PIERRE DUHEM

RESEARCH ON THE HISTORY OF PHYSICAL THEORIES*

All abstract thought requires the control of facts; all scientific theories call for comparison with experience. Our logical considerations about the proper method of physics cannot be judged rationally unless they are confronted with the teachings of history. We must now apply ourselves toward gathering these teachings.

During antiquity, the Middle Ages, and the Renaissance, there has hardly been more than one part of physical theory in which mathematical theory had sufficient development and observation had sufficient precision for us to discuss their mutual relations; this part is astronomy.

With regard to the nature and value of astronomical theory, one might say that the Greek mind, so admirably supple, penetrating, and varied, conceived all the systems that our time has seen flourish again (Duhem 1908b). But among these systems, there is one that wins over the approbation of the most profound thinkers. It can be summarized in the following principle that Plato taught to those who wanted to work in astronomy: "When taking certain assumptions as our point of departure, one must attempt to save what appears to the senses – *Tinon upotethenton,...sozein ta phainomena*." And this principle spans the Arabic, Jewish, and Christian Middle Ages, is repeated at the time of the Renaissance, is explained, specified, or contested, up to the day when Andreas Osiander formulates it thus, in the preface that he placed at the head of Copernicus' book: "*Neque enim necesse est eas hypotheses esse veras, imo, ne verisimiles quidem, sed sufficit hoc unum* [159] *si calculum observationibus congruentem exhibeant.* (It is neither necessary that these hypotheses be true nor even that they be likely, but only one thing suffices, namely, that the calculation to which they lead agrees with the result of observation.)" For two thousand years, therefore, the majority of those who reflected on the nature and value of the mathematical theory used by the physicists agreed to proclaim the axiom that Energetics came to take as its own: the first postulates of physical theory are not given as affirmations of certain suprasensible realities; they are general rules which would have played their role

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admirably if the particular consequences deduced from them agreed with the observed phenomena.

The method followed by Energetics is not an innovation; it can call forth the most ancient, most continuous, and most noble tradition for itself. But, what should we say about the essential notions and fundamental principles of that science? Logic does not require any justification of Energetics when it defines these notions and posits these principles; Logic leaves it free to posit its foundations as it wishes, as long as, having reached its zenith, the edifice is capable of accommodating without constraint or disorder the laws ascertained by the experimenter. Is that to say that Energetics defines these notions haphazardly and posits these principles without reason? Not at all. Although Logic does not impose any constraint upon Energetics, the teachings of history are an extremely sure and meticulous guide for it; the remembrance of past attempts, and of their happy or unhappy fate, prevents Energetics from receiving hypotheses which have led older theories to their ruin, or persuades it to adopt ideas which have already been shown to be fruitful. Energetics would not be able to prove its postulates, and does not have to prove them; but by retracing the vicissitudes they have gone through before they came to have their present form, it can gain our confidence for them – that is, it can obtain some credit for them at the moment when their consequences would be receiving the experimental confirmation we have anticipated.

We undertook to write the history of the great laws of statics and dynamics in order for Energetics to be in the position to understand and exhibit the evolution experienced by each of its fundamental principles.

It was known that important reflections on statics were sketched in the manuscript notes of Leonardo da Vinci. Our reading of Leonardo da Vinci and Cardano drew our attention to the unexplored statics of the Middle Ages; and soon, the act of [160] laying bare all the manuscripts on statics at the public libraries of Paris yielded unexpected discoveries in abundance (Duhem 1905–1906, vol. 1). The Christian Middle Ages had known the writings on statics composed by the Greeks; some of these writings came to it directly and others through the intermediary of Arabic commentaries. But the Latins who read those works were not at all the slavish commentators, devoid of any invention, that people were pleased to depict to us. The remains of Greek thought that they received from Byzantium or from Islamic science did not remain in their minds as in a sterile depository; these relics were sufficient to awaken their attention, to fertilize their intellect. And, from the thirteenth century on, perhaps even before that time, the school of Jordanus opened to students of mechanics some paths that antiquity had not known.

At first, the intuitions of Jordanus de Nemore were extremely vague and extremely uncertain; some grave errors were intermixed with some great truths. But soon, the disciples of the inventor refined the master's thought. The errors were eclipsed and began to disappear; the truths became more precise and firmer, and several of the most important laws of statics were finally established with complete certainty.

Specifically, we owe to the school of Jordanus a principle whose importance was demonstrated, with ever-growing clarity, during the development of statics. Without analogy to the postulates specific to the lever, of which Archimedes' deductions made use, this principle has only a distant affinity to the inexact axiom invoked by Aristotle's *Mechanical Questions*. It affirms that the same motive force can lift different weights to different heights, as long as the heights are inversely proportional to the weights. Applied by Jordanus only to the straight lever, this principle allowed one of his disciples to ascertain the law of the equilibrium of weights on an inclined plane and, by an admirable geometric device, the law of the equilibrium of the bent lever.

Descartes took up almost without change what this anonymous mathematician of the thirteenth century had written; and henceforth, from Descartes to Wallis, from Wallis to Bernoulli, and from the former to Lagrange, then to Gibbs, the principle of virtual displacements continued to be extended.

[161] Toward the year 1360, Albert of Saxony, a master of arts of the University of Paris, wrote:

> It is not true that every part of a weight tends toward its center becoming the center of the world – which would be impossible. It is the whole that descends in such a way that its center becomes the center of the world, and all the parts tend toward the goal that the center of the whole becomes the center of the world; therefore, they do not impede one another....

This center, this point which, in every weight, tends to place itself at the center of the world, is, as Albert repeated on several occasions, the center of gravity.

Therefore, every weight moves as if its center of gravity sought the center of the world – a false idea that, during the seventeenth century, engendered many errors, engaged the greatest geometers, and yielded only after a fierce discussion (Duhem 1905–1906, vol.1); but, in the meanwhile, it was a fertile idea that imparted new truths to statics. In fact, it immediately gave statics the following proposition: a system of weights is in equilibrium when the center of gravity is as low as possible. Torricelli and Pascal one day accepted that proposition as the foundation of all statics, and it gave rise to the theorem of Lagrange and Lejeune-Dirichlet on the stability of equilibrium.

Leonardo da Vinci, that indefatigable reader, leafed through and meditated endlessly upon the writings of the school of Jordanus, on the one hand, and the scholastic questions of Albert of Saxony, on the other. The former, by acquainting him with the law of the equilibrium of the bent lever, led him to the following memorable law, which governs the composition of concurrent forces: with respect to a point taken on one of the composing forces or on the resulting force, the two other forces have equal moments (Duhem 1904, 1905–1906, vol.2, 1906–1913, vol. 1, pp. 257–319). Moreover, Albert of Saxony's ideas on the role of the center of gravity allowed him to discover the rule of the polygon of support (Duhem 1905–1906, vol. 2, 1906–1913, vol. 1, pp. 257–319), which Villalpand plagiarized (Duhem 1905–1906, vol. 2, 1906–1913, vol. 1, pp. 53–89). Thus, we find the origins of several principles essential to statics in the writings composed during the thirteenth and fourteenth centuries.

Was it the same for dynamics?

The dynamics begun by Galileo – and by those who emulated him and his disciples, such as Baliani, Torricelli, Descartes, Beeckmann, and Gassendi – is not an innovation; the modern intellect did not produce it, suddenly and completely, as soon as the reading [162] of Archimedes revealed the art of applying geometry to natural effects.

Galileo and his contemporaries made use of the mathematical skill, acquired in antiquity by the geometers while they practiced their trade, in order to render more precise and to develop a science of mechanics, a science whose principles and most essential propositions had been posited by the Christian Middle Ages. The physicists who taught this mechanics during the fourteenth century at the University of Paris had conceived it by taking observation as their guide; they substituted it for Aristotle's dynamics, convinced of its inability to 'save the phenomena'. At the time of the Renaissance, the superstitious archaism, which delighted equally in the wit of the humanists and in the Averroist habit of retrograde scholasticism, rejected this doctrine of the 'Moderns'. The reaction against the dynamics of the 'Parisians' and the inadmissible dynamics of the Stagirite was powerful, particularly in Italy (Duhem 1906–1913, vol. 3, pp. 113–261). But, in spite of this hardheaded resistance, the Parisian tradition found some masters and savants to maintain it and develop it outside the schools, as well as in the universities. Galileo and his followers were the heirs of this Parisian tradition. When we see the science of Galileo triumph over the stubborn Peripatetism of Cremonini, we believe, since we are ill-informed about the history of human thought, that we are witness to the victory of modern, young science over medieval philosophy, so stubborn in its mechanical repetition. In truth, we are contemplating the well-paved triumph of the science born at Paris during the fourteenth century over the doctrines of Aristotle and Averroes, restored into repute by the Italian Renaissance.

No motion can last unless it is maintained by the continuous action of a motive power directly and immediately applied to the mobile. That is the axiom upon which all of Aristotle's dynamics rests.

In conformity with this principle, the Stagirite wanted to apply a motive power for transporting the arrow, which continues to fly after having left the bow. He believed he had found this power in the perturbation of air; it is air, struck by a hand or by a ballistic machine, which supports and carries forth the projectile.

This hypothesis, which seems to push verisimilitude to the brink of ridicule, appears to have been accepted almost unanimously [163] by the physicists of Antiquity (Duhem 1906–1913, vol. 2, pp. 97–281). Only one of them spoke clearly against it, and he, living during the final years of Greek philosophy, is almost separated from that philosophy by his Christian faith; we are referring to John of Alexandria, surnamed Philoponus. After having demonstrated what was inadmissible about the Peripatetic doctrine of projectile motion, John Philoponus declared that the arrow continues to move without any motor applied to it, because the string has given it an energy that plays the role of motive virtue.

The last Greek thinkers and Arabic philosophers did not even mention the doctrine of John the Christian, for whom Simplicius and Averroes had only sarcastic comments. The Christian Middle Ages, in the grip of a naive admiration for the newly discovered Peripatetic science, at first shared the Greek and Arabic commentators' disdain for Philoponus' hypotheses; Saint Thomas Aquinas mentions the hypothesis only to warn those who might be seduced by it.

But, following the condemnations brought forth in 1277 by Etienne Tempier, the Bishop of Paris, against a set of theses upheld by 'Aristotle and his followers', there appeared a large movement that liberated Christian thought from the shackles of Peripatetic and Neoplatonic philosophy and produced what the Renaissance archaically called the science of the 'Moderns'.

William of Ockham attacked Aristotle's theory of projectile motion with his customary zeal (Duhem 1906–1913, vol. 2, pp. 97–281). He was content, however, in destroying without building, but his critiques restored into repute the doctrine of John Philoponus for some of Duns Scotus' disciples. The *energy*, the motive virtue of which Philoponus spoke, reappeared under the name *impetus*. The hypothesis of impetus – what was impressed into the projectile by the hand or the machine that launches it – was taken over by a secular master of the Faculty of Arts of Paris, a physicist of great genius (Duhem 1906–1913, vol. 3, pp. 1–112). Toward the middle of the fourteenth century, John Buridan took impetus as the foundation of a dynamics that 'accords with all the phenomena'.

The role that impetus played in Buridan's dynamics is exactly the one that Galileo attributed to *impeto* or *momento*, Descartes to *quantity of motion*, and Leibniz finally to *vis viva*. So exact is this correspondence that, in order to exhibit [164] Galileo's dynamics, Torricelli, in his *Lezioni accademiche*, often took up Buridan's reasons and almost his exact words.

Buridan took this impetus, which remains without change within the projectile unless constantly destroyed by the resistance of the medium and by the action of weight contrary to the motion, to be proportional to the quantity of primary matter within the body; he conceived and described that quantity in terms almost identical to those Newton used to define mass. With equal masses, the impetus increases as the speed increases; Buridan prudently abstained from further specifying the relation between the magnitude of the impetus and that of the speed. More daring, Galileo and Descartes affirmed that this relation is reduced to proportionality; thus they obtained an erroneous estimation for impeto and for quantity of motion, which Leibniz needed to rectify.

Gravity increases indefinitely, as does the resistance of the medium, and it ends up annihilating the impetus of a mobile thrown upward, since such a motion is contrary to the natural tendency of that gravity. But with a falling mobile, motion conforms to the tendency of gravity.

Thus, the impetus must be augmented indefinitely and speed must increase constantly during the motion. Such is, according to Buridan, the explanation for the acceleration observed in the fall of a weight, an acceleration that Aristotle's science already understood, but for which the Greek, Arabic, or Christian commentators of the Stagirite had given unacceptable reasons.

This dynamics exposited by Buridan presents in a purely qualitative, but always exact fashion the truths that the notions of *vis viva* and work allow us to formulate in quantitative language.

The philosopher of Béthune was not alone in professing this dynamics; his most brilliant disciples, Albert of Saxony and Nicole Oresme, adopted it and taught it. The French writings of Oresme allowed it to be understood even by those who were not clerics (Duhem 1906–1913, vol. 3, pp. 261–583).

When no resistant medium, when no natural tendency analogous to gravity is opposed to motion, the impetus maintains a constant intensity. The mobile, to which a motion of translation or of rotation has been communicated, continues [165] to move indefinitely in the same manner, with a constant speed. That is the form under which the law of inertia presented itself to the mind of Buridan; it is the form under which it was received by Galileo.

From this law of inertia, Buridan derived a corollary whose novelty we should admire (Duhem 1906–1913, vol. 2, pp. 97–281). The celestial orbs move eternally with a constant speed, because, according to the axiom of Aristotle's dynamics, each one of them is subject to an eternal motor of immutable power. The Stagirite's philosophy required that such a motor be an intelligence separated from matter. The study of the motive intelligences of the celestial orbs was not only the crowning glory of Peripatetic metaphysics, it was the doctrine about which revolved all the Neoplatonic metaphysics of the Greeks and Arabs; the Scholastics of the thirteenth century did not hesitate to receive this heritage of the pagan theologies into their Christian systems.

Now, Buridan had the boldness to write these lines:

> Since the creation of the world, God has moved the heavens by movements identical to those by which they are actually moved. Hence, he has impressed upon them some *impetus* by which they continue to be moved uniformly. In effect, these *impetus*, encountering no contrary resistance, are never destroyed or weakened . . . . According to this imagination, it is not necessary to posit the existence of intelligences moving the celestial bodies in an appropriate manner.

Buridan expressed this thought in various places; Albert of Saxony formulated it also (Duhem 1906–1913, vol. 2, pp. 97–281); and Nicole Oresme, in order to formulate it, made use of this comparison: "Violence excepted, the situation is similar to a man making a clock and letting it go and move by itself."

If we wanted to draw a precise line separating the period of ancient science from the period of modern science, we would have to draw it at the instant when John Buridan conceived this theory, at the instant when the stars stopped being perceived as moved by divine beings, when celestial motions and sublunar motions were admitted as dependent upon a single mechanics.

This mechanics, both celestial and terrestrial, to which Newton gave the form we admire today, [166] was attempting to constitute itself ever since the fourteenth century. The writings of Francis of Mayronnes (Duhem 1913b) and of Albert of Saxony (Duhem 1909) during the whole of that century teach us that there were physicists who maintained that one could construct a more satisfactory astronomical system than the one in which the earth is deprived of motion, by assuming the earth mobile, and heaven and the fixed stars immobile. Of these physicists, Nicole Oresme developed the reasons for this doctrine (Duhem 1909) with a fullness, clarity, and precision that Copernicus was far from achieving. He attributed to the earth a natural impetus similar to the one Buridan attributed to the celestial orbs. In order to account for the vertical fall of weights, he allowed that one must compose this impetus by which the mobile rotates around the earth with the impetus engendered by weight. The principle he distinctly formulated was only obscurely indicated by Copernicus and merely repeated by Giordano Bruno (Duhem 1906–1913, vol. 3, pp. 113–261). Galileo used geometry to derive the consequences of that principle but without correcting the incorrect form of the law of inertia implied in it.

While dynamics was being established, the laws of falling weights were being discovered a few at a time.

In 1368, Albert of Saxony proposed these two hypotheses: the speed of the fall is proportional to the time elapsed from the start; the speed of the fall is proportional to the path travelled (Duhem 1908c, 1906–1913, vol. 3, 261–568). He did not choose between these two laws. The theologian, Peter Tataret, who taught at Paris toward the end of the fifteenth century, reproduced textually what Albert of

Saxony had said. The great reader of Albert of Saxony, Leonardo da Vinci, after having accepted the second of these two hypotheses, rallied to the first. But he was not able to discover the law of spaces traversed by a falling weight; by a reasoning that Baliani took up, he concluded that the spaces traversed in laps of equal and successive times are as the series of whole numbers, while, in truth, they are as the series of odd numbers.

However, the rule that allowed the evaluation of the space traversed, in a certain time, by a mobile moving in a uniformly varied motion was known for a long time. Whether this rule was discovered at Paris, during the time of John Buridan, or at Oxford, during the time of Swineshead, it was formulated clearly in the work in which Nicole Oresme posited the essential principles of analytic geometry (Duhem 1906–1913, vol. 3, 261–568). [167] Moreover, the demonstration that serves to justify it is identical to the one Galileo gave for it.

This rule was not forgotten from the time of Nicole Oresme to the time of Leonardo da Vinci; formulated in most of the treatises produced by the thorny dialectics of Oxford, it was discussed in the various commentaries of which these treatises were the object, during the fifteenth century, in Italy, and then in the various works of physics written at the start of the sixteenth century by Parisian Scholasticism.

None of the treatises of which we have just spoken, however, contains the thought of applying this rule to the fall of weights. We encounter that thought for the first time in the *Questions on Aristotle's Physics* published in 1545 by Domingo de Soto (Duhem 1906–1913, vol. 3, 261–568). A student of the Parisian Scholastics, most of whose physical theories he received and adopted, the Spanish Dominican de Soto admitted that the fall of a weight is uniformly accelerated, that the vertical rise of a projectile is uniformly retarded, and, in order to calculate the path traversed in each of these two movements, correctly used the rule formulated by Oresme. That is to say, he knew the law of falling weights, whose discovery is attributed to Galileo. Moreover, he did not claim the discovery of these laws; rather, he seemed to be giving them as commonly received truths. No doubt they were accepted at the time by the Paris masters whose lessons de Soto followed. Thus, from William of Ockham to Domingo de Soto, we see the physicists of the Parisian school posit the foundations of the mechanics Galileo, his contemporaries, and his disciples developed.

Among those who, before Galileo, received the tradition of Parisian Scholasticism, there was none who deserved more attention than Leonardo da Vinci. During the time he lived, Italy firmly resisted the penetration of the mechanics of the '*moderni*', of the '*juniores*'. Among the university masters, even those who leaned in the direction of the terminalist doctrines of Paris, merely reproduced, under an abridged and often hesitant form, the essential assertions of that mechanics; they were far from being capable of having it produce any of the fruits of which it was the flower.

Leonardo da Vinci, on the contrary, was not satisfied in admitting the general principles of the dynamics of impetus. [168] He meditated endlessly upon these principles, and turned them every which way, pressing them in some fashion to deliver the consequences they enclosed (Duhem 1906–1913, vol. 3, 113–261). The essential hypothesis of that dynamics was similar to the first form of the law of *vis viva*; da Vinci perceived in it the idea of the conservation of energy, and he found some terms of almost prophetic clarity to express that idea (Duhem 1906–1913, vol. 2, pp. 97–281). Albert of Saxony had left his reader in suspense between the two laws of falling weights, the one correct and the other inadmissible. After some tentative steps that Galileo also went through, da Vinci came upon the choice of the correct law. He extended it happily to the fall of a weight along an inclined plane (Duhem 1906–1913, vol. 3, 261–568). Through a study of composite *impeto*, he attempted the first explanation of the curvilinear trajectory of projectiles, an explanation that was completed by Galileo and Torricelli (Duhem 1906–1913, vol. 2, pp. 97–281). He glimpsed the correction that needed to be brought to the law of inertia announced by Buridan, and he prepared for the work that Benedetti and Descartes accomplished (Duhem 1906–1913, vol. 3, pp. 113–261).

No doubt, da Vinci did not always recognize the richness of the treasures accumulated by Parisian Scholasticism. He set aside some of them, which would have been complementary to his doctrine of mechanics. He misunderstood the role that impetus must play in the explanation of the accelerated fall of weights (Duhem 1906–1913, vol. 3, pp. 113–261). He was unaware of the rule which allows the calculation of the path traversed by a body moving of uniformly accelerated motion. It is no less true that the whole of his physics placed him among those the Italians of his time called the Parisians.

Moreover, this title was properly given to him. In fact, his principles of physics were derived from an assiduous reading of Albert of Saxony, and probably also from a meditation upon the writings of Nicholas of Cusa (Duhem 1906–1913, vol. 2, pp. 97–281); and Nicholas of Cusa was also an initiate of the Parisian mechanics. Da Vinci is therefore given his proper place among the Parisian precursors of Galileo.

We have just retraced, in broad strokes, the essential laws of equilibrium and motion at their infancy. On occasion, we have described some portions of physics at the time when that science had reached adolescence. Thus, we have inquired into the sources of the hydrostatic theories of Pascal (Duhem 1905), detailed the role that Mersenne played in the discovery of the weight of air (Duhem 1906b), and sketched the genesis of [169] the doctrine of universal attraction (Duhem 1906a). Now, we did not see any essential principles proceed from the desire to resolve the bodies we perceive and touch into imperceptible, but simpler bodies; we saw none that had as aim to explain sensible motions by means of hidden motions. Atomism did not contribute to their formation in any way. All of them were born from the desire to formulate some very general rules whose consequences 'saved the phenomena'. Thus, the history of the development of physics has come to confirm what the logical analysis of the methods used by that science had taught us. From the former and from the latter, we have gained a renewal of faith in the future fruitfulness of the method of Energetics.

NOTE

*Part III of Duhem 1917, pp. 158–69, translated by Roger Ariew and Peter Barker.

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