis*, 2005, 96:238–243 (little impact); and David Philip Miller, "The 'Sobel Effect,'" *Metascience*, 2002, *11*:185–200 (layman's story of science).

[5] Certainly, some individuals played key roles in these processes, but the overall tendency is to attribute too much to too few and to ignore the plain fact that in order to become knowledge individual claims have to gain recognition by relevant scientific communities. See Kathryn M. Olesko, "Myth 25: That Science Has Been Largely a Solitary Enterprise," in *Newton's Apple and Other Myths about Science*, ed. Ronald L. Numbers and Kostas Kampourakis (Cambridge, Mass.: Harvard Univ. Press, 2015), pp. 202–209.

[6] On the notion of scientific discovery see Simon Schaffer, "Making Up Discovery," in *Dimensions of Creativity*, ed. Margaret A. Boden (Cambridge, Mass.: MIT Press, 1994), pp. 13–51. For a more general discussion of scientific knowledge as a cultural product see Jan Golinski, *Making Natural Knowledge: Constructivism and the History of Science* (Chicago: Univ. Chicago Press, 1998).

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ing these tools we rely heavily on a broad spectrum of available cultural resources. Science is not only a dominant force in our culture, affecting society in many important ways; it is also a product of society, reflecting many aspects of its cultural seedbed.

Unfortunately, the more we condense our narrative of the rise of modern science, the more we seem to approximate the popular view in which knowledge accumulates through a series of discoveries produced by a small scientific elite. Introductory textbooks have little room for the complexities involved in the local and time-bound conditions that we take to be essential to the changes they describe. Contextualizing, then, often becomes a second-order correction. In this respect it would be preferable to have a rough overview of the development of science in which the ties between science and society are built in from the start. Can we expand our geographic horizons and diachronic time spans from the very local and short term without completely losing such connections? Is this feasible without reverting to the pitfalls of vulgar Marxism or other teleological metanarratives? This essay is an attempt to answer these questions in the affirmative. It proposes a radically new big picture of the history of modern science in which different knowledge regimes in subsequent periods are indeed related to society.

Overarching schemes of history can come in several guises. Usually they are based on either a pattern or a plot. Those based on a plot tend to focus on a unidirectional process driven by a single transformative force, whether class struggle, capitalism, or technoscience. These are grand narratives in the proper sense, because every story needs a plot. The tale of the early modern birth of modern science and the successive transformations it effected in modernizing societies through its methods, values, and applications is an example of such a grand narrative.[7] The big picture proposed here is not of this kind. The scheme is analytic rather than historicist, and it presupposes a pattern rather than a plot. The notion of a cyclical pattern may seem inimical to the very notion of historicity, but I do not want to suggest that this pattern is in any way essential to historical change. The scheme I propose can be read as a taxonomic rather than a causal one, although it does suggest certain causal interactions. These, however, are not unidirectional.

The picture proposed here takes its cue from a number of papers by Norton Wise, published a quarter of a century ago as a spin-off of the monumental biography of Lord Kelvin that he and Crosbie Smith composed.[8] In these papers Wise showed how machines like the steam engine could act as productive mediators between industrial and scientific interests.

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[7] Classic examples are A. Rupert Hall, *The Scientific Revolution, 1500–1800: The Formation of the Modern Scientific Attitude* (London: Longmans, 1954); and Herbert Butterfield, *The Origins of Modern Science, 1300–1800* (1949; New York: Macmillan, 1957). A recent example is David Wootton, *The Invention of Science: A New History of the Scientific Revolution* (New York: Harper, 2015). A general survey of the scholarly literature on the origins of modern science is H. Floris Cohen, *The Scientific Revolution: A Historiographical Inquiry* (Chicago: Univ. Chicago Press, 1994). For criticism of traditional conceptions of the scientific revolution see J. A. Schuster, "The Scientific Revolution," in *Companion to the History of Modern Science*, ed. R. C. Olby *et al.* (London: Routledge, 1990), pp. 217–242; and Andrew Cunningham and Perry Williams, "De-centering the 'Big Picture': *The Origins of Modern Science* and the Modern Origins of Science," *Brit. J. Hist. Sci.*, 1993, 26:407–432. For a sophisticated attempt to salvage a refined conception of the scientific revolution and to account for the emergence of modern science see Cohen, *How Modern Science Came into the World: Four Civilizations, One Seventeenth-Century Breakthrough* (Amsterdam: Amsterdam Univ. Press, 2010). Another recent attempt to account for the rise of modern science, extending this process up to the present, is Stephen Gaukroger's multivolume project on this theme, three volumes of which have appeared: *The Emergence of a Scientific Culture: Science and the Shaping of Modernity, 1210–1685* (Oxford: Oxford Univ. Press, 2006); *The Collapse of Mechanism and the Rise of Sensibility: Science and the Shaping of Modernity, 1680–1760* (Oxford: Oxford Univ. Press, 2011); and *The Natural and the Human: Science and the Shaping of Modernity, 1739–1841* (Oxford: Oxford Univ. Press, 2016).

[8] Crosbie Smith and M. Norton Wise, *Energy and Empire: A Biographical Study of Lord Kelvin* (Cambridge: Cambridge Univ. Press, 1989); Wise, "Mediating Machines," *Science in Context*, 1988, 2:77–113; and Wise, with the collaboration of Smith, "Work and Waste: Political Economy and Natural Philosophy in Nineteenth Century Britain," *Hist. Sci.*, 1989, 27:263–301 (Pt. 1), 391–449 (Pt. 2), 1990, 28:221–261 (Pt. 3).

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Concepts developed for the analysis of these machines, like "work" or "mechanical effect," found profitable applications in the realm of natural philosophy. Because of its industrial role, the steam engine brought in its wake an extensive set of connotations and values, many of which were transferred to natural philosophy. It also facilitated the opposite movement, in which concepts and values were translated from science to society. As a model for nature, the steam engine furthered the replacement of older static views of nature, based on the concept of force, by new dynamic views, based on energy considerations. As such it partly replaced the older, static model of the balance, which, as Wise argued, had a strong impact in the late eighteenth century.

This latter suggestion is supported by Bernadette Bensaude-Vincent's penetrating study of the multiple meanings and functions of the balance in Lavoisier's various activities as a tax farmer and political reformer, as well as in his chemical and physiological research. The balance connected economic principles and political ideals with chemical reactions and conceptions of the animal body. As a chemical instrument, it translated natural substances into abstract scientific entities that could be subjected to accounting methods. Like Wise, Bensaude-Vincent stresses the role of the balance as a "universal mediator" or—even more broadly conceived—as "an object that circulates, passes through, connects, mediates, and finally creates the consensus that wields a collective, culture, or community." It is both an abstraction and an object, a symbol and a thing. In this regard she compares the balance to what Michel Serres has called a "quasi-object."[9]

My proposal here is to extend this emphasis on the productive epistemic role of machines and rework it into a big picture of the rise of modern science since the early seventeenth century. Four machines suffice for the rough outlines of this picture. The machines that successively modeled nature in the modern era were the mechanical clock, the balance or weighing scales, the steam engine, and the computer. They did so most prominently during the second half of each of the past four centuries. Following an extended developmental phase, each of these machines came to play a highly visible role in Western society, both socially and economically. Their visibility was heightened by the conspicuous architectural forms to which they were connected: clock towers, city halls, weighing houses, and factories. Most of them at some point entered private households, usually in a miniaturized form.

How did these machines contribute to the shaping of modern views of nature? Actually, they did so in multiple ways, following a remarkable pattern. Not only did their metaphorical use provide a general framework for thinking about nature; their role as models also helped to produce, highlight, and refine some of the key concepts—and the theoretical structures in which these concepts were embedded—that came to play a prominent role in such understanding. As such, they acted as productive resources or heuristics for the understanding of both inorganic and living nature. In each of these cases, there was a tendency to regard the corresponding concept as an explanatory ultimate, denoting a fundamental building block of reality. Each of these machines, moreover, allowed for the translation of concepts and values from the domain of industry, commerce, and society at large into that of the study of nature—and vice versa.

Like the machines on which they were based, all metaphors and related concepts had deep roots in preceding periods. Once emerged, none of the metaphors or the derived concepts fully disappeared from the stage. In some sense they are still with us today, as are clocks, balances, engines, and computers. But in the course of time the metaphors lost their dominant position

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[9] Bernadette Bensaude-Vincent, "The Balance: Between Chemistry and Politics," *Eighteenth Century*, 1992, 33:217–237, on p. 234. She refers to Michel Serres, *Le parasite* (Paris: Grasset, 1980); and Serres, *Statues* (Paris: François Bourin, 1987).

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to one of their successors. Around the time that their metaphorical role flourished, each of the machines was subjected to radical innovation, resulting in improved performance and novel varieties. Partly because of these innovations, all the machines acquired an important role in the investigation of natural phenomena, thereby strengthening the ties between these machines and nature. This pattern has so far repeated itself roughly every hundred years up to the present. I will now expound this scheme in more detail.

THE BIG PICTURE

The Clock: Matter in Motion

During the Middle Ages and the Renaissance, both nature and society were predominantly understood in terms of organic models and metaphors. Extending our scheme backward, it is tempting to connect this fact to the dominant role of bodily work—both manpower and animal power—in feudal societies. A familiar example is the medieval conception of the "body politic." Its origins can be traced back to the writings of Plato, Aristotle, Cicero, and other classical authors, but it was only in the Middle Ages that the metaphor became commonplace. In his *Policraticus* (1159), John of Salisbury explained how each part of the body had a unique counterpart in society. In general, the metaphor promoted a unified and interdependent conception of society. Its best-known literary manifestation in the late medieval period is the political treatise by Christine de Pisan, *Livre du corps de policie* (1407). As a political metaphor the "body politic" has never entirely disappeared.[10]

Nature was likewise understood in organic terms. The revival of Neoplatonism during the Renaissance even reinforced this tendency. The universe was conceptualized as a living organism with a body and a soul, the *anima mundi*. Man, the *microcosm*, faithfully mirrored the universal *macrocosm*. Natural objects were seen to behave in purposive ways and to be related to each other through several hidden connections, such as natural sympathies or antipathies. Metal grew and ripened in the bowels of the earth. Indeed, even the earth itself was best understood through comparison with a living creature. Thus, following classical authors like Seneca and medieval scholars like Jean Buridan, Leonardo da Vinci famously compared the rocks, soil, oceans, tides, and subterranean heat to the bones, flesh, breathing, and internal heat of the human body.[11] Such holistic and organic readings of nature never disappeared entirely, but they soon lost their dominance.

In the course of the seventeenth century, organic views of nature were gradually making way for mechanical conceptions. The comparison of the world to a machine, the *machina mundi*, or, more particularly, to a clock had a long pedigree. What changed in the seventeenth century was that these comparisons became more than superficial analogies. Rather than imitating a machine, the world was now viewed as operating in the same way as a machine. In this respect, the clock metaphor acquired a new meaning. The transition from a vitalistic to a mechanistic account of the heavens is particularly obvious in Kepler's thought. Whereas in his *Mysterium Cosmographicum* he suggested that the sun moves the planets by means of an *anima motrix*, a moving soul, less than ten years later he corrected himself, now arguing that "the machine of

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[10] Andreas Musolff, "Political Metaphor and Bodies Politic," in *Perspectives in Politics and Discourse*, ed. Urszula Okulska and Piotr Cap (Philadelphia: Benjamins, 2010), pp. 23–41.

[11] Stephen Jay Gould, *Leonardo's Mountain of Clams and the Diet of Worms: Essays on Natural History* (Cambridge, Mass.: Harvard Univ. Press, 2011), pp. 17–44.

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the universe is not similar to a divine animated being but similar to a clock." The weakening of the motive force with distance suggested to him that the motive cause must be "corporeal."[12]

Moreover, the clockwork metaphor was extended from the universe as a whole to its several parts. In the Cartesian view even the living body was essentially an intricate piece of machinery—indeed, much like a clock. Both the universe and the body were no longer held to need a soul, until then the very principle of life, to account for their activity. Motion, conserved and transmitted by passive material particles through mutual physical contact, as by the wheels in a clock, did the trick. The clock became the emblem of the mechanical philosophy. Robert Boyle, the man who popularized the phrase "mechanical philosophy" and defined it as the attempt to explain all natural phenomena in terms of those "two grand and most catholick principles of bodies, matter and motion," often referred to the famous clock of Strasbourg. In Boyle's view even chemical processes, including the alchemical transformation of metals, could be understood in mechanical terms.[13]

Mechanical thinking and the new prominence of the clockwork metaphor also affected political thought. Thomas Hobbes's *Leviathan* illustrates the transition from an organistic to a mechanistic approach. The work still appealed to the trope of the "body politic," but the body itself had changed. The Commonwealth, or "artificial man," was essentially a machine. Like all bodies, states resembled automatons, "engines that move themselves by springs and wheeles as doth a watch." "For what is the heart, but a spring; and the nerves, but so many strings; and the joints, but so many wheels, giving motion to the whole body." The political and theological uses of the clock metaphor conveniently converged. Clocks are moved by a single source of activity, be it a weight or a spring. In the mechanical universe and the ideal absolutist state, all power is likewise concentrated in a single source, be it God or the monarch, thereby safeguarding both the natural and the social order. Both nature and the people are in essence passive wheels that merely obey the laws of the sovereign. In the words of King James I: "Kings are justly called Gods for that they exercise a manner or resemblance of Divine power on earth."[14]

As matter itself was stripped of its former qualities, motion took on a newly aggrandized weight. In the hands of mathematicians like Galileo, Huygens, and Newton, the concept of motion was transformed, refined, and eventually subjected to strict mathematical rules or "laws." For Descartes, Boyle, and Newton the laws of nature, established in the beginning by the Divine Lawmaker, were above all laws of motion. Crucial in this process was the new conception of inertial motion, which attributed to motion a kind of autonomy. Motion, once put into the world and unhindered by obstacles, no longer needed a continuous source for its persistence. This also posed a problem, for it called into question the notion of God's enduring providential care. A Cartesian solution to this problem was continuous creation, a doctrine that

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[12] Johannes Kepler to Johann Georg Herwart von Hohenburg, 10 Feb. 1605, quoted in Steven Shapin, *The Scientific Revolution* (Chicago: Univ. Chicago Press, 1996), p. 33; and Richard S. Westfall, *The Construction of Modern Science* (Cambridge: Cambridge Univ. Press, 1978), p. 10. For the new meaning of the clock metaphor see F. C. Haber, "The Cathedral Clock and the Cosmological Clock Metaphor," in *The Study of Time II*, ed. J. T. Fraser and N. Lawrence (Berlin: Springer, 1975), pp. 399–416; and Otto Mayr, *Authority, Liberty, and Automatic Machinery in Early Modern Europe* (Baltimore: Johns Hopkins Univ. Press, 1986).

[13] Robert Boyle, quoted in Daniel Garber, "Remarks on the Pre-history of the Mechanical Philosophy," in *The Mechanization of Natural Philosophy*, ed. Garber and Sophie Roux (Heidelberg: Springer, 2013), pp. 3–36, on p. 6; Mayr, *Authority, Liberty, and Automatic Machinery in Early Modern Europe*, p. 56; Shapin, *Scientific Revolution*, p. 34; and William R. Newman, *Atoms and Alchemy: Chymistry and the Experimental Origins of the Scientific Revolution* (Chicago: Univ. Chicago Press, 2006). However, see also Antonio Clericuzio, "A Redefinition of Boyle's Chemistry and Corpuscular Philosophy," *Annals of Science*, 1990, 47:561–589.

[14] Thomas Hobbes, *Leviathan; or, The Matter, Forme & Power of a Commonwealth, Ecclesiasticall and Civil* (London: Andrew Crooke, 1651), p. 1; and James I of England, "A Speach to the Lords and Commons of the Parliament at White Hall, on Wednesday the XXI of March, Anno 1609," in *The Workes of the Most High and Mighty Prince, Iames* (London: Robert Barker & John Bill, 1616), pp. 527–548, on p. 529.

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generalized the temporal account of initial creation to every moment of time. Newton simply denied the persistence of motion, which owing to friction and other forms of resistance was "more apt to be lost than got and was always on the decay."[15]

If, through its metaphorical role, the mechanical clock furthered the mechanical philosophy and hence the study of motion, the mathematicians reciprocated by improving the mechanical clock itself, above all through Huygens's invention of the pendulum clock in 1656. The spectacular gain in accuracy thus afforded was further increased by subsequent improvements of the escapement mechanism. The invention by Huygens and Hooke of the spiral balance also facilitated the construction of accurate pocket watches. Precision timekeepers not only became vital to several branches of science, above all astronomy; they also furthered trade by allowing for better maps and improved methods for establishing longitude at sea. Indeed, the longitude problem provided one of the main incentives for seventeenth-century attempts to improve clocks.[16]

The Balance: Equilibrium of Forces

In the late 1680s both absolutism and the mechanical philosophy sustained some blows. The Glorious Revolution established a victory of Parliament over the king, resulting in a rearrangement of power. Thus in Britain the authoritarian use of the clock metaphor lost much of its former appeal. Early eighteenth-century British Deists tended to downplay God's providential governance, to stress the active properties of matter, and to strive for a shift of power from the king to members of the lower nobility.[17] A division and balance of powers, rather than a concentration of power, became the dominant political ideal. An early expression of this ideal, partly inspired by the British political system, is *De l'esprit des lois* (1748), in which Montesquieu advocated the division of state power into a legislative and an executive power.

Almost simultaneously with the overthrow of James II, Isaac Newton put a spanner in the wheels of the mechanical philosophy by publishing his *Principia*. The work culminated in his theory of universal gravitation, based on a mutual attraction between all material objects in the universe. Notwithstanding Newton's agnosticism about the cause of gravity, both friend and foe agreed that Newton's attraction could not be explained mechanically. For this reason it took until the middle of the eighteenth century before universal gravitation had conquered the Continent. The Cartesian clockwork vision of the planets being propelled by great whirlpools of celestial matter was now gradually exchanged for a view in which planets moved harmoniously through empty space, their centrifugal tendency balanced by a centripetal attraction.[18]

In the wake of Newton's gravitational attraction nonmechanical forces rapidly multiplied in natural philosophy. The old maxim "Matter cannot act where it is not" eventually lost its former cogency. Appealing to Locke's empiricism, philosophers professed their profound ignorance with regard to the essence of matter. By the late eighteenth century they distinguished electric and magnetic forces, as well as several short-range attractive and repulsive forces responsible

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[15] John Henry, "Metaphysics and the Origins of Modern Science: Descartes and the Importance of Laws of Nature," *Early Science and Medicine*, 2004, 9:73–114; and David Kubrin, "Newton and the Cyclical Cosmos: Providence and the Mechanical Philosophy," *Journal of the History of Ideas*, 1967, 28:325–346, on p. 337.

[16] David S. Landes, *Revolution in Time: Clocks and the Making of the Modern World* (Cambridge, Mass.: Harvard Univ. Press, Belknap, 1983).

[17] Mayr, *Authority, Liberty, and Automatic Machinery in Early Modern Europe* (cit. n. 12), pp. 127–128 (loss of appeal of the clock metaphor); and Steven Shapin, "Of Gods and Kings: Natural Philosophy and Politics in the Leibniz–Clarke Disputes," *Isis*, 1981, 72:187–215.

[18] Frans van Lunteren, "Framing Hypotheses: Conceptions of Gravity in the Eighteenth and Nineteenth Centuries" (Ph.D. diss., Utrecht Univ., 1991).

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for cohesion and adhesion, chemical reactions, and optical and thermal phenomena. By this time the proliferation of forces went hand in hand with a tendency to reify these elusive entities. Some philosophers, notably Kant, even suggested that at the deepest level matter itself was essentially a compound of attractive and repulsive forces, thus making "force" the ultimate building block of nature. In a similar vein, French mathematicians followed Laplace in equipping punctiform particles with alternating attractive and repulsive forces. Nature was pictured as an equilibrium of such forces.[19]

Attempts to quantify other long-range forces, such as electric and magnetic force, depended on the use of the balance, usually a horizontal lever with arms of equal length and a weighing pan suspended from each arm. These traditional balances were profoundly modified during the 1760s, resulting in far greater precision. In addition, other types of balances were introduced, such as the spring balance and the torsion balance. Using the latter, Coulomb was able to support his assumption that the electric and magnetic forces, like gravity, were inversely proportional to the square of the distances between the interacting objects. More impressively, the torsion balance enabled Cavendish to determine the weight of the entire Earth. But the new generation of precision balances played its most impressive role in late eighteenth-century chemistry.

Lavoisier's attack on traditional chemical theories was based in part on the use of the best balances available at the time. In fact, both Lavoisier and Cavendish prompted leading French and English instrument makers to improve the precision of their instruments. Although gravimetric measurements were not new to chemists, the emphasis that a new generation of chemists placed on quantification and precision, as well as on the principle of the conservation of weight, did change chemical practice. As important as the act of weighing itself was the role of the balancing of weights—or, rather, numbers—as a powerful argumentative tool in chemistry. As noted before, Bensaude-Vincent has placed Lavoisier's use of the balance sheet in his chemical researches in a much wider context, even extending beyond his daily work as a tax farmer, which was based on similar accounting methods. His physiological, economic, and political memoirs displayed the same general sense of equilibrium and stability, based in part on the assumption of inbuilt regulative mechanisms in the respective systems.[20]

Norton Wise has also noted the ubiquity of this metaphorical role of the balance in late eighteenth-century thought. Familiar examples, apart from Lavoisier's new chemistry, are Laplace's demonstration of the stability of the solar system, Cuvier's emphasis on the functional interdependence of the different parts of the organism, and Condorcet's view of algebra as basically a balancing of quantities.[21] In the emerging science of political economy, the interventionist doctrines of mercantilism gave way to the ideal of a free market, stabilized by internal mechanisms, such as Adam Smith's balance of supply and demand.

In all these cases disturbances were seen to be ruled out, or to be subdued by feedback mechanisms, or to follow cyclical patterns. As a corollary, long-term stability was the rule. Nature and society were no longer held to need powerful interventions to maintain order. The time-honored notion of the "balance of nature" had come to dominate eighteenth-century

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[19] P. M. Heimann and J. E. McGuire, "Newtonian Forces and Lockean Powers: Concepts of Matter in Eighteenth-Century Thought," *Historical Studies in the Physical Sciences*, 1977, 3:233–306; and J. L. Heilbron, *Weighing Imponderables and Other Quantitative Science around 1800* (*Historical Studies in Philosophical and Biological Sciences*, suppl.) (Berkeley: Univ. California Press, 1993).

[20] Bensaude-Vincent, "Balance" (cit. n. 9). Cf. M. Norton Wise, "Mediations: Enlightenment Balancing Acts, or the Technologies of Rationalism," in *World Changes: Thomas Kuhn and the Nature of Science*, ed. Paul Horwich (Cambridge, Mass.: MIT Press, 1993), pp. 207–256.

[21] Wise, "Work and Waste," Pt. 1 (cit. n. 8).

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natural philosophy, although often couched in different terms, such as the "economy of nature." This harmonious view was partly rooted in the blossoming genre of natural theology, where it derived its most powerful arguments from the study of the living world.

Following John Ray's *Wisdom of God as Manifested in His Creation* (1691), naturalists emphasized the "beautiful contrivance" of God's creatures, the adaptation of "all parts . . . to their several uses," "the provision . . . made for their sustenance," and "their mutual subserviency to each other," as well as to mankind. In his *Physico-Theology* (1713) William Derham added to these considerations some reflections on the "balance of the animal world," which was maintained by a proper proportion of life span and reproduction rate allotted to each species. For Derham, however, the stability of animal populations was a clear sign of a superintending Providence, rather than of "the bare Rules, and blind Acts of Nature." He viewed animal plagues as outside of the balance of nature, tending to interpret them as supernatural interventions.[22]

An avid reader of Derham, Carl Linnaeus, took the concept of the balance of nature a large step further in his *Oeconomia Naturae* (1749) and his *Politia Naturae* (1760). Although these works are firmly based on the natural theological view of a providential creation, nature is consistently interpreted as a self-regulating superorganism. In a more secular vein, his French contemporary Buffon developed a more dynamic view of the economy of nature, in which populations could oscillate between extremes of rarity and abundance. As Frank N. Egerton has pointed out, the term "economy of nature" probably derived from the contemporary term for animal physiology: "animal economy." The latter studied the structural and functional dimensions of the living body, especially how the different parts contributed to the functioning of the entire organism.[23]

Meanwhile, the nature of these parts was no longer held to be purely mechanical. The body was not a mere machine, a system of pulleys and levers, whether or not controlled by a soul. In the course of the eighteenth century physiologists introduced several "vital forces," which they located in the living tissue rather than in the soul. The intellectual father of eighteenth-century vitalism was the Swiss Albrecht von Haller. His experimental work led him to conclude that there existed two distinct vital forces, responsible for motion and sense perception, which he called "irritability" and "sensibility." Referring to the precedent of Newton's gravity, he presented these nonmechanical principles as manifest properties, the causes of which were unknown. Whereas Haller restricted these properties to the tissues of muscles and nerves, French physiologists of the Montpellier school attributed similar properties to all living matter. They disagreed, however, as to whether the vital principle, associated with the activity of the whole living body, was the result of the coordinated organization of the organs or its cause.[24]

To make sense of the emergence of coordinated organization out of homogeneous seminal matter—the problem of epigeneticism—the German physician Johann Friedrich Blumenbach introduced another vital force, which he called the *Bildungstrieb* and distinguished from irritability and sensibility. Later he refined the concept so as to account for several other aspects of life. Like Haller and the Montpellier vitalists, Blumenbach emphasized that the concept of *Bildungstrieb*, like gravity or attraction, should be understood as a power, the effects of which

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[22] John Ray, "Preface," in *Wisdom of God as Manifested in His Creation* (London: Samuel Smith, 1691), [p. 6]; and William Derham, *Physico-Theology* (London: William Innys, 1713), pp. 171, 178.

[23] Frank N. Egerton, "Changing Concepts of the Balance of Nature," *Quarterly Review of Biology*, 1973, *48*:322–350.

[24] Hubert Steinke, *Irritating Experiments: Haller's Concept and the European Controversy on Irritability and Sensibility, 1750–90* (Amsterdam: Rodopi, 2005); Dominique Boury, "Irritability and Sensibility: Key Concepts in Assessing the Medical Doctrines of Haller and Bordeu," *Sci. Context*, 2008, *21*:521–535; and Henry Martyn Lloyd, ed., *The Discourse of Sensibility* (Cham: Springer, 2013).

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were as manifest as it was hidden. Again, we see a gradual shift toward the notion of self-organization based on a coordination of several "forces."[25]

The Steam Engine: Transformation of Energy

As the French and industrial revolutions spelled the end of the static social order of the *ancien régime*, they also marked the downfall of the static, balanced view of the natural order. During the "age of revolution," the balance was replaced by the steam engine as the dominant metaphor. In a series of ground-breaking papers, Norton Wise has analyzed the transition to a more dynamic world picture in an industrial context, focusing on the mediating role of the steam engine. As he made abundantly clear, historicist notions of change and transformation manifested themselves not merely in the earth and life sciences but also in the physical sciences.[26] Not only did the steam engine produce motion; it did so by transforming the chemical powers of coal into both heat and work. The rational analysis of the steam engine eventually gave rise to the new science of thermodynamics, based on two fundamental laws, the second of which came to underline the irreversibility inherent in nature's workings.

Another, even more important, offshoot of this development was the new concept of energy, connected to the corresponding conservation law. The term "energy" itself was introduced in the 1850s as a replacement for what had earlier had been denoted as "force." Whereas the latter concept was interpreted in a broad and somewhat vague sense, "energy" was equated with the capacity to perform work. This capacity was conceptually transferred from machines to nature itself. Prominent men of science, including Maxwell, Thomson, and Tait in Britain and Helmholtz and Du Bois-Reymond in Germany, strongly campaigned for the new energy-based approaches in various fields of science.[27] As a result, in the late nineteenth century energy became the central concept in the emerging discipline of "physics," which had replaced "natural philosophy." And as it was applied to a broadening range of phenomena, including electrodynamic and chemical phenomena, its definition and interpretation were gradually refined.

The fact that energy was seen to be conserved promoted a tendency to reify energy—or, in other words, to regard it as substantial. As Peter Guthrie Tait argued in 1876, to be real meant to be indestructible. Unlike matter and energy, the concept of force, taken as the cause of the change of motion of a material body, did not pass the test. Tait therefore advocated the elimination of all physical forces, which he deemed to be anthropomorphic and metaphysical. Several years later prominent scientists like Wilhelm Ostwald and Georg Helm developed a new program, "energetics," which aimed at reducing all natural phenomena to transformations of different forms of energy. Neither force nor matter, but energy alone, was accepted as the sole "real" substance.[28] Although this program rapidly declined in the early twentieth century, Einstein's famous equivalence relationship between energy and matter once more boosted the universality of energy. On the microscale, the energy of material systems such as atoms was seen to vary discontinuously, in so-called quantum jumps, and unpredictably.

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[25] Timothy Lenoir, "Kant, Blumenbach, and Vital Materialism in German Biology," *Isis*, 1980, *71*:77–108; and Robert J. Richards, "Kant and Blumenbach on the *Bildungstrieb*: A Historical Misunderstanding," *Studies in History and Philosophy of Biological and Biomedical Sciences*, 2000, *31*:11–32.

[26] Wise, "Work and Waste," Pt. 1 (cit. n. 8).

[27] Crosbie Smith, *The Science of Energy: A Cultural History of Energy Physics in Victorian Britain* (Chicago: Univ. Chicago Press, 1998); and F. D. A. Wegener, "A True Proteus: A History of Energy Conservation in German Science and Culture, 1847–1914" (Ph.D. diss., Utrecht Univ., 2009).

[28] P. G. Tait, *Lectures on Some Recent Advances in Physical Science, with a Special Lecture on Force*, 3rd ed. (London: Macmillan, 1885), p. 352; and R. J. Deltete, "Wilhelm Ostwald's Energetics," *Foundations of Chemistry*, 2007, 9:3–56, 265–316, 2008, *10*:187–221.

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It is no coincidence that several among the pioneers of energy conservation had a medical background. From the very beginning energy conservation played a crucial role in the attempts of the Berlin physiologists, including Du Bois-Reymond and Helmholtz, to transform the conception of life. Central to their program was the elimination of "vital forces." Du Bois-Reymond emphatically stressed the metaphysical nature of these vital forces. Above all, they were incompatible with new general principles. Like the steam engine, an organism transforms chemical energy (food) into heat and work. As these different forms of energy match one another exactly, the law of energy conservation leaves no room for intervening "vital" forces. Chemistry and physics thus rule the living world as much as that of inorganic nature. As the new physiology spread through the medical world, it effectively spelled the end of old vitalist traditions.[29]

The growing distaste for metaphysical and teleological notions in the new industrial era induced several attempts to account for transformation and directionality in mechanical terms. Variability, competition, and selection went a long way in underpinning progressive, evolutionary change, both in nature and in society. If Robert Malthus and Adam Smith inspired much of Darwin's views on nature, these views in turn were used to support and justify political ideologies. In physics, the social science of statistics, applied to systems of particles rather than to populations, was used to make sense of the tendency of such systems to move toward states of higher entropy. In return, thermodynamics came to be seen as an instructive model for economics. Thermodynamic analogies, such as those based on the conservation of energy, have permeated economics deeply—fatally so, according to some.[30]

In the late nineteenth century, energy also entered the mental world. The repercussions of energy conservation for the notion of free will were widely discussed. If an immaterial mind somehow acted on the body, wouldn't such action interfere with the energy balance in the physical world?[31] Perhaps one should broaden the concept of energy so as to include "psychic" energy. In the wake of the efforts of the Berlin physiologists to transform the science of life, one of their former pupils, Sigmund Freud, explored the new field of "psychodynamics," based indeed on the notion of a conserved "psychic energy." Several commentators have noted the analogies between psychoanalytic conceptions, such as suppression by the ego, and the mechanisms of the steam engine.

Around the middle of the century, the steam engine itself was subjected to radical innovation. Improvement in speed control and increases in efficiency made the machine suitable for a larger variety of industrial applications. And just as the late eighteenth century saw the emergence of new kinds of balances, in the late nineteenth century new kinds of engines appeared, such as electric motors, internal combustion engines, and steam turbines. Unlike the steam engine, these new appliances were partly rooted in academic research. Indeed, new electric and chemical technologies were changing society at a rapid pace. In turn, the university itself took on an industrial guise with the rise of university laboratories. Around the turn of the century several kinds of engines made their appearance in experimental setups, producing extremely low temperatures, high pressures, and high voltages, thereby changing the nature of experiment. Kamerlingh Onnes's cryogenic laboratory with its engine-driven pumps is a classic

[29] Everett Mendelssohn, "Physical Models and Physiological Concepts: Explanation in Nineteenth-Century Biology," *Brit. J. Hist. Sci.*, 1965, 2:201–219; and Timothy Lenoir, *The Strategy of Life: Teleology and Mechanics in Nineteenth-Century German Biology* (Dordrecht: Reidel, 1982), esp. Ch. 5.

[30] Philip Mirowski, *More Heat than Light: Economics as Social Physics, Physics as Nature's Economics* (Cambridge: Cambridge Univ. Press, 1989).

[31] Marij van Strien, "Vital Instability: Life and Free Will in Physics and Physiology, 1860–1880," *Ann. Sci.*, 2015, 72:381–400.

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example of this development. The rise of industrial laboratories finally sealed the relationship between natural science and industrial society.

The Computer: Processing of Information

In the second half of the twentieth century, Western societies moved into a postindustrial phase. Far more people became employed in the service sector than in the manufacturing sector, and the former is now producing more wealth than the latter. That part of the service sector that provides information services has now grown to such an extent that it has become customary to speak of a quaternary industry, alongside the secondary, or manufacturing, industry and the tertiary, or service, industry. By now the fastest-growing businesses produce services such as information technology, information generation and sharing, and entertainment. Not surprisingly, the machine that processes such information, the computer, has become the leading metaphor for nature, the living world, and the human mind.

The study of communication networks and computers during the 1930s and 1940s gave rise to the new concept of information and the emergence of information theory. Basing his approach on a syntactic conception of information, Claude Shannon was able to develop an elegant mathematical theory of information. World War II intensified research on the communication, coding, and decoding of information, as did the subsequent Cold War. The postwar interdisciplinary field of cybernetics explicitly looked for the underlying principles of such complex systems as society, life, the brain, and, indeed, the computer, once again linking the technical and the social with the natural. Information was a key notion in this program. It was increasingly seen to be fundamental, irreducible, and, as such, on a par with matter and energy. As the father of cybernetics, Norbert Wiener, succinctly put it: "Information is information, not matter or energy."[32]

During the postwar period the computer itself went through a series of radical innovations. Computers now became digital and electronic and featured electronic storage of programming information and data. Radio tubes were replaced by, successively, transistors, integrated circuits, and, finally, "large scale" integrated circuits, resulting in increased speed and diminished size. The 1950s saw the first commercially produced computers and the first programming languages. During the following decade computer science came into its own as a discipline, as the first computer science departments were founded. The 1980s saw the rise of the personal computer, followed by the breakthrough of the Internet and the World Wide Web.

The rise of information technologies changed the nature of both the content and the practice of science. In incorporating information in their views of reality, life scientists took the lead, partly spurred on by exact scientists. Already in 1943 Erwin Schrodinger stated that the hereditary molecule must contain a "code-script" that determined "the entire pattern of the individual's future development and of its functioning in the mature state," and five years later John von Neumann, one of the cofounders of cybernetics, described the gene as a "tape" that programmed the organism. Following the discovery of the double-helix structure of DNA by James Watson and Francis Crick in 1953, biologists gradually came to understand the nature of life in terms of information. The information is said to be *encoded* in DNA molecules, as sequences of nucleotide triplets called *codons*; to be *copied* into messenger-RNA, a process also known as *transcription*; and to be *translated* with the help of transfer-RNA and ribosomes into the buildup of proteins.[33]

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[32] Ronald R. Kline, *The Cybernetics Moment; or, Why We Call Our Age the Information Age* (Baltimore: Johns Hopkins Univ. Press, 2015), p. vi (quoting Wiener).

[33] Lily E. Kay, *Who Wrote the Book of Life? A History of the Genetic Code* (Stanford, Calif.: Stanford Univ. Press, 2000).

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The Human Genome Project, the world's largest collaborative project in the life sciences, resulted in the mapping and identification of the twenty thousand genes of the human genome. Its successor, the ENCODE project, is a collaborative data collection of the functional elements of the human genome that uses next-generation DNA-sequencing technologies and genomic tiling arrays. The development of software tools and other computer-related methods for analyzing and understanding biological data, so-called bioinformatics, has now become an integral part of the life sciences. These data include both DNA and protein sequences. Research in bioinformatics also includes gene finding, drug design, and discovery.

Understandably, the metaphorical role of the computer is even larger in what is now called neuroscience. Throughout the later part of the twentieth century the brain came to be seen as a parallel digital supercomputer. Although its mechanism differs from that of an electronic computer, it likewise acquires external information, which it stores and processes in a variety of ways, much like the processor in a computer. Indeed, in the current €1 billion Human Brain Project, funded by the European Commission, the emphasis is on a large-scale computer simulation of the brain with the use of a new generation of supercomputers. Here, too, we have a new field of neuroinformatics at the intersection of neuroscience and computer science.

More recently, physicists have also discovered "information" as a guide to a deeper understanding of nature. The ties between information theory and thermodynamics go back to the emergence of the former in the late 1940s. It didn't take Shannon long to realize that there are close parallels between the mathematical expressions for thermodynamic entropy and what he called information-theoretic entropy. In 1957 Edwin Jaynes suggested that these parallels involve more than a mere analogy, arguing that thermodynamic entropy can actually be seen as a special application of Shannon's more general information entropy. As he pointed out, his reinterpretation made entropy "the primitive concept . . . more fundamental even than energy." Although he did not manage to convince the majority of physicists that he was correct, most would accept some kind of relation between entropy and information.[34]

During the last three decades, following suggestions from John Archibald Wheeler, physicists increasingly tend to see space, time, and the four basic forces as emergent properties rising out of the distributions of information at—or even beyond—the so-called Planck scale. In this program, information rather than matter, energy, or force is seen as the stuff that ultimately makes up our world, the universe being pictured, in the words of Gerard 't Hooft, as a large machine that processes information. The so-called holographic principle, pioneered by 't Hooft and based on a thermodynamic understanding of black holes, was an important step in this direction. It suggests that our three-dimensional world, like the visible holographic image, emerges from a lower-dimensional reality, corresponding to the holographic plate, in which all the required information is stored. A further but more controversial step in this direction is Erik Verlinde's recent theory of gravity as an emergent, entropic force. Here entropy is understood in terms of information.[35]

The influence of the computer (and computer networks) as a model and metaphor and of the concept of information in all branches of science is hard to overestimate. In economics, the use of game theory for modeling competing behaviors of interacting agents and the related theory of

[34] E. T. Jaynes, "Information Theory and Statistical Mechanics," *Physical Review*, 1957, *109*:620–630, on p. 629; and F. Alexander Bais and J. Doyne Farmer, "The Physics of Information," in *Philosophy of Information*, ed. Pieter Adriaans and Johan van Benthem (Amsterdam: Elsevier, 2008), pp. 609–684.

[35] Charles W. Misner, Kip S. Thorne, and Wojciech H. Zurek, "John Wheeler, Relativity, and Quantum Information," *Physics Today*, Apr. 2009, pp. 40–46; Raphael Bousso, "The Holographic Principle," *Reviews of Modern Physics*, 2002, 74:825–850; and Erik P. Verlinde, "On the Origin of Gravity and the Laws of Newton," *Journal of High Energy Physics*, Apr. 2011, 29:1–26.

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information economics are obvious examples. In the humanities and social sciences, the strong emphasis on networks and network analysis is likewise an offspring of the computer age. Within the new field of digital humanities, the possibility of automatic analysis of vast textual corpuses results in the production of new kinds of knowledge.

Moreover, in almost every area of science computers have become indispensable as tools. Computers are used to solve equations and perform complex calculations, to store and analyze data, to simulate experiments not otherwise feasible, to model complex systems, and to visualize the invisible. In many cases the computer has become an inseparable part of the measuring instrument itself. Computer software enables a multitude of astronomical antennas or telescopes to act as a single instrument. And as the computer has changed scientific practice, science in turn will change the nature of computing by constructing new technologies that make the use of quantum information theory possible. Quantum computing will facilitate vast gains in computing power.

CONCLUSION

For now, this rough outline must suffice. This skeleton can be fleshed out further by attention to appropriate institutions, means of communication, practices, values, audiences, and social uses, each more or less fitting to the periods discussed. Let me conclude this essay by pointing out what I see as its main strengths and weaknesses, both in general and in comparison with other "big pictures." Apart from its simplicity, its strong points are that it allows for a clear periodization in terms of dominant knowledge regimes, that it manages to connect knowledge to society in a nonreductionist, almost symmetric way, and that it undermines naive notions of knowledge as something out there to be discovered. It is also symmetric with regard to the relations between "science" and "technology." Science, in this scheme, appears as much as "applied technology" as technology can be held to be "applied science."

In addition, this approach promises to shed light on a question that has become central to our field: the circulation and globalization of locally produced forms of knowledge. Technological artifacts have a specific advantage over most other cultural products. They are more readily and rapidly adopted and therefore circulate more easily. Knowledge likewise has to circulate and spread in order to become certified knowledge. This latter process may be eased by the mobility of the technology that has inspired and facilitated such knowledge. Finally, the scheme allows us to make a metaprediction through extrapolation, a rare phenomenon in historical analysis. Suppose that in the future—say, in a hundred years' time—we shall have a new and advanced technology with a strong impact on our economy as well as on the way we live. The model predicts that this technology will generate new concepts that will change our views of nature, life, and mind.

The weaknesses of this new picture are also quite obvious. The new scheme tends to privilege natural philosophy, physics, and physiology, to create artificial boundaries between science and technology, to highlight ontologies at the expense of method and practice, and to be Western-centric. Some of these flaws may be reparable by adjusting some missing elements. Whether these can be connected to the existing structure in a natural way is an open question. More generally, most readers will miss some crucial themes and episodes in the picture sketched above. With regard to the scope of the scheme here proposed, some tolerance must be allowed. Grand narratives inevitably involve selectivity in terms of the facts they marshal. They are at best a first-order approximation or even merely a skeletal structure.

How does the big picture proposed here compare with other big pictures? First of all, my scheme can incorporate several aspects of the scientific revolution, although it tends to downplay the presumed uniqueness of that revolution. Admittedly, the seventeenth-century shift from organic to machine-like models of nature is more radical than that from one machine to

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another. That a machine-like view of nature provides a breeding ground for the extensive use of mathematics in its understanding seems only natural. After all, “mechanics,” traditionally the science of machines, had been part of (mixed) mathematics since antiquity. Something similar can be said about the midcentury rise of experiment, based on the intrusion of machines into scientific research. If nature becomes a piece of machinery, the distinction between the (necessarily passive) study of its *natural* behavior, characteristic of medieval natural philosophy, and the (more interactive) study of its *unnatural* behavior, proper to the useful arts, evaporates. To understand the nature of a clock, one has to take it apart; it is not enough to observe its face attentively.

More recently, a big-picture proposal has been advanced by the late John Pickstone, based on what he called “ways of knowing,” later extended with corresponding “ways of working.” Pickstone’s approach is based on the idea that “the multiple configurations of knowledge and working practices seen in the general area of science, technology and medicine (STM), both now and across time, can be analyzed as ‘compounds’—as made up of ‘elementary’ ways of knowing and working.” Pickstone identified several elementary “ways of knowing” (and “ways of working”)—such as “reading” (understanding the world in terms of meanings), “sorting” (describing and classifying), “analysis” (mathematical, substantial), and “synthesis”—which he used to organize his narrative. Some of these elements flourished at particular times, but they do not connect naturally to specific periods.[36]

My scheme differs from that of Pickstone in several ways. It is both bolder and simpler. It is based on ontological categories rather than methodological ones. It focuses on nature’s fundamental principles and substances as perceived in successive periods, rather than on “ways of knowing.” In spite of its “philosophical” nature, it is more firmly embedded in, or connected to, social and economic realities. Above all, it facilitates a convenient periodization. On the other hand, Pickstone’s scheme not only allows for a more balanced treatment of natural philosophy, natural history, and mathematics, but it also encompasses technology and medicine. As our schemes are in many respects complementary, they can perhaps be combined. Whatever may come of synthesizing attempts such as these, I hope to have shown that there is no need to resign ourselves to endless historical fragmentation.

[36] John V. Pickstone, “A Brief Introduction to Ways of Knowing and Ways of Working,” *Hist. Sci.*, 2011, *49*:235–245, on p. 235. Pickstone expanded and refined his scheme over time. See John V. Pickstone, “Ways of Knowing: Towards a Historical Sociology of Science, Technology, and Medicine,” *Brit. J. Hist. Sci.*, 1993, *26*:433–458; Pickstone, *Ways of Knowing* (cit. n. 1); Pickstone, “Working Knowledges Before and After circa 1800: Practices and Disciplines in the History of Science, Technology, and Medicine,” *Isis*, 2007, 98:489–516; Pickstone, “Sketching Together the Modern Histories of Science, Technology, and Medicine,” *ibid.*, 2011, *102*:123–133; and Pickstone, “Natural Histories, Analysis, and Experimentation: Three Afterwords,” *ibid.*, pp. 349–375.

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