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Paolo Palmieri, *A History of Galileo's Inclined Plane Experiment and its Philosophical Implications*
Lewiston, New York: Edwin Mellen Press, Forthcoming, 2011, 220 pages.

Book Review by Curtis Wilson

The project of this book, Palmieri tells us, emerged slowly, in close relation with the attempt to reenact certain of Galileo's experiments, in particular the inclined plane experiment. Galileo's adventure with balls rolling down inclined wooden beams was not a single event to which a date can be assigned, nor yet a set of operations described in sufficient detail to admit of mere copying. It was a sequence of explorations lasting nearly a lifetime, involving difficulties and puzzles that Galileo struggled to resolve, with less than uniform success. A love affair, Palmieri calls it.

Our author seeks to touch the very nerve of Galileo's endeavor. He challenges the assumption—beguiling to some Galileo scholars—that armchair philosophy can plumb the complexities that Galileo met with in the inclined plane experiment. He seeks to put himself in Galileo's actual problem-situation, with its puzzles on both the experimental and the theoretical side. Experimental work and theoretical explanation, carried on in tandem, pose questions of each other. The result, Palmieri reports, is liberating: the experimenter-theoretician-scholar probes more feelingly, with a new intensity. He becomes a participant in a revolutionary endeavor.

The earliest writings we have in Galileo's hand appear in Volume I of the Edizione Nazionale under the title *Juvenilia,* which was assigned by the editor, Antonio Favaro. He took them to be a compilation from unidentified sources (they remain unidentified today). Their late-medieval character is striking. Paragraphs frequently begin with *Advertendum quod. . .* ("It is to be

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noted that. . ."), a scholastic verbal tic implying that the following sentence is accepted on authority. Is our scribe a mere copyist? Palmieri detects indications to the contrary. In places Galileo appears to be paraphrasing or summarizing; here and there he leaves blank spaces as though for later comment or elucidation.

Included in the *Juvenilia* is a discussion of "the intension and remission of forms," a much-treated topic in scholastic discussions from the fourteenth century to at least the early sixteenth century. It concerns increase or decrease in the intensity of a quality. The hotness or hardness of a body may vary from point to point or from instant to instant at a point. There is no evidence that the fourteenth-century schoolmen attempted actually to measure such variations, but they introduced language for describing them as measurable *secundum imaginationem*. One of the qualities thus dealt with was the speed of a moving body.

To the uniform variation of the intensity of a quality, the schoolmen applied a special rule, now dubbed "the Merton rule" after the Oxford college where it seems to have originated. It states that a quality varying uniformly in intensity over a spatial distance or interval of time is equivalent to the unvarying or uniform quality of the mean degree stretching over the same extension, spatial or temporal. Suppose, for instance, that the hotness of a body varies uniformly from two degrees at one end of the body to eight degrees at the other, the degree being an imagined unit of intensity. This "latitude of form" was said to be equivalent to a uniform hotness of five degrees from one end of the body to the other.

Applied to the intensity of motion or speed, the Merton Rule was interpreted as saying that the distance traversed in a motion uniformly accelerated from an initial to a final speed was equal to the distance traversed in a uniform motion having the same duration and the mean speed of the accelerated motion. Compare this with the crucial first proposition of Galileo's treatise "On Naturally Accelerated Motion" in the Third Day of his *Two New Sciences* (1638)—do not both come to the same result? The Merton Rule is not mentioned in the *Juvenilia* or in any of Gali-

leo's writings. Nevertheless, a number of historians of science, Pierre Duhem and Marshall Clagett prominently among them, have concluded that Galileo's theorem was a redaction of the Merton Rule.

The jury, Palmieri objects, is still out: no evidence has yet turned up to show that Galileo actually encountered the medieval enunciation of the Merton Rule. Palmieri suggests that such influence as the medieval discussion may have had on Galileo was likely indirect, through the *Geometry of Indivisibles* (1635) of his friend Bonaventura Cavalieri. The trajectory of Galileo's thinking, Palmieri urges (following Favaro), is best determined from his writings and the experiments he sought to carry out.

At the very time Galileo was writing the *Juvenilia*, and thus becoming acquainted with the scholastic conception of the natural world, he was also annotating Archimedes' *On Sphere and Cylinder*, a strict deduction of mathematical consequences from premises. The analytical thrust of Archimedean thinking, Palmieri believes, peeps through the text of the *Juvenilia.* Galileo sweats to understand the medieval four-element physics of the sublunary realm, and how all qualities are to be derived from the four "prime qualities" or "alterative qualities," hot, cold, dry, and wet. Are motive qualities and speeds grounded in this fundamental Aristotelian ontology? The question is not explicitly addressed in the *Juvenilia*, but shows itself in Galileo's *De motu,* dating from ca. 1590.

The *De motu*, Palmieri observes, is polemical. Galileo denounces his teachers for the way they teach. When introducing the elements of physics, they bring in Aristotle's other works, quoting from *De anima, De caelo,* or *Metaphysics,* as though their pupils already knew everything or else will accept all on faith. Galileo pledges to proceed differently, following the mathematicians in advancing solely by deductive steps derived from explicit premises.

A central question posed in the *De motu* is: How do the weights and speeds of the same body, descending along planes differently inclined but of equal elevation, differ? By considering

the forces needed to equilibrate the weight on the different planes as weights applied to a lever, Galileo shows that the forces are inversely as the lengths of the planes. (Unbeknownst to Galileo at the time of the *De motu,* this same result had been given in the thirteenth-century *Scientia de ponderibus* attributed to Jordanus de Nemore.)

Galileo in the *De motu* also attempts to deal with the question of why a falling body accelerates. The body's heaviness is a *virtus impressa* (impressed force) that acts downward. Were it acting alone, Galileo assumes that it would produce a constant speed of fall. But to this impressed force downward, Galileo adds an accidental lightness or levity, imparted to the body when we raise it from the earth. When we release it, its motion downward accelerates because the impressed lightness exhausts itself over time. The downward acceleration is thus explained in terms of the Aristotelian qualities of heaviness and lightness, with the important additional assumption that the accidental lightness decays with time. Galileo is here entangled in the fundamental ontology and categories of the *Juvenilia*, along with a misconception, widely accepted up to the time of the publication of Descartes's safari, *Principles of Philosophy*, that every velocity has to be maintained by an impressed force. How did he free himself—as he unquestionably did—from the medieval mindset and its stultifying questions?

Palmieri proposes that certain life-worldly learning experiences—among them, finding how to make glass goblets sing and brass plates howl—taught Galileo a lesson about the fine structure of nature. By patiently repeated experimentation, the young Galileo learned how to attend to and control the fine detail of what happens in the production of these effects. The beginnings were in the workshop of his father, Vincenzo Galilei. During the 1580s, Vincenzo, a professional lutist, engaged in musicological controversy. Opposing the Pythagorean claim that numerical ratios are the cause of musical intervals—that the ratio 2:1 is the cause of the octave, the ratio 3:2 the cause of the fifth, and so on—he claimed that these intervals are to be determined by the ear alone. One of his prime exhibits was the singing glass, a

goblet containing water which, on being struck, gave forth a musical tone. The pitch depended on the amount of water. Years later Galileo Galilei in his *Two New Sciences* told of a further result, not previously reported: the goblet could be set singing if its rim were stroked with a wet finger-tip. Concomitantly, a standing wave was produced on the surface of the water. Sometimes the tone shifted up an octave, at which moment the number of waves per unit length in the standing wave doubled.

Palmieri—apparently the first among Galileo commentators to do so—has replicated this experiment. Success requires practice, and it is best to begin with a large goblet (Palmieri used a brandy snifter). One must rub the rim rhythmically, while repeatedly wetting the finger and watching for the evanescent wave pattern. The wave pattern is more readily produced in the brandy snifter than in a smaller goblet, but Palmieri found it possible to obtain Galileo's result also with the latter.

The howling brass plate is another of Galileo's experiments that Palmieri has replicated. As Galileo reports in the *Two New Sciences,* while scraping a brass plate with a chisel to remove stains, he found himself producing sounds. Sometimes they were musical tones, and in such cases the chisel left evenly spaced marks on the plate. On one occasion two tones sounded in succession, forming the interval of a fifth. In the two sets of marks formed on the plate, the numbers of marks per unit length were as 3 to 2. Getting these results was helped by a bit of practice, but was easier than obtaining the standing wave in the glass goblet.

A correct interpretation of these experiments presupposes the physics of sounding bodies, which Galileo himself lacked as have some of his recent commentators. A sounding body vibrates predominantly with certain frequencies that depend on the shape and mechanical properties of the material. These frequencies are the body's "natural modes" of vibration. For a body of regular and relatively simple shape, the predominant frequency modes are harmonically related, e.g. as octave or fifth, etc. The vibrations are reflected from the boundaries of the body, and the reflected waves, combining with the original train of waves, form a standing wave pattern. For a given speed of propagation (which is de-

termined by the medium), the wavelength is inversely as the frequency, and thus the wavelengths of two standing waves have ratios inverse to the integral numerical ratios of the corresponding natural modes. The natural modes therefore account for the emergence of the Pythagorean ratios in these two experiments. By confirming Galileo's experimental results, Palmieri has put them beyond doubt. They form a beautiful early confirmation of the theory of natural modes.

Important as this conclusion is, it is a different point that Palmieri aims primarily to make. Galileo's experimental results are obtained only with patient attentiveness to the fine structure of experience. They yield an experience in which hearing, touching, and seeing are integrated—a holistic experience. Such experience can direct consciousness away from false expectations and toward new facts. This kind of learning, Palmieri proposes, assisted Galileo in liberating himself from the medieval mindset with its pre-established categories.

What about the inclined plane experiment? Here also, besides the visual sight of a ball rolling down the plane, a complex of other sensory data is offered—sounds, vibrations that can be sensed through skin and bone as well as the ear, changes in sound as a bronze or wooden ball descends along the wooden track. Did Galileo attend in a focused way to these effects? We know only of the cases already cited, in which he focused on the details of experimental happenings with attentiveness and care. In the Third Day of the *Two New Sciences,* in the section *On Naturally Accelerated Motion,* he focuses on the kind of acceleration that nature employs for descending bodies—on this, its consequences, and not on causes. The latter question as posed by the schoolmen has been set aside:

> [W]e decided to look into [the properties of this kind of motion] so that we might be sure that the definition of accelerated motion which we are about to adduce agrees with the essence of naturally accelerated motion.

It is this that he is now seeking the essence of—naturally accelerated motion itself.

Galileo's adoption of this new focus, Palmieri believes, could have been triggered by the very intensity of the auditory and vibratory experience of the ball rolling down its inclined track. To receive this nonvisual experience as fully as possible, Palmieri placed his forehead in contact with the underside of the beam serving as inclined plane, and grasped the beam with his hands around its sides so that his fingertips could sense the upper side of the beam. An assistant then released a ball to roll down the inclined plane. As it rolled, Palmieri's fingertips picked up the vibrations induced in the beam, which were also transmitted through his cranial bone, and he heard the sound through his ears as well.

The resulting experience Palmieri calls holistic auscultation. It is no mere juxtaposition of different effects, but an integrated effect. It powerfully suggests that through our senses we can delve deep into the fine structure of physical reality. The experience is markedly stereoscopic. The experimenter, hugging the plane at a particular location, is first aware of the ball's starting to move far up behind his head, then hurtling close by, and finally fading away in the distance. The descending ball produces a sound that varies as the ball speeds up. Sound and speed grow uniformly together, and this togetherness takes center stage. The arresting character of this experience, Palmieri proposes, could have derailed the young Galileo's ambition to reduce changing speed and sound to effects of the qualities dubbed primary by Aristotle and the schoolmen.

> In the scriptorium [where the *Juvenilia* were produced], the hot-cold-dry-wet chemistry of pitch and speed can only be thought-through. But it is possible to leave the scriptorium, visit workshops, and turn life into a tastier affair. . . . We reach a new balance between knowledge and values when we learn how to reconfigure life-worldly objects while letting our senses be affected by them.

In *The Two New Sciences* Galileo stresses the *simplicity* of the means nature adopts—in the case of descending bodies, the increase of speed in proportion simply to time elapsed. Reenactments of Galileo's inclined plane experiment, however, yield at best rough confirmations of this relation. In multiple repetitions of the experiment, Palmieri and his students used a water clock of the type Galileo describes, weighing the water released during the duration of the descent to obtain a measure of elapsed time. In a descent of the whole plane, compared with a descent of one quarter of it, the expected ratio of the times is 2:1. In five trials of a bronze ball one inch in diameter, running on the groove cut by a router into the beam (so that the ball was running as though on rails), the numbers obtained were 2.18, 2.19, 2.15, 2.09, 1.97, averaging to 2.12, hence with 6 percent error and a root-mean-square dispersion from the mean of 0.08. In five trials of a bronze ball seven-sixteenths of an inch in diameter, running in the groove, the numbers obtained were 2.04, 1.90, 1.95, 1.90, 1.84, averaging to 1.93, hence with 3.5 percent error, and a root-mean-square dispersion from the mean of 0.067.

Palmieri records twelve more sets of five trials each. The errors are dramatically larger for decreased inclinations of the plane, especially in the case of smaller and thus lighter bronze balls. Five trials with a bronze ball seven-sixteenths of an inch in diameter and an inclination of 1.36 degrees gave an average of 2.74, hence with 37 percent error; but five trials with a bronze ball one inch in diameter and the same inclination yielded an average of 2.17, hence with 8.5 percent error. An increase of the inclination to 3.8 degrees for these two balls reduced the errors to 18 percent and 6 percent respectively.

The deviations from expected theoretical ratios do not easily admit of a detailed explanation, nor does Palmieri attempt one. Of the factors likely to be operative we mention two. Human reflexes cannot be relied upon to open the water-clock precisely when the ball is released to start rolling, or to close it precisely when the ball hits the stopping block. And, throughout the run, friction is no doubt operative. Friction is an action at or between surfaces. Seeking to find what schoolmen were saying in Galileo's day

concerning friction, Palmieri examined the *Juvenilia* and a book on natural philosophy by Galileo's contemporary, the Paduan professor Giacomo Zabarella (d.1589). He found discussions of "reaction" and "resistance," but not of friction. The presumptive role of friction in the inclined plane experiment, Palmieri believes, was a potent riddle leading Galileo to abandon scholastic explanations in favor of an atomistic ontology. Galileo knew and undoubtedly consulted Lucretius's *De rerum natura*. It gives a psychophysical explanation of pleasant and unpleasant tastes in terms of smooth and rough or hooked atoms. The shapes of atoms could similarly account for friction in the sliding or rolling of one surface over another. Friction would thus be a "fight" between particles of different shapes. The amounts of friction would no doubt differ with the extent of contact between ball and trough, with the shapes of atoms, and with the speed of the ball. Such factors may be the causes of the deviations between observed and expected time ratios above reported. But it is hard to imagine how this hypothesis could be tested quantitatively. Besides, Galileo may have shied away from openly entertaining a hypothesis deriving from Lucretius's philosophy—such a move on his part could have led to a new charge of heresy.

One of Lucretius's doctrines appears to have played a seminal role in Galileo's thinking about falling bodies. Lucretius states that, since bodies falling in the void meet with no resistance, all fall with the same speed. He attributes the observed differences in the rates of fall to the checking action of the medium, which hinders the motion of lighter bodies more than that of heavier bodies. Galileo in the *Two New Sciences* will reach an analogous conclusion, but with a crucial difference: all bodies falling in the void fall, not with the same speed, but with the same *acceleration*. We recall that earlier, at the time of the *De motu*, Galileo had thought that the rates of fall would be as the specific gravities (weights per unit volume) of the bodies. That assertion differed from the Aristotelian position, which made the speed of descent proportional to the body's *weight.* Galileo rejected the latter position on the basis of the following argument. He hypothesized that any heavy body that falls has its speed, or (if accelerated) its

degrees of speed, fixed by nature, so that the speed or the acceleration cannot be increased or decreased without violence. (Thus the argument applies whether the body falls with a constant or an accelerated speed.) He then imagined two bodies equal in volume and weight, e.g., two bricks. If let fall together, their speeds or accelerations are equal, and they remain side by side. If tied together so as to form the double weight, the result does not change: they still fall with the same speed or acceleration, neither "burdening" the other. Hence speed of fall cannot be proportional to weight.

By the time he wrote the First Day of *The Two New Sciences* (probably in 1634), Galileo had concluded that all bodies that fall begin by accelerating, and he was hypothesizing that all bodies in the void, independent of their specific gravities, accelerate with the same acceleration. The reasoning leading to this conclusion, as given in the *Postils to Rocco* (marginal notes on a work in which Antonio Rocco attacked Galileo's arguments in *Two New Sciences*) proceeds as follows. He imagines two equal spheres, one of gold and the other of cork, that are let fall from the same height. Since both are surrounded by air, both are buoyed up by the same force, equal to the weight of the volume of air they displace (the buoyancy effect identified by Archimedes). Each body in its motion will also be slowed by the viscosity of the air, and this effect, since it derives solely from a property of the air, would likewise be the same for both. Friction, which Galileo explains as due to the sticking of particles of the medium to the asperities of the body's surface, can also be imagined to differ negligibly in the two bodies (both could be covered by the same surface material).

Finally, there is the resistance to the speed of each body, which is greater for greater speeds. Galileo does not imagine that this resistance can be eliminated practically (as it was a few years later, after Galileo's death, in experimentation with Torricelli's mercury barometer and with von Guericke's air pump). But experience, Galileo tells us, suggests that this resistance is entirely an effect of the medium. In a fall of the gold and cork spheres through 100 braccia (150 feet?) in air, the gold, he asserts, will

precede the cork by two or three braccia. In a fall of 1 or 2 braccia the difference all but disappears. If in a thin medium like air, differences of speeds all but disappear, then, Galileo claims, we are entitled to hypothesize that in a vacuum the speeds would be identical. For this conclusion, we note, Galileo can claim only a hypothetical status.

Galileo's Third Day of his *Two New Sciences* is in one respect strange—even peculiar! The First and Second Days, dealing with the strength of materials, are clearly about real material bodies. The Fourth Day, likewise, deals with real projectiles, actual bodies moving through the air and resisted by it in their motion. The mathematical part of the Third Day, by contrast, is presented as about *points* descending along inclined *lines*. Real bodies are absent, as are real planes along which they could descend. Friction is nowhere mentioned. The idealization of bodies is at least as drastic as that in Euclid's *Elements*. Galileo's adoption of this extreme idealization may owe something to the seeming impossibility of eliminating the effect of the medium, and the difficulty of quantifying the effects of friction.

Among the numerous theorems proved in the Third Day is the "expansion theorem": points falling simultaneously along variously inclined lines starting from a single point as origin are all at each instant on the surface of an expanding sphere. Galileo has the interlocutors of his dialogue engage in a considerable discussion of this theorem. It may be, Palmieri suggests, a relic of an earlier project to elaborate a Lucretian cosmogony starting with point-atoms—another dangerous project which Galileo may have relinquished to avoid further conflict with the papacy.

Early in his book Palmieri cites John Dewey's *Experience and Nature* for its "take" on Galileo's quest for a science of nature. To Dewey, Galileo's turn to active, controlled experimentation represented a radical challenge to the Graeco-Christian spectator-theory of knowledge. In Aristotle's philosophy, as coopted by Christian philosophers like Thomas Aquinas, high value was placed on detached contemplation of the world. The human being was seen as situated at the center of the cosmos, empowered to survey and understand its parts. But in Dewey's pragma-

tist perspective, true knowledge can be gained only by intervening in the world and attempting to bring disturbing or confusing situations under control. Detached contemplation is "out of touch," powerless to penetrate the intricate mysteries of the world. Only by intervening, risking mistakes and failure, can we begin to learn the world's ways.

Was Galileo self-conscious about the revolutionary break he was making with the methodology of earlier natural philosophy? Palmieri in his Chapter 7 adduces three pieces of evidence suggesting that he was.

During his three-year professorship at the University of Pisa (1589-1592), Galileo had as friend, tutor, and colleague the professor of Platonic philosophy, Jacopo Mazzoni. Mazzoni was a syncretist, seeking to show the compatibility of Plato and Aristotle with each other and with Christianity. He was, indeed, the very model of a late sixteenth-century Graeco-Christian philosopher. Yet there was one opinion, apparently shared by Plato and Aristotle, that Mazzoni took issue with, the opinion that theoretical mind was categorically distinguishable in kind from practical mind. Every branch of philosophy, Mazzoni insisted, has both a *theoria* and a *praxis.* Each of these incorporates operations directed toward particulars. In *theoria* such operations are for the sake of *propping up* the truth; in *praxis* they are for the sake of *attaining* the truth, and of finding the essence of things in the order of existence. Such praxis Mazzoni saw as dangerously rushing toward particulars, plunging the seeker after truth into the perilous world of the unstable, of the disturbed situation where action can make the difference between failure and success. In this characterization Galileo, struggling to make sense of his results in the inclined plane experiment, might have recognized himself.

Another glimpse into Galileo's discomfort with the suffering of experiential learning may be gathered from his *Considerazioni al Tasso.* This consists of notes criticizing Tasso's epic poem, *Gerusalemme liberata.* The publication of the poem in 1581 had sparked a lively debate among Italians as to its merit relative to

Ariosto's *Orlando furioso* (1516). Pro-Ariosto by taste, Galileo was vehemently anti-Tasso. He rejected Tasso's treatment of the human passions. Whereas in Ariosto's poem there was a metamorphosis of *res* into *verba,* leading to a satisfying outcome, Galileo judged Tasso's poetry to lack poetic inspiration, and to end up cobbling together fragmented *concetti* (imaginations) lacking continuity and reciprocal dependence. The result was thus like marquetry, in which colored pieces of wood are fitted together, and the border lines between pieces always remain sharp and crudely distinguishable. Tasso had failed to realize that the passage from *res* to *verba* must be dynamic, transformative.

Aficionados of Tasso found in his poetry a new conception of human feeling: feeling as a force originating from deep sources in the senses and the body, so strong at times as to overwhelm the mind. Imitating the pathos in Tasso's poetry became a project for composers of madrigals like Monteverdi. The resulting works were among those sharply criticized by Galileo's father Vincenzo. Vincenzo saw "modern music" as mixing together voices and modes, diverse words (in polyphony), different rhythms and tempos, and thus giving rise to disparate and confusing emotional reactions in the intellect of the listener. The future of music, Vincenzo urged, lay in resolving the polyphonic "confusion" of voices of the madrigal into a monodic style of singing.

Vincenzo's criticism of polyphonic music as fragmented and unintelligible is closely parallel to the younger Galileo's criticism of Tasso's poetry as marquetry. Palmieri sees Galileo's disdain for Tasso as a disdain for "the real, oblique, polyphonic nature of experiential learning." Galileo's preference for Ariosto is "a preference for an ideal of experience in natural philosophy in which he had been inducted by Mazzoni's teachings." But "Galileo's radically new practice of philosophy . . . had brought him face to face with the reality of experiential learning." A deep rift runs through Galileo's mind, as Palmieri reads him: on the one hand, Galileo ardently strives after a science of nature—which requires dealing with the reality of experiential learning; on the other hand, he would like that science to conform to the ideal sketched

by Mazzoni. Perhaps, Palmieri suggests, Galileo was salvaging something of Mazzoni's ideal in his sanitized accounts of his experiments.

Finally, Palmieri adduces a sonnet written by the dying Galileo, giving it both in the original Italian and in a translation by Dennis Looney. The latter runs as follows:

Enigma

Monster am I, stranger and more misshapen
than the harpy, the siren, or the chimera.
There is not a beast on land, in air or water
whose limbs are of such varied forms.

No part of me is the same size as any other part;
What's more: if one part is white, the other is black.
I often have a band of hunters behind me
who map out the traces of my tracks.

In the darkest gloom I take my rest,
For if I pass from the shadows to bright light,
Quickly the soul flees from me, just as

The dream flees at the break of day.
And I exhaust my discombobulated limbs
And lose my essence, along with life and name.

Palmieri interprets the sonnet as a meditation on experiential learning, caught between the polarities of individuality and universality. The metaphor of the monster captures the jagged contour of experience. The darkness is Galileo's blindness, physical as well as metaphorical. The hunters are his persecutors, real and imagined. Only after death, with the loss of individuality, will the light of truth shine forth. Thus Galileo recognizes that knowledge is not coextensive with human experience. His sonnet refracts as through a prism his lifelong pursuit of truth; an active engagement with the life-world, turning up more difficulty and more unsolved conundrums than he has been able to cope with. The strife, the tension, as he still relives it toward the end, is tragic in its intensity. The only resolution is limitless relinquishment.