REVIEW

Mechanics, Mathematicians, and Experimentation in Early Modern Physics

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Domenico Bertoloni Meli
Thinking with Objects: The Transformation of Mechanics in the Seventeenth Century
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IN THE VERY FIRST SENTENCE of the preface to the first edition of the *Philosophiae naturalis principia mathematica* (1687), the most important work of early modern science, Isaac Newton added authority to his subject by tracing its origins to the ancient Greeks. Citing the mathematician and author of mechanical treatises Pappus of Alexandria, Newton wrote that the ancients "esteemed the science of mechanics to be of the greatest importance in the investigation of natural things." While it is customary and not incorrect to see Newton's *Principia* as groundbreaking, he placed his work in an older tradition—within a set of inquiries he called "rational mechanics" that gained its inspiration from Pappus and Archimedes. Newton contended that the goal of this field, revived during the sixteenth century, was to "subject the phenomena of nature to the laws of mathematics."

For us, living in a post-Newtonian world in which the heuristic powers of mathematics are widely accepted, Newton's goal seems relatively straightforward. Yet exactly how one should proceed in subjecting natural phenomena to mathematics was a vexing question that dated back to antiquity. Many early modern natural philosophers contended that mathematics could not produce theoretical knowledge about the material world. Even if they accepted the applicability of mathematics to nature, mathematicians and natural philosophers still had to reach agreement on the character and techniques of experimentation, measurement, and observation that underlay their mathematical models of nature. Thus despite the fact that the presentation of argument in the *Principia* follows the axiomatic structure of mathematical treatises,

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Newton described the methods and results of his experiments with lodestones, pendulums, and colliding balls, experiments that he believed established his laws of motion. The close relationship between theoretical arguments and mechanical experiments evident in Newton's *Principia* did not arise in isolation; rather, it was part of a tradition that began in the late sixteenth century.

Domenico Bertoloni Meli's *Thinking with Objects: The Transformation of Mechanics in the Seventeenth Century* offers a fresh and detailed account of developments in the methods and import of the science of mechanics from the late Renaissance to the first decades of the eighteenth century. His approach reflects a new direction in telling the history of early modern natural philosophy. Twentieth-century histories, starting with Alexandre Koyré, emphasized conceptual changes. Scholars working in this tradition traced the abstractions and principles that formed the basis of the new physics of Galileo, Descartes, Newton, and their followers. In these accounts, the explananda were the laws of nature (in particular, the laws of locomotion, conservation of energy, and inertia), the geometrization of space, and the replacement of the closed Ptolemaic cosmos with an infinite universe. Bertoloni Meli does not reject the importance of those ideas but rather aims to shift the emphasis to the actual practices and objects that contributed to the emergence and acceptance of those ideas. Though it is well known that seventeenth-century natural philosophers and mathematicians based their theories on observations taken from complex apparatus such as telescopes and air pumps, they also used "simple and mundane tools" (p. 2) such as inclined planes, springs, pendulums, pulleys, pierced cisterns, balances, and beams to understand the nature of motion, gravity, and matter. These tools constitute the subject of Bertoloni Meli's analysis.

Thinking with Objects expertly shows that the creation of knowledge through the manipulation of these simple tools invoked debates over the relation between theory and practice, the mathematical and the physical world, and the artificial and the natural. During the Middle Ages, mechanics did not exist as a distinct discipline in universities. In the last decades of the sixteenth century, however, Guidobaldo dal Monte and Giuseppe Moletti, inspired and informed by Pappus of Alexandria, Archimedes, and the pseudo-Aristotelian *Mechanical Problems,* renewed exploration into the mathematical science of machines. Their works put forth a useful method by insisting on the conceptual reduction of phenomena. This method took its inspiration from Pappus, who had reduced all mechanics to one type: that of the level, or balance. This reduction in turn meant that the seemingly rectilinear motions of simple machines could be treated as circular motion, an argument that was also explicitly made in the pseudo-Aristotelian *Mechanical Problems.* Years later, the epistemological concept of reduction would play a leading role in the mechanical philosophy of the seventeenth century, when Boyle and Descartes, among others, tried to reduce the natural world to the functioning of machines.

In dal Monte's and Moletti's investigations, however, the issue of reduction was more limited than it would be for Boyle and Descartes, who attempted to use reduction to explain nature, not just artificial machines. During the sixteenth century, the problems of applying mathematical rigor to the physical world were at the forefront. These issues were magnified because of the absence of concepts such as experimental error and order of magnitude. The meaning of small discrepancies between theory and experience was ambiguous. Did little differences between predictions and results mean that the theory was correct or incorrect? Did the persistence of such discrepancies suggest that matter was imperfect and contingent and thus not subject to mathematical laws or, rather, that the imperfection lay in the construction of the devices or the reliability of the observers? Dal Monte tried to solve these problems by crafting small pulleys that minimized the effects of friction and the imperfection of matter, thereby creating precursors to the precision tools used by more recent scientists.

The techniques of experimentation, recording observations, and interpreting data, furthermore, were used to answer practical questions even though the applicability of mathematics to the physical world remained an unsettled question. The Archimedean tradition of calculating floating bodies, for example, offered a model for those who wished to work on hydrostatics and beyond. Niccolò Tartaglia applied Archimedean mathematical analyses to considerations of projectile motion. He saw the movement of bodies in the air as analogous to the floating and sinking of solids in liquids. Solutions to problems in hydrodynamics, such as those made in attempts to calculate volumes of flowing water, employed methods that relied on practical solutions in order to circumvent objections to the mathematical arguments. For example, Giovanni Battista Benedetti, in his analyses of the flow of water, perhaps had recourse to the techniques of astronomy that interpreted perturbations in observations caused by atmospheric refraction. As a result of such practical solutions, those working in the mechanical tradition could utilize experiments even if some were skeptical that mathematics could accurately describe matter. Accordingly, late sixteenth-century hydrostatics was a field in which innovative scholars, such as the hitherto unheralded Ragusan Marino Ghetaldi, published tables of experimental results, in Ghetaldi's case, the records of weights of varying substances under water. While published tables of observations had long been part of astronomy, their arrival to the field of mechanics helped natural philosophers solve issues surrounding the interpretation of experimental error. This increased sophistication in presenting and interpreting data meant that experimental results would be used as both evidence for claims and sources for new investigations in the following decades.

Galileo Galilei, in his *Discourses Concerning Two New Sciences,* or *Discorsi*, was far more skilled in his dealings with experimental results than his immediate predecessors. Bertoloni Meli describes three stages to Galileo's theory-formation. Galileo began with private heuristic consideration of experiments, which, in turn, brought about an informal printed presentation of results, which, in the final stage of conceptualization, were arranged in accordance with axiomatic arguments. Experimentation acted as a preliminary aid that eventually led to more formal proof. Reports of experimental results in the *Discorsi* were more convincing than in the works of his predecessors because Galileo utilized the idea of order of magnitude to explain why small differences between the predictions of mathematical theory and empirical findings were statistically insignificant. Galileo related mathematical predictions of air resistance, buoyancy, and friction to empirical results by correcting for the material of the objects used in various tests.

This novel treatment of discrepancy, however, was perhaps not the most significant development for mechanics found in the *Discorsi*. Galileo argued that matter was composed of inalterable particles that cohered together because of microscopic interstitial vacua. The inalterability of matter rendered null any concern about the inapplicability of mathematics to the physical world on account of the contingency of matter. Furthermore, this view of matter meant that mathematical mechanics could be applied to investigations into the nature of matter itself. Working on these assumptions, Galileo measured the resistance to breaking of beams made of various materials, to estimate the density of fibers that made up the substance, thereby broadening the scope of applied mathematics to include matter theory.

Galileo's *Discorsi* provoked numerous responses, some supportive, others contradictory. The Minim Marin Mersenne used inclined planes to check the accuracy of Galileo's claims and found discrepancies between Galileo's theory and the empirical results. Mersenne's own discoveries, however, did not match his published data. The tables in his *Harmonie universelle*, reflecting his Augustinian outlook, were intended to demonstrate nature's regularity, which, as the title suggests, was the premise of the work, notwithstanding the actual results. Bertoloni Meli contends that Mersenne's results were "extrapolations from experimental data," rather than "the direct results of experiments" (p. 131). The Jesuit Honoré Fabri found Galileo's argumentative structure problematic because he had used experience, which was not precise, to establish the foundations of mathematical demonstrations, which ought to be precise. Deviating from these approaches was another Jesuit, Giovanni Battista Riccioli, who in his *Almagestum novum* printed tables that accurately reflected experimental trials rather than preconceptions such as universal harmony. Thus only some of these tables supported theoretical presuppositions, whereas the rest remained to be interpreted mathematically because they did not fit existing models.

Other critics of Galileo set out to expand the application of mechanics. René Descartes objected to Galileo's failure to provide adequate causal accounts of motion. Invoking laws of nature and the immutability of God, Descartes, in the footsteps of Archimedes and Pappus, attempted to reduce all of nature to mechanics. What Bertoloni Meli sees as the beginning of the mechanical philosophy emerged from the Cartesian desire to conceptualize the invisible microscopic actions of nature as those of miniature machines. According to this position, the world is a conglomeration of machines. As a result, mechanics grew in importance, becoming the guide not just to kinematics but to cosmology as well. The study of hydrology, for example, continued to provide practical techniques for water management while at the same time becoming relevant for cosmological debates. Johannes Kepler, for example, had theorized a celestial physics in which the heavenly bodies move through fluid heavens. Descartes argued that the analysis of the whirling motion of aqueous eddies provided experimental data for the behavior of vortices, which he posited to be key to explaining planetary motion.

Celestial mechanics continued to rely on knowledge derived from the manipulation of simple objects. In the later decades of the seventeenth century, experiments with projectiles and oscillating bodies transformed views of the nature of the orbital motion of planets. The discovery of the moons of Jupiter spurred Giovanni Alfonso Borelli to characterize their motion by explaining curvilinear motion as the result of combinations of centrifugal and centripetal impulses, a view that he tried to support with analogies to the motion of pendulums. Christiaan Huygens, combining mathematical research and sophisticated experiments with oscillating bodies, proved that the oscillations of pendulums are isochronous and move along a curve that was unknown to geometers at that time. These discoveries had great import because they led to the invention of the pendulum clock, which greatly aided timing and thus the accuracy of experiment. They also laid the foundations for new understandings of centrifugal forces, which in turn could be applied to planetary motion.

Experimental techniques similar to those of Huygens would be crucial to Newton. Testing the third law of motion (that "to every action there is always opposed an equal reaction"), Newton used a ten-foot pendulum to measure the effects of colliding bobs. Indeed, Newton saw himself as inheriting and furthering a tradition of rational mechanics, as his initial reference to Pappus suggests. For him, rational mechanics utilized trials with simple objects to gain greater understandings of natural forces. Thus his experiments either provided evidence for his fundamental laws of motion, or for other axiomatic foundations, such as definitions. Sometimes he used experiments to test theories; his investigation of resistance on bodies, which he showed was primarily caused by air, allowed him to cast doubt on the Cartesian notion of subtle bodies. While the *Principia*'s structure is axiomatic and Newton originally saw himself foremost as a mathematician, experiments with simple objects underpinned his new world-system.

Thinking with Objects is a significant book. Its success lies in reformulating our ideas of the methods and practices of early modern science. Without eliminating the need for conceptual understandings of science, Bertoloni Meli brings to light the importance that simple objects and experiences based on their manipulation held. These early modern natural philosophers and mathematicians created tests and techniques for interpreting their experiences in order to determine the validity of theoretical expectations as well as simply to enhance knowledge in areas that were not yet accurately known. Experiments did more than confirm theories; at times, they were heuristic, providing evidence for new approaches. Admirably, Bertoloni Meli charts these new areas of historical research with balance and care. In emphasizing the need to understand better the material culture of early modern science, he does not fall into the trap of trying to reduce natural philosophers and mathematicians to plain craftsmen. Though they might have reduced nature to balances or other machines and were informed by technicians, Bertoloni Meli does not transform these philosophers and mathematicians "into carpenters or joiners" (p. 5). Rather, their experiences with these "simple and mundane" objects informed their mathematical analyses as well as their conceptual foundations. No serious future study of early modern physics and its transformations will be able to ignore the analyses and conclusions of this work.

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