Chapter 5
The Balance, the Lever and the Aristotelian Origins of Mechanics

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Abstract The *Mechanical Problems* traditionally attributed to Aristotle is a short problem collection that also contains an ambitious project of reduction, which traces various mechanical devices back to the lever, the balance and the radii of a circle. This work is thus not just a collection of problems, but also the first theoretical mechanical treatise that has come down to us: Basic concepts of technical mechanics such as force, load, fulcrum are abstracted from an analysis of simple technology, and the workings of this technology are explained by arguments cast in syllogistic form. This chapter traces the origins of mechanical theory in this work and analyzes the form and structure of its argument. The key steps in the concept formation of basic mechanics carried out in this treatise are analyzed in detail. We focus on the special role of the balance with unequal arms in the early development of mechanics, on the interaction of various forms of explanatory practice and on their integration into systems of knowledge in the Peripatetic school.

Keywords *Mechanical problems* · Aristotle · The balance · The lever · Peripatetic school

5.1 Introduction[1]

One of the truisms of the traditional story of the Scientific Revolution of the sixteenth and seventeenth centuries is that mechanics was not part of Aristotelian physics, whereas it is constitutive of modern physics. The artificial motions of mechanics and

[1] The basic interpretation of the *Mechanical Problems* presented here was first developed in a research seminar at the University of Constance conducted by McLaughlin, Renn and the late Peter Damerow in 1997. Among the participants were Markus Asper, Elke Kasemi and Paul

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mechanical technology could not be the subject matter of Aristotle's science of natural motions. In fact, it is the rejection of the distinction between violent motion and natural motion that marks the difference between Newtonian physics and Aristotelian natural philosophy. In opposition to this characterization some scholars have construed a greater continuity between medieval thought and modern science, and many recent scholars of sixteenth- and seventeenth-century thought even reject the existence of a scientific revolution.[2] But this one last bastion seems to resist razing. However, there is an alternative to the traditional story of early modern science as a journey along the high road from Copernicus by way of the law of fall to Newton and celestial mechanics. We can also tell a story that follows the low road from the Renaissance technicians to Guidobaldo, Galileo and terrestrial mechanics. In this case Aristotelianism provides not just the focus of attack of the new science but also one of its major resources, a work called the *Mechanical Problems*, in which not only is the law of the lever formulated, but also basic concepts of technical mechanics are abstracted from the study of simple machines. When Italian engineers began to reflect philosophically on their professional activities, they had a model of how to move from technical practice to "philosophical" theory—marketed under the name of Aristotle. If we follow the low road, we find that the contribution of the Middle Ages to modern science lay not just in the mathematical methods of fourteenth-century Franciscans or in the admission of mechanics to science through the back door in the *quadrivium* of Gundisalvus, but also in the technology employed in Dutch windmills and Italian harbor installations. In the opening lines of the *Discorsi* (1638/1974) Galileo praises the Venetian Arsenal for opening up "a large field to speculative minds for philosophizing" about mechanics.[3] The *Mechanical Problems*[4] spoke to Renaissance engineers not just as the source of the law of the lever and some comparatively primitive analyses of mechanical instruments, but also as a model of how to turn reflection on technical know-how into scientific knowledge.

Even the greatest heroes of twentieth-century historiography of science, pursuing the high road to celestial mechanics, often succumbed to what we may call the utilitarian fallacy on the relation of science and technology: If a theoretician is interested in technology, it must be because he wants to apply the theoretical knowledge sought, or already acquired, in some useful practice. But, so the argument goes, seventeenth century technology did not need and could not readily apply seventeenth century science; and if science is not pursued for the sake of technology, it is independent of technology. However, when Francis Bacon

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Weinig, whose subsequent contribution to this project cannot be measured in footnotes. In the intervening years we have profited from collaborations with István Bodnár, Brian Fuchs, Malcolm Heiman, and Mark Schiefsky, as well as Albert de Puis and, for the current version, Joyce van Leeuwen. From the beginning we have benefited from Fritz Krafft's analysis (1970).

[2] See Duhem (1913–1959) and Crombie (1961) for the continuity thesis. See also Shapin (1996).

[3] Galilei (1638, 11).

[4] There is no accepted critical edition of the *Mechanical Problems*. We use the Greek text given in Hett 1936, cited, as is customary, according to page and column of the Bekker edition of 1831. All translations from the Greek are our own. They are intended to be as literal and interpretatively open as possible.

famously proclaimed, that "Nature to be conquered must be obeyed," the notion, that technology (conquering nature) obeys natural laws, is not limited to cases where a law is known and followed obediently in application.[5] It also holds for those cases in which a successful technology is studied in order to learn about and thus to formulate the natural laws that were already being unconsciously obeyed in practice. And given that modern science was not systematically applicable in technology until the nineteenth century, this version of Bacon better explains the almost universal interest of seventeenth-century scientists in technology.[6] Such a study of technology, looking for the general theoretical principles embodied in practice, is basically what the author of the *Mechanical Problems* is also doing—with much simpler machinery.

In the following we shall read parts of the *Mechanical Problems* as a project of abstracting general theoretical concepts from the analysis of concrete technical practice. The treatise formulates a number of basic mechanical concepts, connects them in an embracing conceptual scheme or mental model, and presents its theoretical explanations in the form of deductive arguments. In the context of the peripatetic project of systematizing various areas of knowledge, Aristotle—or one of the best members of his school—analyzes weighing practices, with their techniques of establishing *equality* of weights, and lifting practices, with their techniques for *outwitting* nature so as to raise greater loads with smaller forces. The balance is confronted with the lever and then with a wide range of technical devices. These disparate practices are integrated into a comprehensive system of knowledge by reducing the lifting devices to the measuring devices. It will be further argued that a key prerequisite for this project of reflection on mechanical practice was an innovation in weighing technology: the invention in (or introduction to) Greece of the balance with unequal arms. A by-product of the analysis will be that the law of the lever, taken as a strict proportionality, as it is formulated in this treatise, may be just an afterthought of the reduction program, or even a later interpolation.

In this paper, we will first briefly discuss the history and structure of the text of the *Mechanical Problems*. In Sect. 5.3 we will explicate the work's program of the reduction of technical devices to lever and balance. Section 5.4 illustrates this program through a reconstruction of two paradigm problems. Section 5.5 then presents a detailed analysis of the explanation of the balance with unequal arms in Problem 20. In the final section we analyze the historical conditions under which such an asymmetric balance could contribute to the origin of theoretical mechanics.

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[5] Bacon (1858, §3). For the classic one-sided reading of Bacon, see Koyré (1943); Koyré (1961, 308) also argues that since technology in human history *precedes* science, it cannot be relevant to an explanation of science.

[6] Merton (1939, 5); Westfall (1993, 65).

5.2 The Text of the *Mechanical Problems*

The peripatetic *Mechanical Problems* presents us with the first documented example of a sustained theoretical reflection on mechanical knowledge. Compiled at Aristotle's Lyceum, in part perhaps during his lifetime[7] and passed down as authentically Aristotelian, it seems at first glance to belong to the genre of problem collections that arose out of the question and answer contests of the sophists in the fifth century and was still popular in the school of Aristotle.[8] The treatise was generally taken to be a genuinely Aristotelian work up to the early nineteenth century; but sometime between 1830 and 1870 the opinion of most classical philologists shifted from acceptance to denial of its authenticity—for reasons that probably have more to do with the constitution of classical philology as a discipline than with any characteristics of the text itself. In particular French and German classicists of the later nineteenth and early twentieth centuries tend to be adamant that the work is not Aristotelian—based primarily on a misguided judgment about the scientific quality of the work: Valentine Rose influentially spoke of the "triviality and confusion of the questions" and Paul Tannery considered it "a collection without order or method."[9]

The earliest still surviving manuscript of the *Mechanical Problems* was made in Constantinople around 1300 and all extant manuscripts have been traced back to one archetype from tenth-century Byzantium. Based on the same manuscript tradition, the Byzantine scholar, Georgios Pachymeres (1242–1310) wrote a Greek compendium on Aristotle called *Philosophia*, whose twelfth and last book contains an almost verbatim paraphrase of the *Mechanical Problems.* Some of his very minor emendations found their way into later Aristotle manuscripts and into the first printed edition. The only possibly independent tradition of the work lies in extracts from the Introduction and Problem 1 that were translated into Arabic at the end of the eleventh century. The usual lists of works by Aristotle attribute a work on mechanics to him. In the first century BCE Athenaeus Mechanicus reported that Aristotle's work in mechanics could only be of interest to "younger friends of knowledge" and dismissed any professional benefit for mature practitioners. Those who deal explicitly with some of the actual subject matter of the *Mechanical Problems* (Vitruvius and Hero) mention neither the work nor its author.[10] No

[7] There is no consensus on authorship or dating. Based on the way letters are used to locate points and figures, the work predates the Euclidean reform. On such formal questions see Heiberg (1904) and Netz (1999). Euclid's *Elements* are generally taken to have been compiled shortly after 300 BCE; Aristotle died in 322 BCE. If we don't want to resolve the question of Aristotle's possible authorship by stipulation, we have to date the work at some time between 330 and 270 BCE. Recent commentators tend to favor the later date.

[8] Flashar (1961, 297–316). On the culture of mathematics in this period see Asper (2008, 107–112).

[9] Rose (1854, 192); Tannery (1915, 33).

[10] For the manuscript tradition see van Leeuwen (2012, 2013, 2016); for the Arabic translation see Abattouy (2001). On the ancient lists see Flashar (2004, 189–191) and Hein (1985, 304). On Athenaeus, see Whitehead and Blyth (2004, 44) and Bodnár (2011); Vitruvius (1931–1934, Bk. 10,3); Hero of Alexandria (1900*,* Bk. 2.8; 2.33, pp. 114, 170).

medieval Latin translation of the work has been found. Although number of tantalizing hints at such a translation have surfaced,[11] none of them indicates an influential tradition of reception nor even provides hard evidence for the existence of a Latin text. A broad reception of the work begins only after it was first printed in the *Corpus aristotelicum* by Aldus Manutius in Venice in 1497. Between 1517 and 1629 four complete and two partial translations into Latin as well as some complete or partial vernacular translations were undertaken and more than a dozen extensive commentaries were produced.[12]

The text consists of an introduction and 35 sections, or "problems" generally merely one short paragraph in length. The problems (almost) always begin with the phrase *dia ti* ("Why is it that") and generally ask why a particular technical device performs as it does. This opening question is fairly consistently answered by a rhetorical counter-question *hê dioti* ("Is it because"), which usually identifies (some part of) the device and asks if it cannot be viewed as a lever. Then, in many instances, a general principle is invoked, under which the particular case can be subsumed. This principle can then function as the major premise in a syllogism-like argument with the counter-question as the minor premise. The conclusion of the argument repeats the statement posed as a question at the start. Sometimes the problem then closes with an evaluation. The ideal form of a problem, actually instantiated by a number of them, displays an analysis in the following form: (1) Why are Greeks mortal? (2) Is it because they are men? (3) And all men are mortal: Thus, since Greeks are men, they are mortal.

The *Mechanical Problems* departs from the usual form of the problem genre in as much as the introduction to the work announces a theoretical program of reduction.[13] All technical devices are to be reduced to the lever, the lever is to be reduced to a balance and the two arms of a balance are to be reduced to two radii of a circle, from whose dialectical properties all these devices get their remarkable abilities. The first three problems after the introduction systematically introduce the basic theoretical concepts and principles needed for the reduction that is to be carried out in the subsequent problems. However, many of the "problems" that actually follow have no recognizable connection to the reduction program. Although the text that has come down to us is to a certain extent a hodge-podge of disparate topics thrown together, nonetheless, parts of the work pursue an ambitious program of theoretical investigation of technical devices: the formation of theoretical concepts in the study of technology.

With two notable exceptions the problems are short: the mean length is 24 lines in the Bekker edition (1831). Problem 1 (115 lines) and Problem 24 (89 lines) are both significantly longer than any of the other sections—between three and two times longer than the next longest problem. Alone among the problems these two do not begin with the standard phrase *dia ti* but rather with a different (though

[11] Clagett (1959, 71, n.5 and 75–76, n. 6).

[12] See Laird (1986) and Rose and Drake (1971). The Latin translations were by Fausto (1517), Tomeo (1525), Bechio (1560) and Monantheuil (1599).

[13] The reduction program was already noted by Duhem (1905, 8).

equivalent) formula. Their content and terminology is also significantly more technically mathematical in character than that of other problems, except for the third longest (Problem 23): These three (a third of the text not counting the introduction) deal not with mechanics at all, but with kinematics—or perhaps better: the geometry of moving points. Importantly, in Problem 1 a simple mechanical discussion of why balances with longer arms are more sensitive than those with shorter arms, which carries out the first step of the reduction by comparing the arms of a balance to the radii of a circle, is interrupted by a long, unsuccessful and never relevantly used mathematical proof of the composition of motions. After this interruption the argument continues where it left off without noticeable regard for the proof.

Fifteen of the 32 later problems follow the program of reduction presented in Problems 1–3 and display the 'standard' pattern to some degree, although the reduction most often skips over the balance and goes straight from the lever to the circle—or even skips the lever, too.[14] However, there are a number of other problems, besides the "kinematic" ones (23, 24), that have no recognizable connection to the program of reduction: five problems (8, 10, 12, 19, 31) deal with why it is easier to move objects that are already in motion or tending to motion, and three of the last four problems deal with projectile motion (32, 33, 34). With the exception of the reduction program in Problems 1–3, there does not seem to be any systematic principle structuring the order of presentation. Thus the *Mechanical Problems,* as it has come down to us, seems to have been an open-ended compilation used in a school context and may have collected a number of different projects from different times at the peripatetic school. It displays aspects both of a tight programmatic treatise on mechanical theory and of a desultory collection of disparate questions about mathematics, mechanics and everyday experience. The analysis presented here applies only to those parts of the text that carry out the reduction program of the introduction—about a third.

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Problem 4:	The oars of a ship are identified as levers.
Problem 6:	The mast of a ship is identified as a lever.
Problem 9:	The wheels of pulleys are identified as levers.
Problem 13:	Handles of spindles and windlasses are identified as levers.
Problem 14:	A piece of wood broken over the knee is identified as a lever.
Problem 15:	Pebbles at the beach rotated and worn down by water are identified as levers.
Problem 16:	Wooden planks raised are identified as levers.
Problem 17:	Wedges are identified as consisting of levers.
Problem 18:	A pulley is identified as a lever.
Problem 20:	An asymmetric balance is identified as a lever.
Problem 21:	The forceps of a dentist are identified as a pair of levers.
Problem 22:	A nutcracker is identified as a lever.
Problem 26:	Wooden planks carried on the shoulder are identified as radii.
Problem 27:	Wooden planks raised up to the shoulder are identified as radii.
Problem 29:	A plank carried by two men is identified as a lever.

5.3 The Program of Reduction

The Introduction to the *Mechanical Problems* opens with an affirmation of the distinction between things that occur in accord with nature (*kata phusin*) and things that are contrary to nature or perhaps only 'beyond' nature (*para phusin*) and with an exclamation about the "wonders" of technology, the trenchant negation of which by Simon Stevin (*Wonder en is gheen wonder*) in 1586 now graces the frontispiece and binding of every volume of the *Dictionary of Scientific Biography* (1970–1980). The treatise begins:

> It evokes wonder that there are things that occur according to nature, the cause of which is not known, and that there are things that occur contrary to nature, which are produced by art [*technê*] for the benefit of humans (847a12–13). (Hett 1936)

Phenomena of the second kind, produced by technology, in which the weaker seems to move or master the stronger and which are thus beyond or contrary to nature, are called "mechanical problems" by the author. It is these technical devices that are of special interest, for they seem to exhibit effects that are incompatible with everyday experience (and with central doctrines of Aristotelian physics).

The source of everything wondrous is rather quickly located in the circle, which, we are told, is the unity of opposites and thus has various dialectical properties. The principle of the wonders (*archê tôn thaumatôn*) will turn out to be the fact that points on a moving radius at different distances from the center trace greater or lesser circles depending on how far they are from the center. This principle, which we shall call the *circular motion principle,* refers back to what must have been a very well known passage in Plato's *Laws* (Bk. 10), where Plato engages in an extensive discussion of the wonders of the circle concluding:

> For [this circular motion] is the source of all the wonders bringing about what was supposed impossible, making slowness and speed at the same time harmonize [*homologeîn*] in greater and smaller circles.[15]

A similar principle, formulated numerous times in the course of the *Mechanical Problems*, states in its first formulation (see below) that each different point on a radius moves at a different speed: the farther from the center, the greater the circle traced in the same time, and thus the faster the motion.

After introducing the wonders of the circle the author then formulates the theoretical program of the treatise: The reduction of mechanical devices to the lever, the reduction of the lever to the balance and of the balance to the circle. Just as the end points of radii of different lengths move at different speeds, so too do weights on balances of different lengths move at different speeds. The balance can be interpreted and explained in its workings by the properties of the circle. And just as weights in the pans of balances with longer arms move more swiftly than in those

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[15] Plato (1962, Bk. 10, 893b-e). It is significant that Plato has an exact mathematical grasp of the relation of the circumference (and motion along it) to the length of the radius but makes no reference in this context to any mechanical problems. See Berryman (2009, 61) for a different view.

with smaller arms so, too, does a weight/force applied to a longer lever move the load (at the other) end *more easily* than one applied to a shorter lever. Thus the lever can be interpreted and explained in its workings by the properties of the balance. Finally, every mechanical device can be interpreted and explained in its workings in terms of the lever. Thus, in each of the sections following this presentation of the reduction program a particular mechanical problem is to be solved by reducing the device by way of the lever to a *principle of circular motion*—which is then formulated explicitly:

> What pertains to the balance is traced back [*anagetai*] to the circle, and what pertains to the lever [is traced back] to the balance; and nearly all that pertains to mechanical movements [is traced back] to the lever. But no one of the marks on a line drawn from the center travels equally fast as the other. But always that which is farther opposite the resting [point] is faster. (848a11–17)

Thus we have a program of reduction of mechanical problems ultimately to the circular motion principle, which states that different points on a rotating radius cover different distances in the same time. That this is the explanation of the wonders mentioned in the opening sentence (we are then told) will "become evident in the subsequent problems" (848a19).

The details of the program of reduction are developed in the first three problems where, alongside the center and the radius, the basic concepts of the peripatetic mechanics are introduced. These three sections introduce the basic elements of a balance-lever system or model and begin to turn them into theoretical concepts: lever, balance, fulcrum, suspension point ("cord"), force/mover, load/weight, and the material beam.

Problem 1 begins with the question of why larger balances are more accurate than smaller ones—by which the author seems to mean, why balances with longer arms are more sensitive to weights placed on them than those with shorter arms. This state of affairs is explained by the circular motion principle, which receives its second formulation:

> The reason for this is that in the circle the line removed farther from the center moves faster than the smaller one, which is close, when moved by the same force. Faster has two senses: When something traverses the same space in less time, we say it is faster, and if more [space] in the same [time]. But the greater [line] in the same time describes a greater circle, for the outside is greater than the inside. (848b3–6)

The longer radius ("line from the center") covers more space than a shorter one in the same time even if both are moved by the same force or "strength" (*ischus*).[16] The inference that immediately suggests itself in this context, namely that the longer balance arm, like the longer radius, is moved more swiftly (has a greater displacement in the same time), is not made. Instead the text embarks on a lengthy mathematical

[16] There has been some disagreement in the literature on the meaning of *ischus* (force) here, Duhem (1905 and 1913), De Gandt (1982), and Krafft (1970). See the discussion in Schiefsky (2009, 59–61). For our purposes it suffices to note that motion presupposes a force and that wherever the force is applied to the rotating radius or beam: outside points move faster than inside points.

argument about the composition of two motions of a point.[17] After 85 lines on the geometry of motion, the text resumes the course of the mechanical argument by rehearsing the circular motion principle (this is the third version): "the more distant … the more quickly" (849b21). It then repeats the original question almost verbatim and draws some conclusions rather quickly, thus finally carrying out the first step of the reduction. The suspension point of the balance, the *cord*, is identified with the center of a circle, and the arms of the balance are identified with radii of the corresponding circle:

> For the cord becomes the center (for it stays the same), and each part of the beam is a radius. (849b24)[18]

The form of this reduction step will be repeated later like a formula: Each of the three steps in the program of reduction is carried out by just such an identification: *A becomes B*. Here the cord (*sparton*)[19] becomes (*ginetai*) the center (*kentron*) because it stays the same, (*menei gar touto*). The phrase 'it stays the same' or 'it stays put'—just like the center of a circle stays put—is used expressly by the author (or some later editor) to mark each of the three steps of the reduction. It is used as a formula in Problem 1 where the cord or suspension point is identified with (*becomes*) the center, in Problem 3 where the fulcrum is identified with (*becomes*) the suspension point and in Problem 4 where, in the first application of the reduction program to a concrete problem, an oarlock is identified with (*becomes*) the fulcrum. In these three first steps, as most often in the later problems, the identification of a device with a lever or a pair of radii or the identification of a part of such a device with the fulcrum or center is expressed by *ginetai,* not simply by *esti,* the verb "to be".[20]

The argument being made here is that just like a point farther from the center is moved more/farther, so too, the arm of a balance farther from the suspension point is moved more/ farther by the same force/weight and thus a motion that is scarcely

[17] Since Krafft's analysis in *Dynamische und statische Betrachtungsweise* (1970); this argument about the geometry of a moving point has been the focus of attention of scholars dealing with the *Mechanical Problems*. See also Mark Schiefsky, (2009) and De Groot (2009, 2014). No convincing argument has so far been advanced as to why the later problems should need this proof.

[18] Reading *phalanx* (beam) for *plastinx* (pan). Not only does the sense of this text argue for this reading, but also the next problem, which deals with a material beam balance (without actually calling it a beam), would be much easier to understand if the material beam had already been introduced. No modern translation takes the author to mean 'pan'. Forster (1995, 1302) and Hett (1936, 347), (both take the author to mean "balance" and not "scale pan." The Arabic translation (Abbatouy 2001, 114–115) renders whatever was in the original Greek text all three times as *beam* or *pole*. We thank Sonja Brentjes for advice on the Arabic.

[19] The term *spartion* (the diminutive of *sparton*: cord) becomes a technical term meaning *suspension point* after its identification with the center of a circle here. The two later occurrences of the non-diminutive *sparton* (in Prob. 3 and 20) may be copying mistakes, since in each case the text refers back to a cord previously mentioned in the diminutive form. In Problem 1, on the other hand, we are dealing with *larger* balances, where the larger cord might actually be meant.

[20] The phrase *menei gar touto* otherwise occurs only in Problem 27, where it plays exactly the same role as in 1, 3, and 4. The verb *ginetai* (it becomes) is used to express the identification of a part of a device with the fulcrum or center in Problems 1, 3, 4, 5, 6, 12, 15, 16, 19, 20, 26, 29. In Problems 9, 13, 14, 17, 21, 22, and 27 only the verb *to be* or no verb at all is used.

noticeable if it is near the center/suspension point (because it is so short) will be more easily noticed if it is far from the center/suspension point (because it is longer). That the argument—to the extent that it is plausible—has nothing to do with differences in the effects of a weight (nor with the lever) can be seen from the fact that it applies just as well to the *horizontal* motion of a turnstile.[21] Under the same force (applied to turning a horizontal bar) a point or part of the bar far from the center would move farther (and more noticeably) than one near the center. That is, the question is not really about how sensitive the balance is to a weight placed on it, but about how long and thus how noticeable the segment of the circle is that the weight describes in its motion. What the author needs, however, is an argument that takes him from 'more swiftly' (*thatton*) to 'more easily' (*rhaon*). Furthermore, no comparison is yet made between the motion of a long arm and the motion of a short arm: the comparison is between the motions of the arms of two different symmetric *balances*, one of which has long arms and the other short arms. The additional steps are taken only in Problem 3.

Problem 2 begins with the analysis of the behavior of a balance. We start out with a balance suspended from above its middle by a cord and inclined to one side by a weight in one of the pans. When the weight in the pan is removed, the depressed side of the balance rises. If, on the other hand, the balance is supported from below and the weight is removed it will remain as it is. Both observations are correct for the case that the balance in question is a homogenous material beam. If such a beam is supported from below in the middle and tipped to one side, it will tip still further down as far as it can (presumably until it hits the ground) because more than half the volume of the beam lies on the tipped side of the vertical plane through the fulcrum. Thus in the course of the discussion, it becomes clear that the balance is a material beam balance—although the treatise's term for the material beam (*phalanx*) is not used here. The question as formulated at the beginning of Problem 2 reads:

> Why is it that, if the cord [*spartion*] is from above, when the weight inclined below is removed, the balance rises back up. If however [the cord] is placed below, then it [the balance] does not rise, but stays. (851a3–6)

The author then points out that the vertical plane through the suspension point above or below (which divides a horizontal beam in two equal parts) divides a deflected beam balance into unequal parts: If suspended from above, the upper part of a deflected material beam is larger and heavier than the lower end and will therefore descend, whereas if supported from below, the lower part of the deflected beam is larger and heavier and thus stays where it is (on the ground). For an understanding of the mechanical knowledge embodied in this treatise, it is important to note that the third case, in which a (panless) beam is fixed neither from above nor from below, but in the (vertical) middle of the beam, is not discussed. We know, but the author apparently didn't, that if such a beam is supported in the middle (at its center of gravity), it will remain stationary in any given position. This follow-up question,

[21] The author discusses the horizontal motion of a suspended beam balance in Prob. 10.

which literally makes the fulcrum and the suspension point the center, is obvious only in hindsight.

The task of this problem is to extend the scope of the cord or suspension point of the balance (which has just been identified with the center of a circle) to cover cases in which the balance is supported not from above, as is the rule, but from below: The "cord" is now below the balance. The technical term for fulcrum (*hupomochlion*) is not yet used and the one mention of a "support" uses a term otherwise used for a substrate or substance (*hupokeimenon*).

Problem 3 then extends the identification of the suspension point of the balance with the center of the circle to the fulcrum of a lever: center = cord = fulcrum. The official question is: "Why is it that small powers can move great weights/loads by means of a lever?" The answer is that the lever is a kind of balance that has its suspension point below it and also does not have equal arms, but rather is longer on one side than on the other.

> Is it that the reason is the lever, which is a balance having the cord [*spartion*] below and being divided into unequals? For the fulcrum [*hupomochlion*] becomes [*ginetai*] the cord, for both of them stay the same [*menei gar amphô tauta*] just like the center. (850a34–35)

This is the second step of the reduction: The analysis of the material beam balance is extended to the lever, which—unlike the device considered in Problem 2 with its support below—is no longer equal-armed but rather is longer on one side than on the other. The fulcrum can be identified with the suspension point of an apparently unequal-armed balance. A balance of this kind is studied in detail in Problem 20 (see below). The further reduction step from the balance to the circle is continued immediately as prefigured in Problem 1: "For under the same weight, the greater radius moves faster" (850a36). In the formulations of the circular motion principle in the Introduction and Problem 1, two different-sized balances were compared. In Problem 3 different-sized arms are considered—but there is only one balance (divided into unequal parts). These different arms are reduced to two unequal radii that have different speeds (with the same angular velocity). Similarly the two ends of the same lever/balance move at different speeds. Recapitulating this argument, the text then specifies the various elements of a lever system: besides the bar itself, a lever system consists of a fulcrum, a force and a load. When the system is considered as a balance, however, both the force and the load are *weights*, and the fulcrum is equated with the suspension point (and of course, the center). After the analysis of the lever system into its components, the law of the lever is formulated without any preparation or argument; and only after that, is the inference made to a relation between distance and effect. On a balanced lever the weights or loads are inversely proportional to the distances from the fulcrum:

> There are three [things] concerning the lever: the fulcrum—the cord and center—and two weights [*barê*], the mover and the moved. Thus the weight [*baros*] moved is to the mover as the length to the length inversely. For always the more distant [the mover] is from the fulcrum, the more easily it will move. The reason for this is the one already given, that the line more removed from the center describes the greater circle. (850a37–b3)

Not only is this passage preceded by a brief formulation of the circular motion principle (the fourth version); it is also ends with another longer formulation of the same principle, which is said to be the reason for it all. The formulation of the law of the lever here seems to be an afterthought and may in fact be a later interpretative interpolation.[22] In any case, the real work for the goals of the treatise is being done not by the law of the lever but by the proposition that immediately follows it here—before the circular motion principle is again affirmed (for the fifth time). This proposition for the first time makes the transition from moving *more swiftly* (or moving something *more swiftly*) to moving it *more easily.* There is, so to speak, a corollary to the principle of circular motion: not only do points farther from the *center* of the circle move more swiftly (*thatton*), but forces farther from the *fulcrum* of the lever move a given load more easily (*rhaon*). The formulation of the law of the lever is thus something of a distraction on the way to this assertion, which is the real point of Problem 3. Only after the inference from distance from the fulcrum to ease of motion is made, is it even possible to specify the relation further as a proportion. Thus, the law of the lever would seem to have been inserted one sentence before it makes any sense to formulate it.

The inverse proportionality of weights and lengths formulated here is in fact never used or referred to in any of the later problems—which instead appeal directly to the circular motion principle ('more swiftly') or to the corollary derived from it ('more easily') to explain whatever it is they purport to explain. The circular motion principle, as Plato used it, had already formulated proportionalities: the circumferences of various circles are proportional to their radii. And motions along these circumferences in the same time should display similar proportions. Plato, in the passage cited above (893b–e) speaks explicitly of ratio (*logos*) and proportion (*analogon*)—as does the *Mechanical Problems*, too, occasionally when it is doing geometry instead of mechanics. However, the explanatory principle, as formulated in this treatise, never demands a proportionality between distances from the center and speeds or effects, just an increase in speed or effect with increasing distance from the center.

The formulations in the later problems explaining technical devices are always qualitative, comparative and generally adverbial: the greater the force, the faster something moves; the farther removed from the center, the more something is moved; the closer … the more slowly; the greater … the easier, etc. Often, easily quantified expressions are avoided: the greater force generally doesn't move more *weight,* it moves weight *more* or *more easily*. With the exception of the law of the lever (expressed using a technical term for inverse proportionality, *antipeponthen*) the relations of distances and weights or of speeds and forces are formulated merely qualitatively. Often the term *hosô* is used to suggest the coupling of two properties

[22] Stevin (1586, 65, 509) condemned Aristotle for this internally contradictory formulation. The strict proportionality of lengths and weights holds only in equilibrium, that is, in that case in which there is neither a moving weight nor a moved weight. When one weight moves the other, they are not in equilibrium. If we assume the author was aware of this fact, we have an explanation for his avoidance of the language of proportions.

or their increments. And in some of the problems a standard contrast form, *hosô … tosoutô* (*as x so y*)[23] is used—a formulation that is certainly a bit more formal but still entails no quantification (similar to the Latin *tantum … quantum*, which can but need not express a proportionality). Such formulations could later be interpreted as proportions, whether or not they were originally intended as such—or the *tantum-quantum* formula could have been added later to make the text clearer to someone who already knew the law of the lever. The functions are so to speak formulated as monotonic but also happen to be linear. In fact outside the mathematical arguments of Problems 1 and 24 on the composition of motions, we encounter neither the concept of proportion (*analogon*) nor even of ratio (*logos*).[24]

5.4 The Application Paradigm: Problems 4 and 6

Problem 4 in spite of some internal inconsistency presents the paradigm of the third step of reduction: the working of a technical device—in this case, an oar—is explained as an instance of a lever system. The three elements of the lever system just analyzed (in addition to the bar of the lever itself) are identified in a concrete device. The oar is the lever bar, the oarlock is the fulcrum, the sailor on one end of the oar is the moving force and the sea on the other end is the load:

> Why do those in the middle move the ship most? Is it because the oar is a lever? Thus the oarlock becomes [*ginetai*] the fulcrum (for it stays the same [*menei gar touto*]) and the sea is the load which the oar pushes. The mover of the lever is the sailor. The farther the mover of the load is away from the fulcrum the more it always moves the load. For thus the radius is greater, and the oarlock, which is the fulcrum, is the center. In the middle of the ship the most oar is inside. For the ship is broadest at that point, so that it is possible, that on both sides a greater part of the oar is inside the ship. (850b11–18)

Apollonius Rhodius tells us that when Jason and his Argonauts first boarded the ship, the seats on the benches running fore to aft were assigned by casting lots—except for the two seats on the bench in the middle, which were reserved for the heroes Heracles and Ancaeus.[25] So how could the two strongest men contribute most by sitting in the middle?

The *Mechanical Problems* gives an answer: The phenomenon to be explained is considered as an instance of the application of a lever to a load. The various elements of the lever are identified in concrete objects. A general principle is adduced and a compelling answer to the question is given. The text illustrates the typical three-step argument:

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[23] For instance: Problems 16, 20, 29. As we shall see in Problem 20: With a given lever and a given force, the closer to the load the fulcrum is put, the greater the load that can be moved, but the increase in effect is not proportional to the change in distance from the fulcrum.

[24] There are two uses of *logos* in a different sense in Prob. 19 and 23.

[25] Apollonius Rhodius (1967, 31: Bk. 1, 394–401). See van Cappelle (1812, 199–200).

1) Question:	Why is it that the rowers in the middle move the ship most?
2) Counter-question:	Is it because the oar is a lever?—The elements of the lever are identified and the oarlock is said to *become* the center-cord-fulcrum, which stays put.
3) Principle:	A corollary to the circular motion principle is adduced. A force farther from the fulcrum effects more. This is a further step in relation to the corollary formulated in problem 3. There we learned that the same force moves a load more easily; here we learn that the same force moves a greater load.

The three steps can then be read backwards as a quasi-syllogistic argument. The principle is the major premise, the counter-question is the minor premise and the transformation of the original question into an assertion is the conclusion.

Major premise:	Forces farther from the fulcrum effect more.
Minor premise:	Rowers in the middle of the ship are forces farther from the fulcrum.
Conclusion:	Rowers in the middle effect more.

This presents an argument of the following form: [All] Bs are C. [All] As are B. Thus [All] As are C, which is a good approximation of a *Barbara* syllogism.

This kind of argument is made again and again in the *Mechanical Problems.* The important point is that, within this scheme, given that the identifications are plausible and the principle is accepted as certain, the answer generated is in a certain sense compelling. The identifications can of course be wrong and thus the answer may be false—even absurd, but the solutions given are not just empirical assertions, they are the logical consequences of the identifications, given the principles. The answer to the question is thus the conclusion of a compelling argument.[26]

After the appeal to the qualitative lever principle (the farther, the more) the text just quoted then takes a further step from the lever to the radii of a circle and from the fulcrum to the center. The next two sentences explain to us why the sailor in the middle sits farther from the fulcrum: the ship is wider there and since the benches are in a line down the middle of the ship, the sailor sitting at the place where the ship is widest has more oar inside the ship than at any other point. Presumably the oars all have the same length outside the ship.

[26] In this particular case the rower in the middle does not in fact effect more, he just has an easier time of it. Moreover, if the arm-length of the rowers is the same, the rower on the longer lever moves it the same length as the rowers on the shorter levers (oars) and thus actually effects less. Problem 3 asserted: *the farther, the more easily*; Problem 4 asserts: *the farther, the more effective*. Whereas Problem 3 held that the *same* effect is achieved with *less* force, Problem 4 wants to assert that a *greater* effect is achieved with the *same* force.

The discussion (see below) then continues, repeating the argument, but it is inconsistent with the previous course of argument. The identification of the elements of the lever is redone with different results; it is also not schematic, or even explicit. The lever appealed to now becomes a lever of the ‘second kind’. In a lever of the *first kind* the fulcrum lies between the force and the load as in the ship construction just described, and the force applied pushes in the opposite direction of that in which the load is supposed to move. In a lever of the *second kind* the load is located between the fulcrum and the force—normally one end of the lever is on the ground and the load is between it and the raising force. The force at the end of the lever pushes in the *same* direction as the intended motion of the load. As the text continues, the point in the sea where the oar is placed is now seen as the fulcrum and the ship attached to the middle of the oar at the oarlock is the load:

> So the ship moves because, when the oar is fixed [*apereidomenês*] in the sea,[27] the end of the oar that is inside goes forward, and the ship which is bound to the oarlock also goes forward in the direction in which the end of the oar is [going].

The text then recapitulates the argument (ignoring the second lever model):

> For where the oar raises up the most sea, there the ship is necessarily pushed forward most. And it raises the most where the part of the oar from the oarlock is greatest. That is why those in the middle of the ship move it most. For in the middle of the ship the part of the oar from the oarlock inside is the greatest.

Thus, in order to solve a mechanical problem, we must be able to identify among the material bodies that we are dealing with something that can be viewed as a lever, something that can be viewed as the fulcrum—and of course the force and the load. Given the corollary to the circular motion principle, the principle of the lever, that the force farther from the fulcrum effects more, the problem can be solved.

This procedure, illustrated by Problem 4, can also be seen equally well in Problem 6, which also better illustrates how the scheme can go wrong. Problem 6 inverts the following quasi-syllogism:

Major premise:	Forces farther from the fulcrum effect more (Bs are Cs).
Minor premise:	Sails on higher yard-arms (blown by the wind) are forces farther from the fulcrum (As are Bs).
Conclusion:	Ships with higher yard-arms sail faster (As are Cs).

The text of Problem 6 follows the standard form.

Question: Why is it that As are C?

[27] The verb *apereidein* means to *fix* or *support* and is related to the term *peisma* for the ship’s cable used to tie down the ship to land. This sentence may be a later insertion since the text then continues with a renewed identification of the sea as the load and a repetition of the explanation of why the lever (now of the first kind again) is longer in the middle. There is clearly some corruption in the text. Renaissance authors often pointed out that Aristotle should have used a lever of the second kind in his analysis. See Galileo’s letter to Giacomo Contarini, March 22, 1593, in Galilei (1968, vol. 10, 55–57); Biancani (1615, 159); Baldi (1621, 41).

> "Why is it that the higher the yard-arm the faster the ship [moves] with the same sail and the same wind?"

Identification: Is it because As are B? The four elements of the lever are specified.

> "Is it because the mast becomes [*ginetai*] a *lever*, the base in which it is fixed [is] a *fulcrum*, the *load* to be moved [is] the ship, and the *force* [is] the wind in the sail?

Principle: Bs are C. The farther from the fulcrum the force is, the more easily and swiftly it achieves its effects.

> "If, then, the farther away the fulcrum is, the more easily and more swiftly does the same power [*dunamis*] move the same load, then the yard-arm drawn higher makes the sail also farther away from the base, which is the fulcrum." [28]

In this case the argument, given the identifications, is compelling, but the result of the argumentation is absurd: The higher the yard-arm, the more likely the ship is to tip over, not to sail more swiftly.

5.5 The Asymmetric Balance and the *Mechanical Problems*

The crucial step in the program of reduction carried out in Problem 3 identified the lever as a beam balance supported from below and divided into unequal parts. The treatment of the question in this passage left it open whether this identification was a purely conceptual speculation or whether the author had some specific technical device in mind. Later in Problem 20 the author makes it clear that he did have a particular technical device in mind that instantiates this identification, a balance that is in fact divided into unequal parts, though it is still suspended from above. The asymmetric balance seems to have played a role analogous to that of Thales' Theorem, which was a major step in the development of geometry but in Euclid's *Elements* (Bk. 3, prop. 31) is just a trivial special case of an angle inscribed in a circle on an arbitrary chord. The unequal armed balance may thus represent a special case that made a cognitive advance possible.

The technical device that occasions wonder and needs an explanation in Problem 20, as we shall analyze in detail below, is what the author calls a "half-balance": If we wanted to weigh out a side of beef at the market, we could take a very large beam balance and put a number of large lead cylinders in the scale pan on one side and the beef on the other side. On the other hand, we could (and the Greeks apparently did) put the meat on a pan or a hook at the end of a beam that is shorter, and perhaps thinner and lighter, than the large balance and has a relatively small counterweight at the other end. We could then suspend the whole construction from a point quite

[28] The three sentences quoted make up the entire Problem 6, 851a38–b6. Note that the principle invoked is that the *same* force moves the *same* load more easily and thus more swiftly—and thus has a greater effect.

close to the hook hanging up the beef and "wonder" how this device can do the same job as a much larger symmetric balance with very large measuring weights. The author asks why we can weigh out *large* quantities of meat with a *small* counterweight by means of a device that seems to be only half a balance, seeing that it has only one (real) arm and one pan (or hook):

> Why do beams weigh out meat (great loads) by means of a small attachment [*artêma*], the whole being a (small) half-balance?[29] For the scale pan is suspended only there where the load [*baros*] is put in, but on the other [side] is only the beam. (853b25–28)

This half-balance (with only one pan) can nonetheless perform the same task as a full balance of even greater size. How can that be? What sort of device is this?

The scale balance is ancient; it was in widespread use in Egypt and Mesopotamia by the beginning of the third millennium BCE. Systems of weights are undocumented in Mesopotamian sources before 3200 BCE; but after 3000 they prevail over other measuring systems. All balances known from the two and a half millennia after its invention were of the same type: balances with equal arms. These do not seem to have given rise to any generalized mechanical concepts other than weight.[30]

The first theory of mechanics, attempted here, seems to have arisen in conjunction with the invention of the balance with unequal arms. This new type of balance differs from the earlier ones in that two *different* weights at *different* distances from the suspension point are compared with one another. In this practice weight and distance had to be coordinated such that unequals were in equilibrium. The theoretical quantity that emerged from thinking about this practice came in the course of time to be called variously *moment* or *positional gravity.* The Greek term adapted to denote it was *rhopê*. It is not known exactly when or where the asymmetric balance was invented, but the balance with unequal arms, called a *steelyard* in English,[31] was quite widespread in the early Roman Empire. The Roman steelyard (in modern Italian called *statera*)—normally made of iron or bronze—was so common at the end of the first century CE that literally hundreds of them have been preserved in the ruins of Pompeii as well as in many other places. Greek balances, on the other hand, were typically made of wood, and evidence is much more sparse. Greek vase paintings picture only balances with equal arms, but there is literary evidence of asymmetric balances that shows them to have been quite well known in Athens of the late fifth-century BCE.

There are two fundamentally different kinds of asymmetric balance. Best known is the Roman steelyard, which has a fixed pan or hook, one or more fixed suspension points and a moveable counterweight. The vast majority of steelyards preserved

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[29] *hêmizugiou.* This is the only occurrence of the term in the classical Greek corpus: it could either be an adjective (*hêmizugios*) meaning "forming a half-balance," Liddell et al. (1996) or (as Markus Asper has suggested to us) a diminutive noun (*hêmizugion*) meaning "small half-balance."

[30] On the history of the balance in general, see Robens et al. (2014).

[31] From the end of the Anglo-Hanseatic War (1474) until 1598, Hanseatic merchants (who apparently used such devices) had a compound on the north bank of the Thames near London Bridge called the "Stalhof" (steel yard).

from Roman antiquity are of this type. On the other hand, both the pan and the counterweight can be fixed, in which case a balance can weigh out only one particular measure; or, if the suspension point is moveable, it can weigh out a number of different weights. A few examples of this moveable type of balance from the early Roman period have been preserved. This kind of balance, sometimes called the *bismar* (*bessmer*, *besemer*) or *Danish steelyard*, was however common enough in Athens in the later fifth-century BCE for Aristophanes to be able to make a joke by referring to it. In the comedy *Peace,* first performed in 421 BCE, Aristophanes alludes to an unequal-armed balance of the simple bismar type.

It is significant that the first documented reference to the asymmetric balance apparently describes a merely one-portion measuring instrument, which evidently presupposes no knowledge of the law of the lever and from which it is also highly unlikely that the law could be just read off. Let us take Aristophanes' example: An arms merchant, who has been complaining about not being able to sell off his wares because of the new peace, asks what he should do with a particularly expensive war trumpet. He is given some suggestions about what to do with it, including the following: "Well, here's another idea. Pour in lead [into the bell of the trumpet] as I said, add here a pan hung on strings, and you will have something to weigh out the figs for your slaves in the field."[32] A sample representing the amount of figs that each slave is to receive can be placed in the pan hung from the mouthpiece of the trumpet, and the suspension point at which the lead-filled bell end balances the figs can be found empirically. Any predetermined weight portion can be built into this weighing instrument without any theoretical knowledge just by attaching a cord where the trumpet hangs horizontally. The invention and retainment of such a one-pan balance presupposes at most a weighing practice common and specialized enough to want one-portion weighing devices. And the introduction of standards for weights and coins accelerated by the reforms of Solon at the turn of the sixth century BCE would seem to accommodate such practices. As a matter of fact, to build such a device, the standard weight in the weighing pan of a normal symmetric balance could simply be built into the beam of the balance—even before it was learned that a different suspension point would balance a different standard weight.

A balance found in Pompeii, which in the past was wrongly interpreted as a Roman steelyard turns out to be just such an improvised *bismar* balance. It was produced from a vessel that looks like a saucepan, using the pan itself as the fixed counterweight, while its handle serves as the beam. A slit cut down the length of the handle makes it possible to hang the pan from a chain at different points along the handle. The object to be weighed was then hung from the end of the handle, where a rivet is fixed. Along the slit in the handle a scale is marked, evidently produced by empirically gauging each mark, that is, independent of any theoretical knowledge of the law of the lever.[33] Given the evidence, it would seem that the asymmetric balance with a moveable suspension point was the earlier device and was then replaced by the much more efficient Roman steelyard with a moveable counterweight.

32 Aristophanes (1998, lines 1245–49, pp. 58, 304).

33 See Damerow et al. (2002).

With this background, let us return to the text: why can a simple beam (with a counterweight) do so much? The answer begins with the standard form of identification in a counter-question, in which the beam is identified as a balance and a lever at the same time. In his exposition the author then explains (1) why the "half-balance" is in fact a (full) balance, (2) why it is not only one balance, but many different balances, (3) why it is also a lever and then (4) what is the specific difference of this balance to the lever. Let's look at the first step. In answer to the question, how a small counterweight can balance a great load, the author asks:

> Is it because it happens that the beam is a balance [*zugon*] and a lever [*mochlos*] at the same time? A balance inasmuch as each of the cords becomes the center of the beam. Only that on the one [side] it has a scale pan, but that on the other [side] instead of the scale pan [it has] the counterweight [*sphairôma*][34] which lies on the balance, as if one were to put the other scale pan and the measuring-weight [*stathmos*][35] on the end of the beam.[36] For it is clear that it draws just as much load laid in the other scale pan. (853b28–35)

A load or heavy thing has a weight, which can be measured by placing the load in one scale pan of a balance. In the other pan we place a standardized measuring weight, or several of them. But the measuring weights and the pan holding them could also simply be fastened to the beam of the balance instead of hanging loosely from it—or they could even be replaced by an equivalent counterweight built into the beam, as long as the counterweight draws the same load as the pan and measuring weights did. This would also explain why this device is indeed a sort of half-balance, since it has only one scale pan. The cord by which the beam (*phalanx*) is suspended and which divides it in half at the center turns it into a balance (*zugon*). In fact as long as the beam with the counterweight still balances out the load placed in the one pan, the cord suspending the device could actually be moved off-center to a different place on the beam—in which case each of the new suspension points would constitute a new "center" of the device. But except for the as yet uncalled-for plural ("each of the cords") the argument thus far merely describes an equal-armed balance with only one pan. The second step justifies viewing this new balance as many different balances:

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[34] *sphairôma*: literally "round thing"

[35] The term *weight* can be used in two quite different senses: Like *length* it names an abstract physical quantity, but it also can name a concrete material thing such as a measuring weight. If a piece of silver weighs three talents, the silver *has* a weight, the talent *is* a weight. Greek of Aristotle's time sometimes distinguished the two senses by the gender of the noun: *ho stathmos* (masculine) could refer to the abstract quantity measured and *to stathmon* (neuter) to the standardized measuring weight placed in the pan [see Liddell et al. (1996)]. The author of the *Constitution of Athens* (presumably Aristotle) uses the terms in this manner (Aristotle 1995, pp. 2346, 2373; ch. 10.1–2 and 51.3). However, Aristotle at one prominent place (*Metaphysics N*, 1087b37) uses the masculine form for the measuring unit. The standard published versions of Problem 20 use both forms of the word: masculine twice and neuter once. Of the relevant manuscripts, all but the one on which the first print edition was based have only the masculine form. We thank Joyce Van Leeuwen for checking the manuscripts for us.

[36] Reading (with Cappelle) *phalanx* (beam) for *plastinx* (pan).

> And in the same way as the one balance is many balances, many such cords lie in such a balance, in each of which that [part] on the side of the counterweight is half of the beam, and the weight [*stathmo*s] [behaves] in the same way as the cords are moved with respect to one another so that it is measured how much load that which is placed in the scale pan draws; so that, whenever the beam is straight [= horizontal], one knows from which cord [is used] how much load the scale pan holds, as has been said. In short, this is a balance having one scale pan in which the load is weighed out, but [having] the other in which the measuring-weight [*stathmos/on*] is in the beam. And therefore the counterweight is the beam on the other side. Being such, there are many balances, as many as there are cords. (853b35–854a7)

The cord by which the beam is suspended and which divides it in half at the center could also be moved to a different place on the beam—in which case the balance would weigh out a different load. Each time we move the cord, the counterweight weighs out a different load. We can have as many different (one-portion) balances as we have different places to attach the cord. These new balances are asymmetric in two ways: one side has a scale pan with a load in it while the other has only a counterweight and furthermore the two *halves* of the beam, divided at the *center* where the cord is fastened to the beam now have different lengths. This makes it clear that the balance under consideration is a *bismar* that can effectively be treated like a symmetric balance with a weight fixed to one side of the beam. To a certain extent this is just an empirical description not an explanation: as a matter of empirical fact the balance is horizontal. If two different objects placed successively in the pan, using the same suspension point, each make the beam horizontal, then they are of the same weight.

It is clear that the half-balance is very much like a real balance. But it is still necessary to show that it is also a lever since this will explain why this kind of balance can do what it does. This is the third step in the text. The asymmetric balance can be viewed as a kind of lever: If the length of the beam is given, then the closer to the load the cord is set, the farther the counterweight is from the cord and the greater is the load that it can balance. The reason for this, the author tells us, is that the whole construction is a sort of lever that is upside down in the sense that the fulcrum, instead of supporting the beam from below, is actually the cord suspending it from *above* and that the load to be moved is not on top of the beam, but is rather located in the pan hanging *below* it. We know (from Problem 3) that the farther from the fulcrum the force is placed, the more easily it moves a load.

> Always, the nearer the cord is to the scale pan and to the weighed-out load, the greater the load it draws because of the fact that the whole beam becomes a lever, which is upside down, for each cord is a fulcrum [*hupomochlion*] being from above, and the load is that which is in the scale pan; but the greater the length of the lever from the fulcrum, the more easily it [the lever] moves there, but here it makes counterpoise [*sêkôma*] and weighs out the load of the beam toward [in relation to] the counterweight. (854a7–15)

As we noted in the discussion of Problem 3, the law of the lever plays no explanatory role in this text. It would indeed have been difficult to extract this law either from mere technical practice with the lever or from handling a bismar type of balance as treated here. In contrast to an idealized steelyard with a weightless beam, the scale of the bismar as it is here described is nonlinear and also depends on the qualities of the material beam that is used. Accordingly the text makes use of functional descriptions that can hardly be directly translated into mathematical relations. It is true, as the text formulates, that the closer to the load the fulcrum is pushed, the greater is the load that can be moved by a given force because the other side of the lever, where the force acts, gets longer. And the closer to the pan the cord is placed, the farther from the cord is the counterweight located and thus the greater is the weight that it can balance out. However, it is not true that the load moved or the weight balanced increases merely proportionally with the distance of the force/counterweight from the fulcrum/cord—since the length added to one side is also subtracted from the other side.[37]

The conclusion (fourth step) drawn in the last clause above returns to the original question of why the asymmetric balance can do what it does. On a lever, the farther from the fulcrum the force is placed, the more easily it moves a load. However the counterweight does not actually *move* a load, but rather *balances* a load ("makes counterpoise" as the author puts it), that is, induces equilibrium. Thus, because the half-balance is like a lever, the farther the counterweight (which plays the role of the force) is from the cord, the greater the load it can weigh out. Problem 20 thus explains the asymmetric balance in terms of the lever, which has already been reduced to the symmetric balance.

The fact that this text deals with a *bismar* not a Roman steelyard is significant, and it was scarcely recognized in the early modern reception. Almost all Renaissance commentators (one notable exception is Biancani 1615) interpret the balance as a Roman steelyard and many identify the round counterweight at the end of the beam (the *sphairôma*) with the moveable counterweight of the steelyard called a *romanum* or *marcum.*[38] The prevalence of the Roman steelyard led these commentators to misunderstand the text. In fact, given the comparative rarity of the *bismar* once the Roman steelyard came into use, it is possible that already in the Hellenistic period the argument had become effectively unintelligible even to the Greeks, which might account in part for the corruption of the text.

Let us return briefly to the reduction program and see how it works in this particular case. In the few cases analyzed so far we have seen the reduction of a technical device to the lever, then to the balance, and then to the circle. In this case, however, we have a balance to begin with, which purportedly only works the way it does because it is simultaneously a lever. The argument is not circular since the balance to be reduced is of a different kind. Moreover, the example even suggests that the origin of the entire reduction program depended on the identification of balance and lever enabled by this device. The asymmetric balance embodies this

[37] In the text just quoted, the appeal to the lever principle of Problem 3 "the greater the length … the more easily (*rhaon*) it moves" is marked by the *tantum-quantum* formula *hosô … tosoutô*. On the other hand, the state of affairs that this principle is supposed to explain "the nearer the cord … the greater the load it draws" is not so marked.

[38] Biancani (1615, 183); cf. Piccolomini (1547, 42v); de Monantheuil (1599, 147): "… aequipondium, Graecis dictum *sphairôma*, nostris Marcum vel Romanum…." Even Baldi (1621, 134), who mentions that "we could use the steelyard in a different manner" and then describes a *bismar*, does not suggest that this might have been intended by Aristotle himself.

identification; it really does work simultaneously as a lever and a balance. It thus seems plausible that the invention or use of such balances constituted the historical starting point for the reduction program itself.

5.6 Historical Conditions for the Origin of Theoretical Mechanics

The aim of the *Mechanical Problems*—at least of that part of it that exemplifies the mechanical reduction program—is to explain technical devices and to show that their 'wonderful' success is compatible with other aspects of everyday experience as well as with certain principles of Aristotle's physics, in particular, with the principle of the correspondence of force and effect. This is taken up early in the Introduction:

> For as Antiphon, the poet, said, this is so: "By means of art we master that by whose nature we are conquered." Of this kind are those in which the lesser master the greater and things possessing little moment [*rhopê*] move heavy weights, and all similar devices, which we term mechanical problems. (847a20–24)

The cornerstone of this project is the equation of the balance and the lever. What is shown again and again in the work is that technical devices can be made intelligible by assimilating them to a *balance-lever model*. Technical devices can now be analyzed in terms of levers, loads, fulcrums and forces, which are no longer just directly given concrete things but also instantiations of abstract concepts, which can stand in logical and even quantitative relations to one another. What the author does is systematically to derive these abstract concepts in the study of technical devices or, perhaps better, to articulate and to reflect on the identifications that actually occur in mechanical practice. Viewing an iron bar and a small stone as a *lever* and a *fulcrum* involves a process of abstraction—even if the concrete objects and the abstraction products retain the same names. Viewing a wheel as a circle involves a similar abstraction. And when parts of technical devices are identified with ('become') parts of the balance-lever system, a further abstraction is made. What we can see in the text is scientific theory arising from reflection on a particular kind of technical practice.

As we have seen, the asymmetric balance, which is both a balance and a lever, plays a special role in the construction of the *Mechanical Problems,* providing the point of departure and the model for the cognitive development realized in the treatise. Why, of all the possible technical devices of the period, could the asymmetric balance play this special role? And why of all places did this happen in Greece?[39] As we have already mentioned, there had been around 2500 years of weighing practice, before the *bismar* was invented without any indication of mechanical theorizing,

[39] On the possibility of comparable developments in China in the same period, see Renn and Schemmel (2006).

and ancient civilizations also had knowledge of many devices that display the lever effect in a simple and perspicuous form. However, relatively soon after the invention of the bismar, we see the beginning of theoretical mechanics.

In the course of three millennia in the construction of the temples and monuments in Mesopotamia and Egypt all the devices known to us as "simple machines" came to be employed. Studying the passageways in the Pyramids archaeologists can reconstruct from the putlog holes in the walls where the pulleys were placed to lower the sarcophagus of the Pharaoh. Thus it is clear that the machines were not only used, but also discussed and reflected on beforehand by the construction planners and overseers. But there is no evidence that this kind of planning practice led to any abstract mechanical theory in connection with these devices.

How does the situation in Greece compare to these highly developed civilizations? Due to the military and architectural activities of the Greeks, practical mechanical knowledge of the simple machines and the planning knowledge needed for construction was widespread in Greece as well. More specifically, such devices as the *shadoof* (or sweep-beam, *kêlôn*), which is discussed in Problem 28 of the *Mechanical Problems,* and the counterbalanced long spear (*sarissa*) of the Macedonian army indicate that counterweights, which practically embody the complementarity of weight and distance, were a common aspect of ancient Greek culture. Any one of these could in the right context have provided the occasion for theoretical questions. Just as Galileo much later used the Venetian Arsenal as an occasion for philosophical reflection, so, too, could Aristotle have used Alexander's exercise yards or the nearest temple construction site. But there are good reasons why the asymmetric balance is a much better candidate than these others for initiating the development that led to the foundation of mechanics. The main reason is simply that a balance is a measuring instrument that by its very nature establishes equivalence between cause and effect.

One foundational experience of practitioners' knowledge since antiquity has been the equivalence of the weight of a body and the force needed to raise it. This equivalence is prototypically embodied in a real instrument, namely the balance with equal arms, which lies at the center of a social practice of weighing and grounds an associated shared mental model that we can call the *balance model*. The heavy body placed in one scale pan that keeps the balance horizontal is equal in weight to the body in the other scale pan. The force applied to one scale pan that keeps the balance horizontal (in equilibrium) is equal to the weight in the other scale pan.

However, the practical knowledge of the technicians of antiquity also involved other basic experiences, in particular, the experience that the constraints set by the equivalence of weight and force could be overcome. In fact, the art of the mechanical technician consisted precisely in overcoming the natural course of things with the help of instruments such as the lever and other machines. In this practice a mechanical instrument achieves (with a given force) a greater effect than could have been achieved without the instrument. That a weight can be moved by a smaller force seemed to involve a "wonderful" trick against nature, called *mêchanê* in Greek and from which the term *mechanics* is derived. This unnatural trick of mechanics is prototypically embodied in a real instrument, the lever, whose use unifies a different practice and grounds a different mental model we can call the *mechanics model*.

Both forms of practice and the mental models they embody could (and did) peacefully coexist without a problem as long as the areas of application remained separate. And even where some practices overlap, no contradiction need occur. Any water-carrier balancing two buckets at the ends of a pole across his nape and shoulders who was unfortunate enough to get different amounts of water in his buckets had to make adjustments in the position of the pole. Neither the water carrier nor even the makers of asymmetric balances have to possess knowledge of the law of the lever or of any similarly specific quantitative rule. They need only know what must be done to keep the beam horizontal. Even though the asymmetric balance seems to instantiate two incompatible mental models or forms of practice, there is no conflict so long as they are not exercised at the same time. It is of course a completely different state of affairs when the two potentially conflicting practices are made the subject of philosophical reflection with a view to integrating them into an embracing system of knowledge.

The appearance of the asymmetric balance in Greece some time before Aristotle made it possible to combine the *mechanics* model with the *balance* model, producing the *balance-lever* model of the *Mechanical Problems* and integrating theorizing on the two areas of practice. The balance-lever model can be understood as a generalizing transformation of the balance model, associated with the ordinary balance with equal arms. In the case of an equal-arms balance, weight differences are balanced by adding weights; in the case of an unequal-arms balance, they are balanced by changing the distance of the counterweight by changing the position of the suspension point. This necessarily extends the simple balance model: Not only can heavy things be moved by a small force, but weights can be compensated not only by weights but also by distances. This is not just practical knowledge gained by using the devices but also a kind of theoretical knowledge gained by systematizing.

As far as explanatory power is concerned, there is a difference between the balance and simple machines like the lever. The balance ascertains equality of weight. The machines apply force. Both deal with weight since weight is what demands the application of force to raise it; but the machines make it possible to raise a weight with less force than is needed without them. Machines make the mover stronger; balances ascertain equality. Equating the lever with the balance, as is done in *Mechanical Problems* on the basis of the asymmetric balance, is a singularly strong explanatory move. Insofar as they are levers, asymmetric balances partake of the general property of mechanical devices by achieving large effects with small forces (great loads, small counterweight). But insofar as they are balances, they must establish equivalence between cause and effect, which is just what is required for an explanation within the Aristotelian framework. This equivalence is achieved by appealing to the compensation of weight by length as it takes place in the asymmetric balance. Thus, it was the practical knowledge related to balances with unequal arms that ultimately provided the empirical basis for the formulation of the law of the lever.

While this is certainly one very important element in an explanation of why mechanics became possible in Aristotle's Greece, there is more to the story: The development of a theoretical science would not have been possible without a pre-existing theoretical tradition concerned with the explanation of natural phenomena. The emergence of mechanics, the realization of the theoretical possibilities of the lever-turned-balance, took place in a particular social setting in which theoretical reflection was already pursued in a number of other areas of experience and in which there existed a strong culture of disputation and persuasion by (public) justification in the form of arguments. The political and juristic customs of the Greeks (at least in Athens) made the success of someone's projects often depend not just on the usual mechanisms of common interest, bribery and nepotism, but also on the effective persuasion of others by rhetoric and argument. Proof in court and in mathematics had a peculiar relevance in Aristotle's Greece. Furthermore, throughout the Mediterranean world with the spread of trade and coined money, weight standards and the associated practices also spread. In Athens one of the feats for which the semi-legendary Solon would be praised by Aristotle was the establishment and reform of standards for weights and coins.[40] Finally, the formation of abstract concepts such as length, and weight already had a firm place in Aristotelian natural philosophy, which also possessed the means to treat simple functional relations such as proportionality and sought to bring ever more areas of human practice into its system of knowledge.

The articulation of the practical knowledge of the balance-lever model in this theoretical context thus constituted an important step in the integration of mechanical practice into systematic knowledge, which led (somewhat later we think) to the formulation of the law of the lever. The *Mechanical Problems* represents one of those rare instances in the history of science where an intermediate or transitional stage has been preserved, showing practical knowledge being turned into the theoretical foundation of science.

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[40] See the already cited passage from the *Constitution of Athens,* ch. 10, in Aristotle 1995, p. 2346.

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