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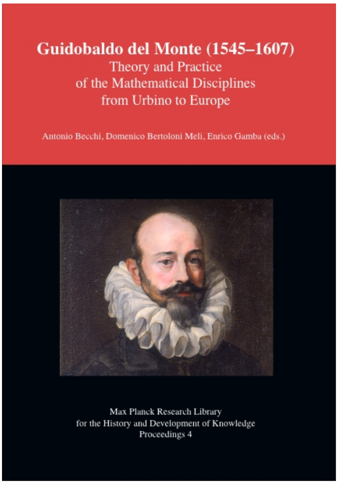
Walter Roy Laird:

Guidobaldo del Monte and Renaissance Mechanics



In: Antonio Becchi, Domenico Bertoloni Meli and Enrico Gamba (eds.): *Guidobaldo del Monte (1545–1607) : Theory and Practice of the Mathematical Disciplines from Urbino to Europe*
Online version at http://edition-open-access.de/proceedings/4/

ISBN 9783844242836
First published 2013 by Edition Open Access, Max Planck Institute for the History of Science under

Printed and distributed by:
Neopubli GmbH, Berlin
http://www.epubli.de/shop/buch/27498

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de

Chapter 2
Guidobaldo del Monte and Renaissance Mechanics

Walter Roy Laird

To historians of mechanics, Guidobaldo del Monte presents something of a paradox. On the one hand, he attempted to found mechanics on the strictest principles of abstract, Archimedean statics. On the other, he insisted that mechanics was not a purely abstract, mathematical science, but rather was essentially concerned with actual machines. He vigorously criticized Tartaglia (among others) for vainly attempting to separate a mathematical from a physical mechanics, "as if mechanics could be considered apart from either geometrical demonstrations or actual motion."[1] His practical interest in the workings of actual machines has been remarked on by a number of historians, including Alex Keller, Enrico Gamba, Gianni Micheli, and Mary Henninger-Voss; they and others, notably Paul Lawrence Rose, Stillman Drake, and Domenico Bertoloni Meli, have also called attention to Guidobaldo's important role in the sixteenth-century Archimedean revival. These two features of Guidobaldo's mechanics—the practical and the Archimedean—were perhaps his most significant contributions to the renaissance of mechanics in the sixteenth century.[2] But Guidobaldo has also come under considerable criticism from historians, both for his unreasonable demands for an excessive mathematical precision in mechanics, and for his failure to include principles of motion and dynamics. He is notorious, for example, for trying to take account of the convergence of the arms of the balance to the center of the earth, a convergence that is immeasurably small even in the largest balances. For this reason Pierre Duhem dismissed him as a narrow-minded geometer, whose "exaggerated regard for deductive rigour" (le souci exagéré de la rigueur déductive) and his "uncritical admiration of the Ancients" (l'admiration exclusive de anciens) blinded him to the promising results reached through more intuitive reasoning by Jor-

[1] "Ac si aliquando, vel sine demonstrationibus geometricis, vel sine vero motu res mechanicae considerari possint" (Monte 1577, f. **1v; tr. Drake and Drabkin 1969, 245).

[2] See (Drake and Drabkin 1969, 44–48; Rose 1975, 222–242; Keller 1976; Gamba and Montebelli 1988; Bertoloni Meli 1992; Micheli 1992; Gamba 1998; Henninger-Voss 2000; Bertoloni Meli 2006, 26–32).

danus de Nemore, Girolamo Cardano, and Niccolò Tartaglia.[3] More recently, Stillman Drake repeated Duhem's criticisms, but specified that what Guidobaldo had missed in Jordanus and Tartaglia was the general principle that the products of force and virtual displacement are equal for systems in equilibrium. According to Drake, this was because Guidobaldo had insisted that a greater power was necessary to produce motion than equilibrium; and Guidobaldo had excluded all dynamical concepts such as work and virtual velocity from mechanics because he held that Archimedean statics had superseded the dynamical approach of the pseudo-Aristotelian *Mechanical Problems* (Drake and Drabkin 1969, 48). Paul Lawrence Rose went even further, to assert that for Guidobaldo, statics and dynamics were "two entirely separate sciences without common principles" (Rose 1975, 232; see also 233, 234–235, note 2). According to Rose, Guidobaldo

> despaired [...] of there ever being a mathematical science of dynamics and himself erected unbridgeable barriers between dynamics and mathematical statics. (Rose 1975, 229)

But as Maarten Van Dyck has shown in a recent article, Guidobaldo was not so slavish a follower of the ancients, nor so blinded by a concern for mathematical rigour, as Duhem and others have thought. Guidobaldo did take account of the convergence of the ends of the balance, but only to refute the mechanical principles of Jordanus and Tartaglia, which was necessary to defend the coherence of what he saw as the sovereign principle of mechanics, the equilibrium of centers of gravity, understood within an earth-centered Aristotelian cosmos. Van Dyck has thus restored to Guidobaldo's criticisms of Jordanus and Tartaglia their original purpose and intent (Van Dyck 2006). In a similar way, I should like to show how Guidobaldo's so-called failure to include in his mechanics dynamical principles such as virtual velocities was the natural result of his adoption of the equilibrium of centers of gravity as its foundational principle. In other words, I should like to recover the original scope and intent of Guidobaldo's mechanics from the expectations imposed upon it by historians looking back through later developments.

Given that Guidobaldo had adopted the equilibrium of centers of gravity as the sovereign principle in mechanics, how did he attempt to apply it to the actual motion of real machines? And how did his choice of this principle determine the nature and scope of the mechanics that followed from it? To answer these questions I shall first look at the application of the principle to the simple machines in Guidobaldo's *Mechanicorum liber* (1577), his major mechanical work. His other

[3] See (Duhem 1905-1906, I, 209–226; tr. Duhem 1991, 148–159). The phrases quoted are on p. 151 and 159.

published work on mechanics, the *Paraphrase* of Archimedes's *On Plane Equilibrium* (1588), concerns the establishment and mathematical applications of this principle, and so has little to add concerning its mechanical applications, though its Preface contains some interesting comments on mechanics. But in addition to these two printed works, Guidobaldo also made a number of notes on mechanical matters that form part of his unpublished *Meditatiunculae de rebus mathematicis* (musings on mathematical topics), the manuscript of which Guglielmo Libri discovered in the Bibliothèque Nationale, in Paris, and from which he printed a few extracts in 1840.[4] These notes on mechanics, at least some of which were written after the publication of the *Mechanicorum liber*, include both an attempt to recast the pseudo-Aristotelian *Mechanica* in an Archimedean mold, and Guidobaldo's own treatment of the inclined plane. My argument will be that, because the principle of the equilibrium of the balance is Guidobaldo's fundamental principle of mechanics, mechanical motions for him are fundamentally disequilibriums; this means that while equilibrium is a determinate state and thus subject to mathematical exactitude, disequilibrium produces motion, which is thus indeterminate and subject to unavoidable and unaccountable material disturbances. This explains, I think, both the source of his criticisms of Jordanus and Tartaglia, and his apparent neglect of motion and dynamics in his mechanics.

But before I turn to the *Mechanicorum liber*, I should like to sketch briefly the state of mechanics before Guidobaldo. The work that set the scope and program of mechanics and gave the first definitive content to the nascent science in the sixteenth century was the pseudo-Aristotelian *Mechanica* (or *Quaestiones mechanicae*). In its introduction, the *Mechanica* reduced mechanical marvels to the balance and ultimately to the marvelous properties of the circle. Analyzing the movement of the ends of the balance into a natural and a violent or preternatural component, it argued that a power is swifter and thus more effective the greater its natural component over its violent. For this reason a weight or a power is more effective the longer the arm of the balance, since the longer arm partakes more of the natural than the violent movement. This principle of circular movement was then applied to a number of questions, the first few concerning the balance and the lever, later ones taking up the wheel, the wedge, pliers, and the like, including a number of questions on topics such as the motion of heavy bodies, projectile motion, and whirlpools that have little or nothing to do with the principle of circular movement. The *Mechanica* was translated into Latin early in the sixteenth century and was the subject of several commentaries and para-

[4] Paris, Bibliothèque Nationale, fonds lat. ms 10246. See (Drake and Drabkin 1969, 48). The *Meditatiunculae* has been edited by Roberta Tassora (2001), a partial copy of which Pier Daniele Napolitani, who directed the thesis, kindly made available to me after this paper was written; the passages quoted from the *Meditatiunculae* are in my own transcriptions. The mechanical pages of the *Meditatiunculae* are discussed by Tassora (2001, 75–100).

phrases by mid-century, including an influential paraphrase and commentary by Alessandro Piccolomini. It was lectured on at the University of Padua by Pietro Catena in the 1560s, by Giuseppe Moletti in the 1580s, and by Galileo in the 1590s.[5]

At the same time as the pseudo-Aristotelian *Mechanica* was becoming more widely known, the medieval science of weights (*scientia de ponderibus*), represented especially by the works attributed to Jordanus de Nemore, was reintroduced in the sixteenth century, first by Peter Apian's printing of the *Liber de ponderibus* in 1533, and then by Tartaglia's printing of the magisterial *De ratione ponderis* in 1565.[6] For Jordanus, the swiftness and thus the effectiveness of a weight depended on the directness or obliquity of its motion, where motion on the circumference of a larger circle is more direct than motion on a smaller. Significantly, Jordanus recognized that the speeds and the distances of the motions of weights were to be measured along their vertical descents, which led him to the correct solution of the inclined plane and historians to the conclusion that he was, in effect, appealing to the principle of virtual work. For Niccolò Tartaglia, the science of weights from Jordanus provided the principles of the mechanics found in the pseudo-Aristotelian *Mechanica*. Book 7 of Tartaglia's *Quesiti et inventioni diverse* (*Diverse Questions and Inventions*, 1546) was thus devoted to a discussion of the *Mechanica*, while Book 8 established its principles using the science of weights.[7] To the pseudo-Aristotelian *Mechanica* and the medieval science of weights, a third tradition in mechanics was added. By the mid-sixteenth century, the works of Archimedes were already being edited, translated, and assimilated into mathematics, notably by Francesco Maurolico in Messina and Federico Commandino in Urbino. Lacking Archimedes's text, Maurolico (by his own account) reconstructed *On the Equilibrium of Planes* in his brilliant *De momentis aequalibus* (*On Equal Moments*); like Guidobaldo, as we shall see, Maurolico saw equilibrium as providing the foundation for mechanics, which he developed as a commentary on and an extension of the pseudo-Aristotelian *Mechanica*, although neither of his works on mechanics was to be published until the next century.[8] Guidobaldo, on the other hand, knew the *Equilibrium of Planes* in the translation published by Federico Commandino in 1565. But the greatest difference between Maurolico and Guidobaldo was in the scope and content of mechanics: where Maurolico included in mechanics more or less everything in the pseudo-Aristotelian *Mechanica,* Guidobaldo restricted it to Heron's five sim-

[5]On the sixteenth-century tradition of the *Mechanica*, see (Rose 1975; Rose and Drake 1971; De Gandt 1986; Laird 1986).

[6]See (Nemorarius 1533 and 1565).

[7]For Jordanus and the medieval science of weights, see (Moody and Clagett 1952; Tartaglia 1546; excerpts tr. Drake and Drabkin 1969, 104–143).

[8]See (Maurolico 1613; Tucci 2004), on Maurolico's mechanics, see (Laird in press).

ple powers or machines, an account of which he had found in Commandino's translation of the *Mathematical Collection* of Pappus of Alexandria.[9] And from Pappus Guidobaldo also adopted Heron's general challenge for mechanics: to move a given weight with a given power using a machine. Guidobaldo's purpose in writing the *Mechanicorum liber*, then, was to demonstrate the principle of equilibrium of centers of gravity, exposing the errors of those like Tartaglia who relied on the science of weights, and then to apply this principle in turn to explain each of the five simple machines in order to answer Heron's challenge.

The *Mechanicorum liber* thus has six parts or treatises, the first devoted to the demonstration of the principle of equilibrium of the balance, the subsequent five to the lever, pulley, wheel and axel, wedge, and screw. The first part has already been treated elsewhere in detail by Vico Montebelli (1988) and by Maarten Van Dyck (2006). To their accounts I should like to add only that the source and foundation of Guidobaldo's criticism of Jordanus and Tartaglia seems to have been that, in attributing mechanical effects to the swifter or slower speeds of more or less direct or oblique motions, they had mistaken effects for causes. For according to Guidobaldo, they simply could not demonstrate that a weight on the end of beam is heavier when the beam is horizontal than at any other position, since its straighter or swifter movement at the horizontal position is merely a sign (i.e., a result) rather than a cause; nor do they prove that the weight is heavier by its *being* at that place, but only by its *departing from* that place.[10] For the true foundation of mechanics is not direct or oblique motion, according to Guidobaldo, but Archimedes's principle of the equilibrium of centers of gravity. In the Dedicatory Letter of the *Mechanicorum liber*, Guidobaldo stated that in Archimedes's *Equilibrium of Planes* "all the theories of mechanics are gathered as in an abundant store."[11] And in the Preface to his later *Paraphase* of *On the Equilibrium of Planes*, he wrote that "the whole of mechanics depends on this sole and foremost foundation," that is, on the principle that in equilibrium the weights are inversely as the distances.[12]

That speed and motion are results, not the causes, of equilibrium and disequilibrium Guidobaldo states explicitly in the corollary to Proposition 6 of the first treatise, *De libra* (On the Balance). In Proposition 5 Guidobaldo had proved

[9] On Commandino's edition and translation of Pappus's *Mathematical Collection*, and Guidobaldo's role in its publication, see (Rose 1975, 209–213).

[10] See (Monte 1577; tr. Monte 1581; tr. Drake and Drabkin 1969, 267–268).

[11] "Eruditissimus tamen libellus de aequeponderantibus prae manibus hominum adhuc versatur, in quo tanquam in copiosissima poenu omnia fere mechanica dogmata reposita mihi videntur" (Monte 1577, f. **1r; tr. Drake and Drabkin 1969, 244).

[12] "Tota mechanica facultas tanquam unico, praecipuoque fundamento innititur" (Monte 1588, 4); the Preface is edited and translated into German in (Frank 2007), the quotation is on p. 118; the translation quoted here is by Rose (1975, 234).

the central theorem of equilibrium, that weights are in equilibrium when their distances from the center are inversely as their weights. In Proposition 6 he then proves that equal weights weigh in proportion to their distances from the center. And from this follows the corollary that, since the farther a weight is from the center of the balance the heavier it will be, so its motion will be the swifter. Relegated to a corollary, speed and motion are thus the results, not the causes, of greater or lesser heaviness.[13]

Having established in these first propositions the principle of the equilibrium of the balance, Guidobaldo then applied it in turn to each of Heron's five simple powers or machines—the lever, pulley, wheel and axel, wedge, and screw. In each case, he used the principle to find the power needed to sustain the load in equilibrium; he then assumed that actually to move the load would require a somewhat greater power. In the case of the lever, he stated this as follows:

> For the space of the power has the same ratio to the space of the weight as that of the weight to the power which sustains the same weight. But the power that sustains is less than the power that moves; therefore the weight will have a lesser ratio to the power that moves it than to the power that sustains it. Therefore the ratio of the space of the power that moves to the space of the weight will be greater than that of the weight to the power.[14]

The conditions of equilibrium having been established, motion is produced only by the addition of some indefinite amount of power. Notice that Guidobaldo has no aversion to comparing the spaces moved by powers and weights, in exactly the way that Jordanus and Tartaglia did. But for Guidobaldo, these spaces and motions are the results of the disequilibrium caused by an indefinite increase of power; they are not themselves the causes.

In the treatises on the pulley, on the wheel and axel, and on the screw, Guidobaldo also introduced the time taken to move the weight and its speed, noting that the more easily a power can move a weight, the more slowly it does so.[15]

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[13] See (Monte 1577, ff. 30v–36r; tr. Monte 1581, ff. 29v–33v; tr. Drake and Drabkin 1969, 296, proofs omitted).

[14] "Percioche lo spatio della possanza allo spatio del peso ha la medesima proportione, che il peso alla possanza, che sostiene il detto peso. Ma la possanza, che sostiene è minore della possanza che move, però haurà proportione minore alla possanza che lo move, che alla possanza, che lo sostiene. Lo spatio dunque della possanza che move allo spatio del peso haurà proportione maggiore, che il peso all'istessa possanza." See (Monte 1577, f. 43r–v; tr. Monte 1581, f. 39v; tr. Drake and Drabkin 1969, 300).

[15] See (Monte 1577); *De trochlea*, Prop. 28, Cor. 2, f. 107 v; tr. (Monte 1581, 101 v; tr. Drake and Drabkin 1969, 317); *De axe in peritrochio*, Prop. I, Corollary [3], f. 110r; tr. (Monte 1581, f. 106 r; tr. Drake and Drabkin 1969, 319); *De cochlea*, Prop. 2, Corollary, f. 128 r; tr. (Monte 1581, f. 125 r; tr. Drake and Drabkin 1969, 326).

He thus fully understood the central principle of Galileo's mechanics, but with this crucial difference: he saw it as an effect, rather than as a cause.[16]

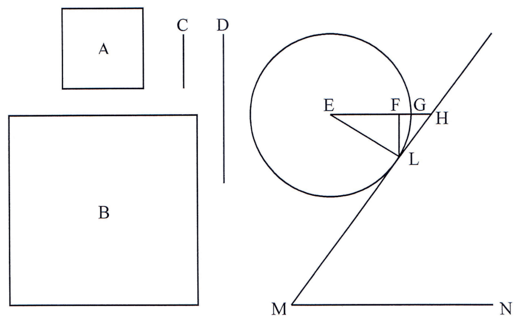

Figure 2.1

In his treatises on the wedge and on the screw, Guidobaldo cited Pappus's theorem on the inclined plane, since both the wedge and the screw can be reduced to inclined planes, and Pappus reduced the inclined plane to the lever and thence to the balance. But significantly, Guidobaldo did not present Pappus's theorem, although Pigafetta added it in the commentary to his Italian translation; it is possible that Guidobaldo was not happy with Pappus's proof, and that he omitted it from his Latin text for this reason.[17] Pappus had assumed that a certain power C is needed to move a sphere of weight A on a horizontal plane, and then undertook to determine the power needed to sustain the same weight on an inclined plane (see Figure 2.1). This he did by placing one end of a horizontal balance at the center E of the sphere, the other on its circumference at G, and the fulcrum F directly above the point of contact L between the sphere and the plane. The weight of the sphere acts at its center E, so that the balance is in equilibrium and the sphere is at rest on the plane when this weight is counterbalanced by a second weight B applied at G such that the ratio of weights is the inverse ratio of their distances EF and FG from the fulcrum. Next, he assumed that the ratio of a power D, needed

[16] For Galileo's statement of the principle, see (Galilei 2002, 45–47); tr. (Drabkin and Drake 1960, 147–149).

[17] Guidobaldo, *Mechanicorum liber*, *De cuneo*, f. 115 r, tr. (Monte 1581, f. 110 r; tr. Drake and Drabkin 1969, 321); *De cochlea*, [Prop. 2], ff. 126 r–127 r; tr. (Monte 1581, ff. 121 r–122 r; tr. Drake and Drabkin 1969, 325–326).

to move the second weight B on a horizontal plane, to the power C, needed to move the original weight A on a horizontal plane, will be equal to the ratio of the weights B to A. The power necessary to move the sphere up the plane, then, is the sum of these two powers C and D.[18]

In the *Meditatiunculae*, Guidobaldo sketched his own version of Pappus's theorem on the inclined plane, although with several significant differences. Like Pappus, Guidobaldo reduced the inclined plane to the lever, though he extended his proof to include all three classes of levers (see Figures 2.2 a, b and c). Now, because he was interested only in finding the sustaining power, not the moving power, he does not assume, as did, that a certain power is needed to move the weight on a horizontal plane. Instead, he simply finds the ratio of the sustaining power to the weight of the body as Pappus did, by placing them on the unequal arms of the balance. And he completely omits Pappus's crucial last step, of finding the power of moving the second weight on a horizontal plane and adding it to the power of moving the original weight. This means that the sustaining power actually has to be equal to or greater than the weight of the sphere itself for planes that place the fulcrum more than half way from the center of the sphere, and that on a vertical plane it becomes infinite. Pappus's theorem at least gives an intuitive approximation of how much power is needed to move a body up an inclined plane, though it too implies that the power needed to move the body up a vertical plane is infinite; Guidobaldo's theorem produces paradoxical results for all but the shallowest planes. His note at the end, that, if the fulcrum is located directly above or below the center of the sphere, the sustaining power should be equal to the weight of the sphere, suggests that he was aware of this consequence and wanted to correct it (see Figure 2.2d).[19]

[18] See (Monte 1581, ff. 121 r–v; tr. in part in Drake and Drabkin 1969, 325–326); as Bertoloni Meli pointed out (Bertoloni Meli 1992, 25, note 42), Drake's translation mistakenly prints H instead of G throughout; Pappus's full proof can be found in translation in (Cohen and Drabkin 1958, 194–196); a discussion of Guidobaldo's use of Pappus's proof can be found in (Bertoloni Meli 2006, 35–37).

[19] The proof is as follows: "Ducatur GH horizonti equidistans, cui ad rectos angulos ducatur CH, DK, sitque in hoc circulo constituenda potentia spheram sustinens in G. Sphera vero secetur per centrum et per C, plano horizonti erecto, quod quidem in sphera circulum efficiat maximum ABC. Sphera enim ABD habeat centrum D, que subiectum planum EF horizonti inclinatum in C contingat. Potentia invenire que datam spheram subjectum planum horizonti inclinatum tangentem in dato puncto sustineat. Oportet vero potentiam ita in sphera constituere ut circulus maximus per potentiam, et tactum transiens sit horizonti erectus. Intelligatur itaque GH vectis, cuius fulcimentum est in H, cum planum EF spheram tangat in C. Pondus vero in K esset appensum. Cum enim D sit centrum gravitatis sphere, erit perinde, ac si in K esset appensum ex dictis in tractatu de vecte nostrorum mechanicorum. Quam vero proportionem habet GH ad HK, ita fiat gravitas sphere ad potentiam in G. Potentia igitur in G cognita erit. Ac in prima quidem figura erit primus modus vecte, in secunda secundus, in tertia tertius. Notandum tamen quod si potentia esset in G, ita ut ducta horizonti perpendicularis per centrum sphere D transiret, ut DG tunc potentia totam sustineret spheram ac propterea ipsi equalis existeret.

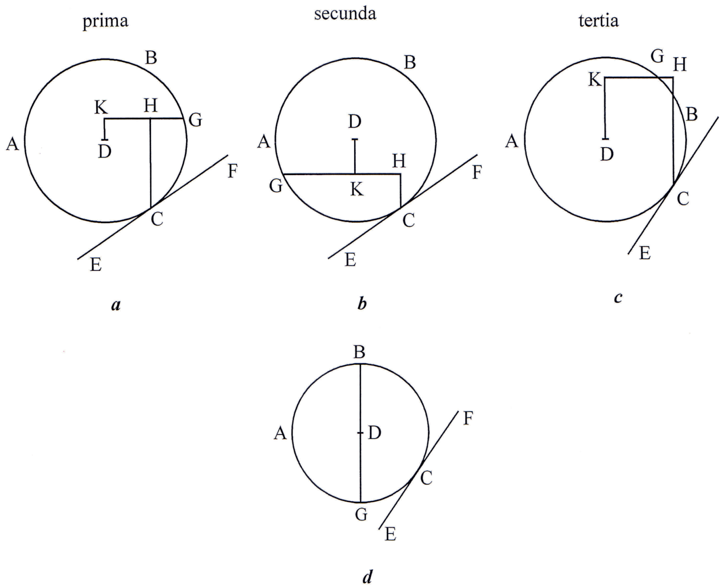

Figure 2.2

Despite his general emphasis on equilibrium, motion and its effects do find their way into his mechanics, notably in his treatment of the wedge, but only as secondary causes. In the *Mechanicorum liber*, after attempting to reduce the wedge to a pair of levers and thus account for its effectiveness, Guidobaldo adds the power of the blow striking it as another explanation. The power of the blow, he explains, depends both on the weight of the hammer and the distance through which the hammer moves, which is greater the longer the handle. The longer the handle, then, effectively the heavier the hammer and so the stronger the impulse of the blow. So far these effects can be seen to arise from the properties of the lever and thus the balance. But then he adds that the effectiveness of the wedge also arises in part from the very strong force of percussion, citing Question 19 of the *Mechanica*, which in fact his explanation echoes. Here he has moved en-

Veluti in puncto quoque B ob eandem causam" (Guidobaldo del Monte, *Meditatiunculae de rebus mathematicis*, Paris, BNF, fonds lat. ms 10246, 64; see Tassora 2001, 302–303).

tirely away from equilibrium as the cause of a mechanical effect and invoked the unexplained power of percussion.[20]

Each of the separate treatises on four of the five simple machines ends with Heron's problem, that is, to find the conditions under which a given weight can be moved by a given power using each machine. In the case of the wedge, however, Heron's program breaks down. With a wedge, according to Guidobaldo, any given power cannot move any given weight, since any given power cannot move any given weight by means of an inclined plane, though he does not explain exactly why. Further, since a wedge is in effect two opposing levers, as it splits the load the fulcrums of these levers themselves move and thus fail to maintain a constant ratio of load to power. In his general comment at the end of his translation of the *Mechanicorum liber*, Pigafetta explains that the wedge and the screw, unlike the other machines, are suitable only for moving weights, not for sustaining them; and,

> Since the powers that move may be infinite [in number], one cannot give a firm rule for them as may be done for the power that sustains, which is unique and determined.[21]

In fact, this is true for all of the machines, for while the conditions for equilibrium in each case are determinate and subject to an exact mathematical rule, the conditions for motion are many and indeterminate and thus in principle are unknowable with any precision.

According to Guidobaldo, Archimedes had clarified the principles of mechanics by accepting the explanations in the pseudo-Aristotelian *Mechanica* for the power of the lever, but then went further to discover and to demonstrate the exact relation between weights and distances, which is the sole foundation of mechanics.[22] In the *Meditatiunculae*, he in fact attempted to prove several of the questions from the *Mechanica* using Archimedean principles. The first two of these are headed *Questiones Aristotelis de libra aliter demonstrate* (Aristotle's questions on the balance demonstrated in another way) and begin with a single supposition: *centrum gravitatis deorsum tendere* (the center of gravity tends downwards). In the two propositions that follow, Guidobaldo proves the stability of equilibrium of a balance supported from above, and the instability of one supported from below, by appealing to the position of the balance's center of

[20] See (Monte 1577, f. 118 v–119 r; tr. Monte 1581, f. 114 r–v; tr. Drake and Drabkin 1969, 322–323); on the force of percussion, see (De Gandt 1987; Laird 1991; Roux 2010).

[21] "Percioche essendo, che le possanze lo quali movono possano essere infinite, non sene puo assegnare ferma regola, come si farebbe della possanza, che sostiene, laquale è una sola e determinata." See (Monte 1581, f. 127 v; tr. Drake and Drabkin 1969, 328); the insertion is mine.

[22] See (Monte 1588, 4; Frank 2007, 118; see Rose 1975, 234).

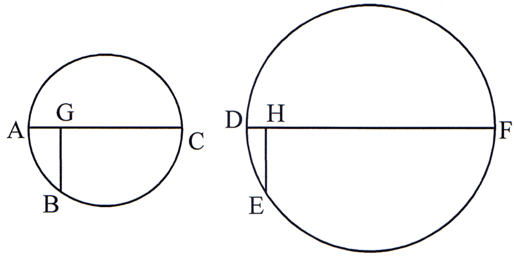

Figure 2.3

gravity; these proofs are in effect identical to those in the *Mechanicorum liber*. In the note that follows them, he criticises Alessandro Piccolomini's *Paraphrase* in its Italian translation, and he refers to his own *Mechanicorum liber* of 1577, which shows that he was writing this after 1582, when the Italian *Paraphrase* was printed.[23] On the next two pages there follows a proposition effectively the same as Proposition 6 of the treatise on the balance of the *Mechanicorum liber*.[24] Some twenty pages later, Guidobaldo offered a fuller proof of Aristotle's Question 1, why larger balances are more exact than smaller. This proof makes no appeal to centers of gravity, but relies entirely on considerations of motion. First he demonstrates as a lemma, citing the appropriate propositions from Euclid, that of two equal lines GB and HE dropped perpendicular from the diameter to the circumference, the line GB in the smaller circle has a smaller ratio to GA than the line HE in the larger to HD (see Figure 2.3). Then he applies this lemma to the balance by showing that when a longer and a shorter balance are deflected an equal vertical distance, in the motion of the longer arm there is a greater proportion of natural (vertical) motion to preternatural (radial) motion, so that the larger balance is easier to move and is moved more swiftly in the same time by the same power (see Figure 2.4).[25] What is significant about this proof is its appeal exclusively to motion and displacement rather than to centers of gravity.

[23] Del Monte, *Meditatiunculae*, 30; see (Tassora 2001, 266).

[24] Del Monte, *Meditatiunculae*, 31–32; see (Tassora 2001, 267–268).

[25] Del Monte, *Meditatiunculae*, 55–56; see (Tassora 2001, 292–293); a similar proof is given by Giuseppe Moletti in his unpublished *Dialogue on Mechanics* of 1576, for an edition and English translation of which see (Laird 2000, 97–99).

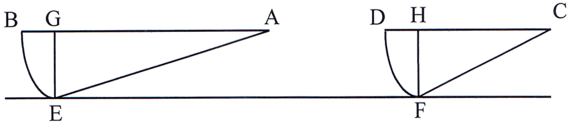

Figure 2.4

Guidobaldo's attempt to take into account the material resistance of real machines comes up in several notes inspired by questions in the *Mechanica* concerned with wheels. Question 11 of the *Mechanica* asked why weights are more easily moved on rollers than on wheels despite the fact that rollers are smaller in diameter than wheels; the answer there was because wheels are subject to friction at the axel. Pietro Catena, in his *Universa loca* of 1556—and presumably also in his now-lost lectures on the *Mechanica*, which Guidobaldo heard in Padua in 1564—had added to this "physical" explanation a "truly demonstrative" geometical proof supposedly showing that rollers, with their smaller diameter, make less contact with the ground than wheels do and so encounter less resistance to rolling. Guidobaldo came to the opposite conclusion: with the help of a geometrical lemma, he showed why it is in fact easier for a larger wheel to roll over an obstacle of the same size than for a smaller wheel (see Figure 2.5). Treating the obstacle effectively as an inclined plane, he reduced the problem to the lever, again invoking Pappus's theorem on the inclined plane.[26]

But in a variation of Question 9 of the *Mechanica*, Guidobaldo attempted to take account of the friction of the axel mentioned in Question 11. He asks why weights are in practice more easily moved with larger wheels, meaning in this case on a windlass. He imagines two equal weights suspended from A and C on the circumferences of two unequal wheels concentric around center G (see Figure 2.6). Since the weights at A and C are equal, the powers needed to sustain them in equilibrium at D and B will also be equal. But to move the weights, additional power must be added at D and B, since the axel resists motion because of contact and friction, which Guidobaldo represents as a load applied at E. Since the ratio of BG to FG is greater than the ratio of DG to FG, less power must be added at B

[26]See (Catena 1556, 81–83; del Monte, *Meditatiunculae*, cit., 60–61; Tassora 2001, 298–300); that Guidobaldo heard Catena's lectures, see (Rose 1975, 222).

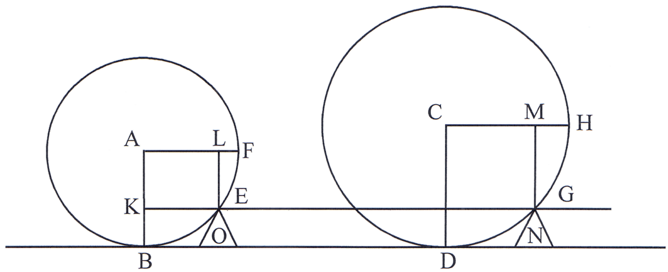

Figure 2.5

to overcome this resistance than at D. Thus weights are moved more easily with larger wheels.[27]

These fragments are apparently all that he wrote, or all that survive, in his attempt to reduce the pseudo-Aristotelian *Mechanica* to Archimedean principles, and they are, at best, a mixed success. But they show several important features of his approach to mechanics: they show his general determination to bring mechanical effects under Archimedean principles (though on occasion he resorted to motion and speed), and they show how he tried to take into account the material resistance of real machines. And the material resistance of real machines lies at the heart of Guidobaldo's attempt to exclude motion from the causes and principles of mechanics. A letter he wrote to the mathematician Giacomo Contarini in 1580, the substance of which he repeated shortly afterwards in a letter to Filippo Pigafetta, the Italian translator of the *Mechanicorum liber*, offers a clue to this. Both Contarini and Pigafetta had raised doubts about theoretical results contained in the *Mechanicorum liber*, since they did not seem to conform to experience. In his reply to Contarini, Guidobaldo asserted that, if a balance in equilibrium fails to move when a slip of paper is added to one of its weights, it is not therefore inaccurate:

> where one must consider that the resistance that the material makes is made when weights are to be moved and not when they are merely to be sustained, because then the machine neither moves nor turns.[28]

[27] Del Monte, *Meditatiunculae*, 59; see (Tassora 2001, 297–298).

[28] "dove è da considerare che la resistanza che fa la materia lo fa quando si hanno da mover i pesi e non quando se hanno da sostenere solamente, perché all'hora l'instrumento non si move né gira."

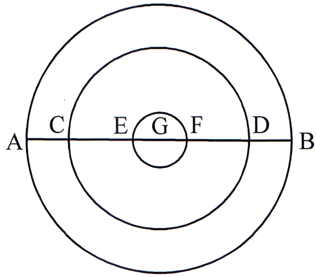

Figure 2.6

Because resistance arises only when there is motion, according to Guidobaldo, a balance in equilibrium corresponds exactly to abstract mathematical theory; but to disturb that balance, to set it into motion, is to introduce all the irregularities and uncertainties of matter. And working machines are precisely such disturbed equilibria.[29] This view of motion as the result of disturbed equilibrium and as subject to unaccountable material hindrances seems to lie at the root of his rejection of the dynamical tradition of mechanics represented by Jordanus and Tartaglia. Since motion is the *result* of disequilibrium, it cannot be the *cause* of either equilibrium or disequilibrium. And once equilibrium is disturbed, the resulting motion is indeterminate because of the material hindrances it is subject to. However true their conclusions, then, the fundamental error of Jordanus and Tartaglia was to mistake effects for causes.

Guidobaldo's main contribution to the renaissance of mechanics in the sixteenth century was to take the vague and wide-ranging scope of mechanics suggested by the pseudo-Aristotelian *Mechanica* and restrict it to Archimedean explanations of Heron's five simple machines. In his attempt to found a demonstrative, mathematical science of mechanics, the sole principle he recognized was the principle of the equilibrium of centers of gravity as established by Archimedes. Only equilibrium is susceptible to exact mathematical treatment;

Guidobaldo del Monte to Giacomo Contarini, Pesaro, 9 October and 18 December 1580, ed. Antonio Favaro (1899-1900); quoted in part in (Gamba and Montebelli 1988, 75–76); for the letter to Pigafetta, see (Keller 1976, 28).

[29] On this point see (Van Dyck 2006, 398–399).

motion and speed, since they are the results of disequilibrium and are subject to material hindrances, are in principle indeterminate and thus unknowable with any great precision. But they can be known to some extent, and mechanics is the science of knowing the actual motions and effects of real machines within these natural limits. This, I think, accounts for the apparently paradoxical nature of Guidobaldo's mechanics, with its insistance on both extreme mathematical rigour and actual practical machines. As for impetus and percussion—themselves merely the results of motion—they seem to lie outside of Guidobaldo's mechanics, and in this sense Rose's conclusion about his unbridgeable barrier between statics and dynamics holds true. If there could be an exact science of motion that included such things—and Guidobaldo's notes on projectile motion and falling bodies suggest that he did not entirely despair of one[30]—it would be entirely separate from the science of real machines that he attempted to establish on Archimedean principles.

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[30] See, for example, his notes on bodies falling through resisting media (Guidobaldo, *Meditatiunculae*, 41–42) and on the path of projectiles (op. cit., p. 236); see also (Tassora 2001, 90–93, 181–186, 281–283, 545–547).

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