1. The Context of the Practioners: Mechanics and its New Objects

https://doi.org/10.1017/S026988970100031X Published online by Cambridge University Press

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Galileo Engineer: Art and Modern Science

The Argument

In spite of Koyré's conclusions, there are sufficient reasons to claim that Galileo, and with him the beginnings of classical mechanics in early modern times, was closely related to practical mechanics. It is, however, not completely clear how, and to what extent, practitioners and engineers could have had a part in shaping the modern sciences. By comparing the beginnings of modern dynamics with the beginnings of statics in Antiquity, and in particular with Archimedes — whose rediscovery in the sixteenth century was of great consequence — I will focus on the question of which devices played a comparable role in dynamics to that of the lever and balance in statics. I will also examine where these devices came from. In this way, I will show that the entire world of mechanics of that time — "high" and "low," practical and theoretical — was of significance for shaping classical mechanics and that a specific relationship between art and science was and is constitutive for modern sciences.

Koyré's Provocation

In 1943, Alexandre Koyré wrote: "The Cartesian and Galilean science has, of course, been of extreme importance for the engineer and the technician; ultimately it has produced a technical revolution. Yet it was created and developed neither by engineers nor technicians, but by theorists and philosophers" (Koyré 1943a, 401 n. 5). In the same essay: "Their [Galileo's and Descartes'] science is made ... by men who seldom built or made anything more real than a theory" (ibid., 401).

Against these and other similar arguments by Koyré, it is not difficult to show that Galileo pertains just to the tradition of the Italian engineers of the Renaissance. The facts are so well known that it will be sufficient only to list some points:

• his training in mathematics in the early 1580s by the mathematician and engineer Ostilio Ricci (see Galilei 1890–1909 XIX, 36; see also Masotti 1977), who is said to have been a pupil of Tartaglia (Drake 1978, 3) and taught later mathematics at the Accademia del Disegno in Florence, founded, on instruction of Cosimo I, Duke (then) of Florence, by Vasari, an educational institution for artists and engineers like Gresham College in London in the seventeenth century;

https://doi.org/10.1017/S026988970100031X Published online by Cambridge University Press

• his lectures on practical mathematics (see Galilei 1890–1909 XIX, 149–158) – fortification,[1] surveying, mechanics, optics, use of the sector[2] etc. — given in Padua in addition to his regular teaching activities at the university;

• his running his own workshop in Padua, which was not so much of use for performing experiments but served as a workshop for manufacturing instruments[3] that he either invented or developed in a special way;

• his successful application for a patent (*privilegio*) of the *Signoria* of Venice for a device for raising water in 1593–94 (see Galilei 1890–1909 XIX, 126–129);

• his varied activities as an inventor, which prompted Leonardo Olschki to write: "One has to imagine that every one of Galileo's discoveries in physics and astronomy is closely connected with any instrument which was either invented or modified in a special way by him" (Olschki 1927, 140);

• his occupation with engineering problems — pumps, regulation of rivers, fortification etc. — all his life;

• his function as mathematician at the Medicean court in which capacity he had to supervise all suggestions of important engineering projects.

Finally, there are indications that Galileo saw himself within the tradition of the Italian engineers of the Renaissance: His last and perhaps most important book bears the title *Discorsi e dimonstrazioni mathematiche intorno a due nuove scienze attenenti alla Mecanica & i movimenti locali.* Alluding thus to Nicolo Tartaglia's *La Nuova Scientia*, it seems to me that Galileo himself ranked his *Discorsi* as within the tradition of treatises that are known as vernacular engineering literature of early modern times.

All these facts were of course known to Koyré as well, whose writings on Galileo are later than those of Olschki or of Zilsel.[4] Conversely, it was known to Olschki and Zilsel that there was not only accordance between men like Tartaglia and Galileo and common practitioners and engineers, but there was also distance and even open conflicts. What Koyré wanted to deny was that it was possible to gain anything for a true understanding of the modern sciences — and these sciences are of course at issue when Galileo is the topic — by studying, as their context, the world of craftsmen and engineers, the "tradition of the workshops" (see Mittelstraß 1970, 175 ff). According to Koyré, the modern sciences resulted from a radical turn of philosophical paradigms, that is, from the replacement of a view of nature in the tradition of Aristotle — seen as bound to sense perceptions and to everyday life concepts — by a mathematical one in the tradition of Plato.

Even if little convinced of Koyré's claims and rather inclined to follow Olschki,

[1] See also Galileo, "Breve instruzione all'architettura militare" (Galilei 1890–1909 II, 15–75), and Galileo, "Trattato di fortificatione" (ibid., 77–146).

[2] See also Galileo, "Il compasso geometrico e militare" (Galilei 1890–1909 II, 343–361), and Galileo, "Le operazioni del compasso geometrico e militare" (ibid., 363–424).

[3] See above all the bookkeeping accounts regarding "L'officina di strumenti mathematici in Padova" (Galilei 1890–1909 XIX, 131–149).

[4] Koyré mentions Edgar Zilsel's *The Social Roots of Science* (1942) as well as Olschki's book (see Koyré 1943a, 401 n. 6).

one has to admit that Koyré's claims remain provoking as long as it is not really clear what is meant by the opposite claim that the emergence of the modern sciences becomes only intelligible when seen in the context of the world of craftsmen and engineers, of the tradition of the workshops. As discussed extensively elsewhere (see Lefèvre 1978, especially Part I), it seems clear that one possible meaning drops out in advance — the meaning that the modern sciences can be derived from needs or bottlenecks of the technology of early modern times.

Though not on the level of regular (non-agricultural) production, which was almost completely performed by a smoothly-functioning system of crafts and artisanship, there were in fact serious problems and bottlenecks in the few exceptional areas of "high tech" production. The problem of regulating the water level in mines of some depth with water pumps is one such example. Such problems were certainly stimulating for theoretically-interested people but it is clear that the sciences of that time were not able to contribute much to the solution of such problems: Contrary to Koyré's position, the world of production gained almost no benefit from the modern sciences before the nineteenth century.[5] Furthermore and perhaps more importantly, it did (and does) not depend on the practical urgency of a problem whether it was the subject of theoretical investigations with fruitful consequences for the sciences or not. That problems which occur in the high tech areas of production are rather unsuitable candidates in this respect is impressively shown by Leonardo da Vinci's admirable inquiries into mechanical problems. The fact that these inquiries were apparently of rather limited consequence for scientific mechanics might be due to the fact that he treated these problems with the nearly unreduced complexity that confronted the men of praxis.

But can we then expect more from the world of craftsmen and engineers, from the tradition of the workshops, than that, at best, it contributed among other factors to a favorable and stimulating climate for the development of the modern sciences? At any rate, it seems not yet sufficiently clear how and to what extent the sphere of practitioners and engineers could play an important role in shaping the modern sciences.[6] In order to examine these questions further within the surroundings of Galileo's life and work, I will start by calling to mind one of the achievements that has earned Galileo a place as one of the founding heroes of the modern sciences.

[5] This applies even to fields like construction, irrigation, and draining, or military architecture where engineers made wide use of geometry, statics, etc., i.e. of sciences, but very rarely of modern sciences. Achievements like the eighteenth-century moon tables, so desperately needed for navigation, were indeed genuinely the fruits of modern science, viz. of Newton's moon theory, but at the same time rather exceptions.

[6] For a more recent "Interim Assessment" of the debate on the tradition of the workshops and the emergence of early modern science, see Cohen 1994, 345ff.

Dynamics — "An Entirely Modern Science"

Galileo's contribution to the foundation of modern dynamics proved to be a decisive step toward the emergence of the modern sciences.[7] Considering the impact he actually had on the development of modern scientific mechanics, one even can say — *cum grano salis* — that his contribution consists precisely in his derivation of the law of free fall and of the projectile trajectory in vacuum. This assessment of his achievements is of course anachronistic. From the perspective of the later, fully developed scientific mechanics, the criterion for judging significance is which of his theories — as reformulated as they may be — was incorporated into classical mechanics. On the other hand it should also be recognized that the decisive event of the seventeenth-century scientific revolution in the field of physics was in fact the origin of modern dynamics. The concepts of these new dynamics enabled the generation of Huygens, Leibniz, and Newton to lay the foundation stone of the building of scientific mechanics in its specific modern shape.

Ernst Mach regarded dynamics as "entirely a modern science." "The mechanical speculations of the ancients, particularly of the Greeks, related wholly to statics. Only in mostly unsuccessful paths, does their thinking extend into dynamics" (Mach 1989, 151). It actually seems that the physicist Mach was unable to take seriously natural philosophy in the tradition of Aristotle, with its statements on natural and forced motion, heavy and light bodies, etc. Koyré, conversely, too solid an historian of ideas not to recognize the legitimacy of the Aristotelian dynamics, emphasized that these dynamics are — perhaps with the exception of the theory of projection (see Koyré 1943a, 411) — much more plausible for understanding everyday life than modern dynamics. Nevertheless, both Mach and Koyré agree on what is most relevant for us: among the theories of mechanics before Galileo's time, only the field of statics and hydrostatics theories can be assessed as scientific from a modern point of view. This is by no means true in the field of dynamics.[8] For Mach and Koyré, there exists no previous history of dynamics in the Middle Ages[9] or in Antiquity, whereas both establish such a

[7] Damerow et al. have shown that Galileo himself remained within the limits of pre-classical mechanics (see Damerow et. al. 1992).

[8] Seen from the perspective of modern mechanics, a rigid distinction between statics and dynamics is artificial. To a certain extent, it is even artificial with respect to the history of mechanics from Antiquity to the early modern era. Within the mechanics tradition of that period, we find not only classical topics of statics, but also of dynamics. In addition to treatments of these statics topics without any application of concepts of movement or force (above all Archimedes), we also find treatments of these topics which make use of dynamics concepts, such as the pseudo-Aristotelian treatise on *Mechanical Problems*. The distinction I want to make here (borrowing from Mach) is the following: Whereas certain classical topics of statics, like the lever, were treated in a modern way in Antiquity by men like Archimedes, essential topics of dynamics — free fall, impact, projection etc. — were handled in a manner known from Aristotle's *Physica*. When I speak of statics or dynamics in this article, I thus always refer only to different topics and not to absolutely separated scientific fields.

[9] Koyré was familiar with the writings of Duhem on the Parisian nominalists of the fourteenth century (see Koyré 1943a, 406).

history for modern statics beginning in the Hellenistic period with Archimedes. Koyré came to see Archimedes and Galileo, though separated by almost two thousand years, as a kind of twin figure personifying the true founding hero of the modern sciences:

> the new, Galilean, physics is a geometry of motion, just as the physics of his true master, the *divus Archimedes*, was a geometry of rest. ... Motion is subjected to number; that is something which even the greatest of the old Platonists, the superhuman Archimedes himself, did not know, something which was left to discover to ... the Platonist Galileo Galilei. (Koyré 1943b, 347f.)

Postponing all objections prompted by these statements, I want to single out two of them with which I agree:

- Modern dynamics, which goes back to Galileo, is a genuine novelty of modern times, whereas modern statics goes back to Archimedes.
- The way in which Galileo treated problems of dynamics is — in principle, regarding the type of treatment — comparable with the way in which Archimedes treated problems of statics.

Thus, it may be appropriate to have a short look back to the mechanics of Archimedes.

Archimedes — A Scientific Engineer

I will start by recalling some well known things. Although it is today a sub-discipline of physics, and became the archetype of physics for the generations after Galileo, mechanics did not belong to physics from Antiquity until the time of Galileo (see Hoykaas 1963) when it was conceived of as knowledge about devices and machines. This knowledge, according to a traditional understanding, which Galileo still had to criticize,[10] was thought of as a means of outwitting nature. Accordingly, it did not make sense to expect that one could gain knowledge about nature by investigating those devices. To complete the picture, making it more complicated at the same time, we have to add that, on the other hand, certain topics that are treated today within a sub-discipline of scientific mechanics were regarded as belonging to physics since the time of Aristotle, namely — as previously mentioned — dynamical topics. The situation is thus the following: Topics that now belong to the realm of statics or hydrostatics as sub-disciplines of mechanics were then the subject matter of "mechanics" in the sense of knowledge — not about nature, but — of art; whereas topics that now belong to the realm of dynamics as a sub-discipline of mechanics were then the subject matter of "physics," in the sense of an all-encompassing natural philosophy.

[10] See the introduction of Galileo's *Le meccaniche* in Galilei 1960, 147f. (Galilei 1890–1909 II, 155f.).

With respect to Archimedes, one consequence of this situation was that, until the time of Galileo, his writings on statics and hydrostatics were not considered to be writings on physics, as was the case for writings like the *Collectiones mathematicae* of Pappus or the *Mechanica* of Heron of Alexandria. They were counted as "mechanics" in the sense of a doctrine on art. Accordingly, only from an anachronistic point of view, could Koyré claim that Archimedes obtained his achievements in statics and hydrostatics because of a mathematical view of nature. The old distinction between mechanics and physics brings our attention to the real content of Archimedes' mechanical writings: theories on certain tools, instruments, simple machines, and devices — on devices the installation, adjustment, and application of which sometimes exceeded the capacities of regular craftsmen and were thus the business of experts who were later called engineers in the West. Archimedes, for Koyré "the greatest of the old Platonists," was honored in Antiquity as the most outstanding engineer whose inventions became entangled by an interweaving of legends not easily deciphered. Even his biography seems to show that the engineer Archimedes preceded the mathematician (see Schneider 1979).

Of course, skills and abilities in the field of technology do not explain those in the theoretical field. There is no gradual transition from the practical experiences and knowledge of the engineer Archimedes to the theoretical form of knowledge his writings on mechanics demonstrate. Compared to engineering treatises like the *De Architectura Libri Decem* of Vitruvius which pass on practical knowledge and experiences, these writings of Archimedes mark a qualitative difference — a difference which is comparable to that between experienced and skilled mathematical practitioners and theoretical mathematicians. In arithmetic and geometry, the decisive step which led in Greek Antiquity to systems of knowledge with a deductive structure was made by reflecting on the possibilities of acting with the symbol systems of the time — means of counting or constructions of spatial relations, respectively. A basic prerequisite of this reflection was an external, i.e. non mental, representation of the elaborated characters, structures, and laws of these actions with symbols, in this case a representation in the medium of the colloquial but written language (see Damerow and Lefèvre 1998, 88f.). The theoretical achievements of Archimedes in the field of mechanics can be understood analogously. They resulted from the reflection on the possibilities of acting with certain material means; not of symbolic operations, but with those of technical operations. In this case too, an external representation of the elaborated characters, structures, and laws of these actions with technical tools was a basic prerequisite of this reflection, but this time Archimedes could use the already available theoretical mathematics for this representation. These mathematical procedures were doubtless of great significance for his success. The precondition for such an application of mathematical tools as a means of theoretical representation and of deduction in statics was, however, that there were devices and mechanical arrangements by reflection and measurement of which the quantities and the kind of relationships expressed by such laws can be obtained.

In the case of Archimedes, we know which technical devices he used to develop his theoretical statics; he developed them on the so-called simple machines (*potentiae staticae*), especially the balance (lever). If we agree with Koyré that Galileo's theories of dynamics are in principle similar to Archimedes' theories of statics, the question becomes what devices did men like Galileo then use to develop modern dynamics in early modern times?

New Problems in Dynamics

Western Europe got to know of the preserved mechanical writings of Archimedes — *On the equilibrium of planes* and *On floating bodies* — in the thirteenth century through the translations of William of Moerbeke.[11] One cannot speak of a real appropriation and assimilation of these writings, however, before the sixteenth century. Their first publication as printed text in 1543 (Archimedes 1543), an event of serious consequence, was the act of the self-educated engineer and mathematician Nicolo Tartaglia. It can be stated generally that the sixteenth-century revival of the classical tradition of mechanics was not in the first place the concern and work of natural philosophy at the universities or of the humanist movement,[12] but of laymen in classics, namely of engineers who were interested in theoretical questions.[13] This confirms once more that the traditional distinction between mechanics and physics was still valid in the sixteenth century.

It is striking to observe that this appropriation of traditions of classical mechanics by theoretically interested engineers was genuine, original, and creative from its beginnings. They tried to apply it to solving problems like impact, momentum, free fall, and projection etc., to problems that went beyond the limits of statics and hydrostatics passed on from Antiquity. It does not mean that these engineers aspired to develop a new treatment of the traditional problems of dynamics within the natural philosophy taught at the universities. Rather, they were striving to solve the dynamics problems which occurred within their practical occupation as engineers, and only in consequence of that did it happen that they were sometimes forced to discuss theories from academic natural philosophy.

This connection between the independent appropriation of the classical mechanics traditions by sixteenth-century engineers, the application of this inherit-

[11] Among the lost writings of Archimedes was one with the title *On balance*. For its presumed contents, see above all Knorr 1982.

[12] One has to add immediately, however, that the humanist movement of fifteenth-century Italy provided the ground on which laymen like Tartaglia could base, namely the collection of the antique texts in several libraries (see Rose 1975, particularly chap. 2).

[13] Within this paper, we have to pass over the short and isolated renaissance of studies in statics in the thirteenth century centered on writings attributed to Jordanus Nemorarius (see Moody and Clagett 1960). It may be of interest to observe that the rediscovery of these sources in the sixteenth century was the result of editorial activities of those engineer figures of the Renaissance, of Apianus (*Liber Jordani Nemorarii ... de ponderibus ... Petro Apiano ...* Nürnberg 1533) and again of Tartaglia (*Iordani opusculum de ponderositate Nicolai Tartaleae ...* Venice 1565).

ance to problems which arose from their practical occupation, and occasional examinations of dynamics theories from academic natural philosophy is obvious, for instance, in the case of projectile trajectory, a central problem for engineers from Tartaglia to Galileo. No theoretical investigation of this problem could ultimately avoid dealing with key concepts from the doctrine of motion in the tradition of academic natural philosophy – concepts like heaviness, lightness, natural versus forced motion, the Aristotelian theory of free fall, the theory of projection in the Aristotelian tradition as well as in the tradition of the *impetus* physics, etc. But theoretically interested engineers discussed these traditional problems and concepts of motion in light of their new questions, freed these from traditional connections to the old conceptual framework, and put them in new ones, discussing, for instance, the Aristotelian propositions regarding free fall within the conceptual framework of hydrostatics (see Galilei 1960, 35ff.; Galilei 1890–1909 I, 271ff.).

The practical context of the new dynamic questions that these engineers raised is well known: ballistics, water pumps, transmissions, etc. The technical revolution of early modern times constituted the general background to these questions, and their outcome is known as well: These engineers dealt with and developed the topics in dynamics, which had previously been treated within traditional natural philosophy, in a way so new that within an interval of only one hundred years — Tartaglia's *Nuova Scientia* appeared in 1537, Galileo's *Discorsi* in 1638 — they produced the preconditions for the development of modern classical mechanics in the second half of the seventeenth century. Although the practical context of the new questions in dynamics and the new ways of their treatment are clear, at least in principle, the exact contribution of this context to the emergence of the new mechanics remains unclear.

Devices of Production and of Scientific Research

It seems obvious that the mere fact that these engineers had motives[14] for being interested in problems in dynamics explains very little. The desire to solve a problem does not constitute a sufficient reason or basis for actually solving it. The Archimedean attitude of these men does not explain much more either. To be able to treat problems in dynamics in an Archimedean way requires not only highly developed mathematical competence, but, above all, suitable technical arrangements with which the problems can be investigated. Thus, we have to examine the devices men like Galileo used to perform their research, the type of devices they used, and investigate where they came from.

These questions seem even more natural in the case of dynamics than in statics.

[14] And perhaps not only professional ones, but also motives which were connected with the contemporary struggles of world views.

It is obviously much more difficult to investigate dynamic phenomena like projection, free fall, impact, etc. than those of statics. One need only think of the swiftness of such phenomena and consider in addition how poor — compared to today — the instruments of that era were, for measuring short intervals of time, for example. Galileo's inventive spirit in working with such difficulties has long prompted special admiration among Galileo scholars; one example is his idea of investigating the law of free fall by letting spheres roll down an inclined plane (see Galilei 1974, 169f. [Galilei 1890–1909 VIII, 212f.]).

Galileo's fame as a founding hero of modern sciences rests not least on the fact that he was one of the first scientists who performed experiments. In contrast to the time when Koyré dominated the research on Galileo, today almost nobody doubts that Galileo performed experiments.[15] Instead, nowadays the opposite danger exists — in seeing Galileo in the light of the narrow and absolutely ahistorical view of experimentation developed by the traditional philosophy of science. According to this view, experiments are only carried out in order to test theories, and the exploratory character of experimentation is largely ignored.[16] It does not seem clear to me, for example, whether the usual emphasis on the genius of Galileo's experiments with the inclined plane is misleading or not. It is known that investigations concerning motions on inclined planes were undertaken at that time which had nothing to do with the problem of free fall — Galileo's own earlier investigations on "ratios of motions of the same body over various inclined planes" (*de proportionibus motuum eiusdem mobilis super diversa plana inclinata*), for instance, were not only connected with problems of statics but were, moreover, pursued within the conceptual framework of statics (Galilei 1960, 63ff. [Galilei 1890–1909 I, 296ff.]; see Drake 1978, 23ff.). Thus, it would be interesting to know the significance of the experiences and insights gained through these earlier studies for his later experimental research on free fall reported in the *Discorsi* (see Galilei 1974, 169f. [Galilei 1890–1909 VIII, 212f.]). Inventions require discoveries, and the question of which technical arrangements are suitable to treat a given mechanical problem in an Archimedean way is not primarily a question of brilliant inventions but of discoveries which require a close familiarity with the available technologies of the time.

This point is valid not only for finding suitable arrangements in order to investigate an already clear-cut problem, but also for finding the problems themselves. Whether problems can be treated in an Archimedean way depends on the technologies available in an era; the technical possibilities of a given time shape the specific form in which problems can be investigated. Thus, finding the problems

[15] Concerning the efforts to reconstruct Galileo's experiments, see above all the writings of Thomas B. Settle. The English version of Settle 1995 appeared in 1996 as a preprint of the Max-Planck Institut für Wissenschaftsgeschichte, Berlin.

[16] Jürgen Renn et al. ("Hunting the White Elephant," in this volume) present new insights into Galileo's experimental practice which may necessitate rethinking, among other things, the usual understanding of established or supposed experiments of Galileo as theory testing key experiments (see, for instance, Drake 1978, 127ff.).

themselves is also a question of discovery that requires familiarity with the available technologies of the time.

The example of the pendulum might be helpful in determining whether problems can be treated in an Archimedean way in order to illustrate the significance of familiarity with technology for the modern sciences. The pendulum is so suitable a device for investigating dynamics problems, it can seem that it had been invented for this purpose. Galileo discovered the pendulum law at the beginning of his career.[17] The anecdote that he discovered it by observing the swinging chandeliers of the cathedral of Pisa has long been ranked among the fables of science. I am not sure that it is such a great advance to assume that experiments his father Vincenzio performed in connection with theoretical questions of music led the son to his discovery (Drake 1978, 21). In any case, the old fable with the chandeliers had at least one advantage: It makes us wonder why the characteristics of pendulum motion were not noticed much earlier. Such swinging objects can be found in civilizations much less developed than Tuscany at the turn of the sixteenth to the seventeenth century. What other prerequisites were needed to discover the characteristics of pendulum motion? It is striking that the pendulum law was not established before pendulums were used as elements of certain machines — a use that can not be traced back to any document older than Leonardo da Vinci (see Feldhaus 1970, column 1218; Usher 1988, 310)[18] — and which was first publicized through Jacques Besson's *Theatrum instrumentorum et machinarum* (1569 and 1578),[19] — only a few years before Galileo's discovery (see White 1966, 108) (fig. 1). Inversely, a new practical utilization of the pendulum emerged apparently in close vicinity of Galileo's investigations — its application as time-keeper.[20]

[17] It is not always clear what is meant by Galileo's discovery of the pendulum law: the simple law that the swinging time depends solely on the length of the thread or the (wrong) isochronism law, i.e. the assumption that a pendulum traverses equal arcs in equal times. The latter "law" is an implicit main topic of the Third Day of the *Discorsi* and can be traced back at least to 1602 (see Galileo's letter to Guidobaldo del Monte from November 29, 1602, in Galilei 1890–1909 X, 97–100). Earlier remarks of Galileo on the pendulum focus on the time pendulums of different weight take to come to rest — see Galileo Galilei: Memoranda on Motion in Drake and Drabkin 1969, 383 (memorandum 20a) (Galilei 1890–1909 I, 413.); see also Galileo Galilei: *De motu*. Galilei 1960, 108 (Galilei 1890–1909 I, 335). For the purposes of this article, it is of less interest which aspect of the pendulum was actually studied by Galileo at a certain time than the very fact that he made the pendulum an object of theoretical investigations which, to my knowledge, was never done before.

[18] The trebuchet (leverage artillery), a medieval ballistic device which makes use of a lever to which a counterweight is attached, may well have been inspiring for the heavy pendulum as it occurs with Leonardo and later with Besson since it was still known in early modern times. It is, however, no precursor of those machines with heavy pendulums because, in contrast to the latter, it does not use the reciprocating movement of pendulums. About the origins of the trebuchet, see Huuri 1941; Needham 1976; Hill 1973; Hansen 1992. See also White 1962, 102f.

[19] An Italian edition of Besson's *Theatrum* with the title *Il teatro de gli istrumenti* appeared in 1582. For the machines with heavy pendulums as elements displayed in Besson's *Theatrum* (see Beck 1899, 191ff.). Later, as mathematician at the Florentine court, Galileo had to evaluate a proposition for a machine which apparently suggested the use of a heavy pendulum as a device for "accumulating power" in the way of fly-wheels (see Galilei 1890–1909 VIII, 571–584).

[20] The *pulsilogium*, a pulse-clock that used a pendulum, was first described by the Venetian physician Santorio Santorio in 1602 (*Methodi vitandorum errorum qui in arte medica contingunt*. Venice). Santorio was a friend of Guidobaldo del Monte and acquainted with Galileo who, as

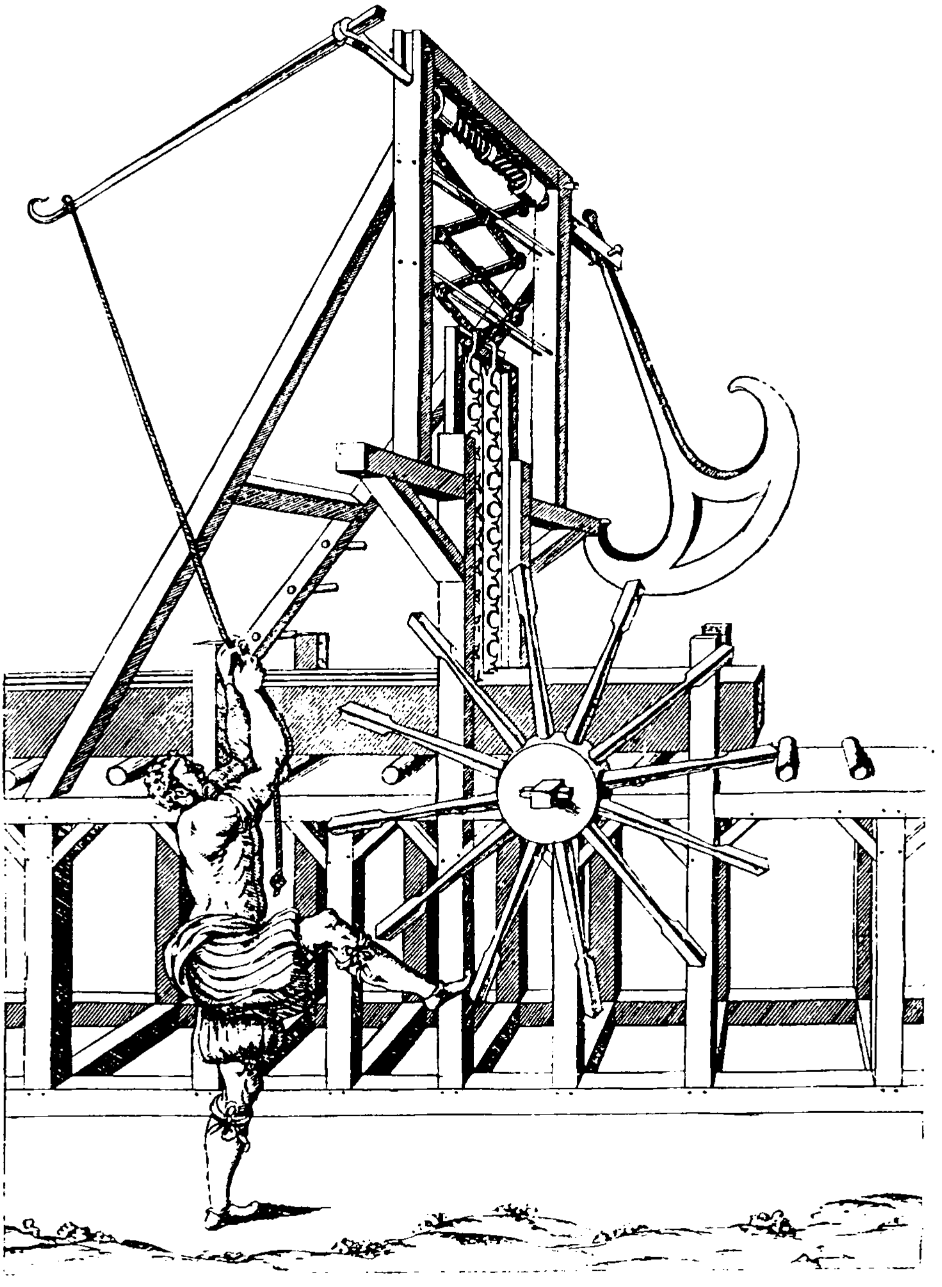

Fig. 1. Sawing-machine with a heavy anchor-pendulum. From Jacques Besson: *Theatrum instrumentorum et machinarum*. Lugdunum 1578, Plate 14. Courtesy Niedersaechsische Staats- und Landesbibliothek Goettingen.

Was that a mere coincidence or was there a systematic connection between the practical utilization of the properties of pendulums by engineers or physicians and the establishment of these characteristics in a theoretical way? Without knowing more about the particulars — for instance, about engineers' concepts of pendulums — one cannot dare to give a definitive answer in this case. It is generally clear, however, that the properties of a device like the pendulum cannot be discovered by mere observation. That is the systematic reason why anecdotes like the one told about Galileo or Newton and the falling apple are implausible — all other faults aside. The properties of objects can only determined by practical experience proving what is possible and what impossible. Compared to observation, it constitutes an entirely different basis for conceptualizations if those properties are already exploited in certain technical arrangements — whatever the practitioners actually think.

What is interesting here is therefore not that the first attempts to frame the pendulum law were undertaken just a few years after the first use of the pendulum as an element of machines. It is not important in the first place how long it had been used practically in devices like the swinging anchors in Besson's machines and not merely as a possible subject of observation like swinging lamps. The devices whose role for modern dynamics can be compared with that of balances for statics in Antiquity need not necessarily be new inventions in the early modern era. As in the case of the inclined plane, even devices which were well-known in Antiquity could be of significance for the beginnings of modern dynamics. What is decisive is rather that they actually were such subjects of practical use and experience. The experiences gained by practical use are not only an obvious prerequisite for developing theories of such devices, but also for detecting questions of theoretical interest that can be studied by means of them. Stressing this significance of technologies for scientific conceptualizations, Lynn White coined the illuminating phrase: "Art has always been a highly selective mirror of nature" (White 1966, 110).[21]

Machines, devices, and techniques using certain material objects have had this significance for modern sciences since the sixteenth and seventeenth century. The role of technology and art deserves special attention at their beginnings, however, when they were still far away from the stage of institutionalized research enterprises with a systematic praxis of experimentation. To a certain extent, this role can be described as compensating for the lack of systematic experimentation. The differ-

mentioned above, wrote at the end of the same year a letter to Guidobaldo del Monte about the alleged isochronism of pendulums. Mitchell 1892 and more recently Bedini 1991, 7f., have assumed that Santorio's instrument has to be regarded as a fruit of Galileo's experiments with pendulums. It seems to me no less plausible to assume that Santorio's instrument – which, of course, only made use of the comparative simple relationship between length of the thread and swinging time — was a source of inspiration for Galileo (for Santorio, see Grmek 1977).

[21] Peter Ruben has suggested that the epistemological theory of mirroring, notorious in Lenin's version, might lead to fruitful consequences if it is separated from a sensualistic understanding and if the "mirrors" are conceived of as material entities which serve as material means of thinking, entities which are constructed historically and hence are subject to historical change (see Ruben 1978).

ence between an experiment and a technical operation within the realm of production consists not in a divergence with respect to the devices and materials used but in the divergence of the purposes. As an extreme case, even the same physical procedure with the same technical arrangement can be both: an experiment when it is performed in order to gain knowledge, or an act of production if its goal is the use of the produced effect. Thus, there is no principled impediment why men with theoretical questions could not study technical processes carried out in workshops, mines, or factories as if they were performed to gain insights. The most important role the technical revolution of early modern times and the tradition of the workshops played for the modern scientific mechanics might therefore have consisted in unintentionally creating devices that were suitable for finding and investigating questions in dynamics and that can be regarded as prototypes of experimental arrangements.

Low and High Mechanics

Galileo combined his investigations on bodies descending inclined planes and on the motion of pendulums by attempting to reconstruct the falling arc of the pendulum by approximating its segments through an infinite number of infinitely small inclined planes of decending. In our context it is not of great interest that the result of this endeavor, namely the isochronism of the circular pendulum, proved to be wrong, as Huygens would show. Such combinations themselves deserve attention here. What kind of intelligence enables one to contrive such subtle combinations? How and where does one get the idea of investigating pendulum motion by means of inclined planes? Can that be ascribed alone to the mathematical competence of Galileo or does it testify at the same time to the capacity of a more practical imagination that inventive engineers have at their disposal. Olschki went so far as to suppose that Galileo's scientific achievements cannot be understood properly without taking into account a specific ability which we can perhaps call engineering heuristics. "His [Galileo's] technical genius is the essential prerequisite for the scientific experiments that first shaped the true dimensions of his theoretical originality" (Olschki 1927, 140).

Even if this statement of Olschki seems exaggerated, it gains its significance from the background of the shown role of technologies and art in the early modern era. For without something like "technical genius," Galileo might have been unable to realize the possibilities for theoretical mechanics which the arts of his time provided. The personal abilities of the protagonists, and not least their interest in and their understanding of technical arrangements, constituted an important part of the prerequisites for the realization of these possibilities. They gained their significance, conversely, by a world of mechanics which, due to effective methods of communication, had become a connected space of experience by the sixteenth century, reaching from the activities and skills of practitioners without any intellectual ambitions to educated and exceptionally creative engineers, and even to engineering scientists like Galileo. Here, we only need call to mind well known general factors for this development: the continued economical prosperity of the Northern Italian states; the commerce and trade among them as well as with other parts of Europe; new means of communication such as printed books and the use of the vernacular language in writings on professional and theoretical topics; new institutions of education such as the Accademia del Disegno, and courts as centers of communication between experts in different fields, etc. J. A. Bennett has shown for the world of "mathematics" in seventeenth century England — reaching from practitioners like sea captains or surveyors who only used mathematical instruments to theoretical mathematicians and natural philosophers — that particularly the producers of mathematical instruments functioned as an intermediary center of this world, rendering it a realm of exchange between "low" and "high" mathematics (see Bennett 1986, 1–28). It would be desirable to have an accordingly close investigation of the special functions of the different types inhabiting the world of mechanics in Northern Italy, The Netherlands, and England at the turn of the sixteenth to the seventeenth century.

In this paper, I only want to draw our attention to the existence of this world of mechanics not unified by theory — it was probably not before the nineteenth century that even scientific mechanics itself became a truly coherent theoretical building — but which constituted nevertheless a connected realm of experience, a realm within which the established theories were not more than a few scattered islands. The theoretical achievements of men like Galileo are only properly understandable by recognizing that they were based on the whole realm of mechanics of the time — on the "low" mechanics no less than on the "high." Not only specifically scientific strategies of gaining empirical knowledge like experiments, but those strategies together with experiences and reflections on devices and procedures used in the world of production led to the threshold of classical mechanics.[22]

Nature and Art

The creative appropriation of the classical mechanics tradition as well as the development of the real starting points of modern dynamics in the sixteenth and in the first decades of the seventeenth century was — as I tried to show — the work of men who must be thought of no less as engineers than as scientists. It does not diminish the fame of Galileo when we state that in this respect, no categorical difference can be established between him and Tartaglia, Benedetti, or Guidobaldo del Monte. There are no convincing reasons for calling the one a scientist and the other an engineer. But, of course, we have to distinguish between such theoretically

[22] The same was shown for chemistry at the turn from the seventeenth to the eighteenth century by Ursula Klein (see Klein 1994).

committed engineers on the one hand and engineers and practitioners — not to mention common craftsmen — on the other who never thought of solving problems in any other than a pragmatic if not a traditional way. The dialogues in Tartaglia's *Quesiti et inventioni diverse* (1546) are excellent documents for showing the differences, misunderstandings, and the latent or open tensions between men of such a pragmatic bent and theoretically interested ones like Tartaglia (see Olschki 1927, 81f.). The latter do not cease to be engineers only because of their success in treating some mechanical problems in a theoretical manner comparable to that of men like Archimedes in Antiquity.

What makes it difficult to consider men like Galileo engineers is perhaps not primarily the fact that they produced truly scientific writings; the difficulty might lay elsewhere. It could be that we are not used to recognizing that the theories of these men — and *a fortiori* it is valid in the case of theories seen as part of the history of modern mechanics — are theories about technical arrangements and procedures. Moreover, we have to recognize them as theories about technical arrangements that were most significant within the sphere of production — including military — whereas arrangements set up for research purposes, i.e. experimental arrangements, played a more minor role. Galileo's famous *Discorsi* is the classic example in this respect. Used to considering the modern sciences, the sciences based on experimentation, to be physics in the Aristotelian sense of theories about nature as such, we are a little embarrassed when the beginnings of these sciences in the early modern era make it clear that their statements are statements about nature mediated by our technical intervention. In other words, theories that show nature "mirrored" by art.

The truly important replacement of deeply rooted philosophical paradigms that accompanied the birth of modern sciences was not an exchange of an Aristotelian view of nature for a Platonic one. Rather, through the activities of men like Tartaglia or Galileo, the fundamental change consisted of transforming "mechanics," traditionally conceived of as mere knowledge about art, into the paradigm for physics.

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