The mechanical philosophy: mechanics

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Related Topics

- Early modern science of mechanics
- Mechanical intelligibility
- Mechanical causes

1. Introduction: from the science of mechanics to the mechanical philosophy

Sixteenth century Europe showed a marked rise in attention for machines as objects for theoretical reflection. Medieval society had a rich material culture involving both traditional instruments and striking new inventions (White, 1962). Scholastic philosophers were familiar with some Alexandrian and Arabic texts treating the principles of the science of weights, to which authors such as Jordanus Nemorarius offered further developments (Moody & Clagett, 1952). But there are no signs of the specific mode of articulation between material practice and theoretical treatment that would start to be explored in the sixteenth century. There are a number of factors that played a role in the shift that took place (see, among many other studies, (Long, 2001)). Social and cultural changes impacted the kind of value attached to material practices, which offered new possibilities for practitioners interested in raising their standing within society. The printing press and humanist projects led to the wide circulation of ancient texts that offered points of leverage for these interests, and invited the development of theoretical discourse that was directly linked to and possibly implicated in the material practices. By the beginning of the seventeenth century, this had led to the establishment of an unprecedented area of possible intersection between philosophical considerations and practical concerns and skills (Bennett, 1986).

Two ancient texts that resurfaced in the sixteenth century are of particular interest for the topic of the present chapter: the Aristotelian Mechanical Problems (attributed to Aristotle himself in the period), and the eighth book of Pappus of Alexandria's *Mathematical Collection* (fourth century AD, but based mainly on the first century *Mechanica* by Heron of Alexandria) (Rose, 1976). Whereas the medieval science of weights had been mainly limited to the principles behind the use of the balance as a measurement instrument, both the Aristotelian text and that of Pappus were devoted to explaining the operation of a diverse array of machines used to move heavy bodies. They shared a reductive program that showed that these diverse operations could be explained by appealing to one underlying model, which explicated the crucial features of the geometrical disposition of the weights and forces (Schiefsky, 2008). Pappus' text explicitly presented the science of mechanics as engaged in constructive problem-solving: once one understood the basic model, one could in principle devise appropriate machines to meet the demands set by any practical challenge (see (Van Dyck, in press-a) for the impact of this constructive mode of reasoning on ideals of natural philosophy in the period). Guidobaldo del Monte's *Liber Mechanicorum* (1577) and Simon Stevin's *Weeghconst* (1586) were probably the most successful and popular theoretical elaborations of the mathematical underpinnings of this basic scheme, which crucially depended on Archimedes' law of the lever (Bertoloni Meli, 2006; Van Dyck, 2006, in press-b). The same decennia also saw the publication of so-called *Theaters of Machines*, spectacular books that displayed seemingly endless variations on mechanical contrivances that could in principle attain different ends (Vérin & Dolza, 2000). The images that made up the bulk of these books gave striking illustrations of the compositional aspect inherent to mechanical practice: one could diversify the machines by using different combinations of basic mechanisms. The same images also illustrated how this could easily lead one to invent complicated contrivances of exceedingly large scales. At the other end of scale, the period also witnessed a marked rise in the quality of miniature mechanisms that was driven by a search for ever finer watches (Landes, 1983).

It is clear that these developments had a profound impact on philosophical thought, and that they form an important part of the background against which we have to understand the rise in the seventeenth century of what became known as the mechanical philosophy (see (Garber, 2013) for the genesis of the category of "mechanical philosophy"). The sixteenth century texts themselves give an important clue about one element that played a crucial role in triggering this development. Some Latin texts from antiquity had linked Archimedes' construction of a rotating sphere imitating the motions of the heavenly spheres with the divine government of the world (most prominently Cicero, but also the third century theologian Lactantius and the fourth century poet Claudian) (Lehoux, 2018). These ancient passages were not very elaborate, but the explicit echo's that recurred in the introductory material of many of the late renaissance books could start to take on a whole different meaning and possible consequences in this new context. There are actually two factors that are important about this context. First, whereas the ancient texts merely singled out Archimedes' singular, quasi-divine ingenuity as responsible for his extra-ordinary feat, Guidobaldo del Monte significantly added that "God willed that in mechanics he [Archimedes] should be a unique ideal which all students of that subject might keep before them as a model for imitation" (Drake & Drabkin,1969, p. 243). Archimedes' sublime inventions were now for the first time embedded within a discourse that linked them to a theoretical foundation that was implied to have been responsible for them, and which was in the process of being further elaborated upon while simultaneously being put into practice (see (Hoyrup, 2019) for the changing image of Archimedes from antiquity to the renaissance). This last point is crucial to properly determine the impact of the reference to divine creation in these texts, and this is the second factor that must be noted. Lactantius had already referred to Archimedes' rotating sphere in the context of a critique of the stoic postulation of active principles within nature: the device that was built by a human designer who remained wholly external to its functioning could possibly offer a model for the relation between motions in nature and the divine creator (Blumenberg, 1960, pp. 72-73). Medieval scholastic philosophers who shared the concern for the transcendence of the divine were led to radically rethink the precise mode of operation of Aristotelian final causes within natural phenomena, which were emptied of all immanent teleologically directed activity. This development clearly shows the pivotal importance of this transcendence for the development of a Christian natural philosophy (Carlin, 2012; Des Chene, 1996). But it is only with the rebirth of mechanics as a prominent theoretical and practical endeavor, that it could for the first time become an option to develop Lactantius' implicit suggestion into a full-scale alternative philosophical program, bringing both factors together. (A similar remark must be made concerning the use of the expression of *machina mundi*, which was also used in antique and medieval texts, but which functions very differently when used in the absence or presence of mechanics as simultaneously a theoretical discourse and spectacular practice (Popplow, 2007).)

Given the successes and general appeal of the science of mechanics, it had become at least not completely implausible to think of natural phenomena as theoretical challenges for mechanical reconstruction in an attempt to make intelligible a wholly passive nature artfully designed by a supremely intelligent creator – an attempt that could further lean on the scale-independence suggested by existing mechanical practice. Many authors could be cited here, but probably the most exemplary case was Robert Boyle, who was always very explicit on the theological underpinnings of the philosophical program that he had baptized as "mechanical philosophy" (Cook, 2001). (There is also an inverse hypothesis to be suggested here. Late antiquity had known a period in Alexandria in which mechanical theory and practice had reached at least the same level of accomplishment as in late renaissance Europe (Pappus' treatise was a late testimony of this Alexandrian tradition). The hypothesis that natural phenomena could be understood on the analogy with mechanical contrivances was also occasionally discussed by ancient authors at least familiar with this context. But it was almost invariably ruled out by pointing to the same qualitative differences in behavior that early modern mechanical philosophers would explicitly overrule by claiming that they could be reduced to a quantitative difference in degree of complexity (Berryman, 2009, chapter 6). This very different reaction might be explained at least in part by the absence of the early modern Christian worldview as providing the impetus to try to stretch the limits of what could be achieved by cleverly disposing passive matter.)

To be clear, authors such as Guidobaldo del Monte and Stevin Stevin were no mechanical philosophers. They conceived of the science of mechanics as having a clearly delineated domain, and showed no sign of interest in the philosophical programs associated with later thinkers who tried to extend the scope of mechanical treatments to all natural phenomena. In the remainder of this chapter I will show that the further impact of their work (and that of their followers) on the mechanical philosophy was not straightforward at all, and that it crucially depended on the question which aspects of their work were considered to be most essential – and thus at least in part constitutive of the new kind of "mechanical explanations". This can help understand some of the tensions and ambiguities that characterized the ideals of a mechanical philosophy and that played an important role in determining its further fate. Needless to say, there were other traditions that were important in shaping these ideals (and creating further tensions), not least the revival of Epicurean and Lucretian atomism, but these fall outside of the scope of the present chapter.

2. Mechanical causes

A traditional image of the mechanical philosophy stresses its focus on efficient causation to the detriment of the other Aristotelian causes. This is not the most evident way to theoretically approach machines, though. Their operation was typically analyzed from a structural perspective that focussed on the mutual dependence between the motions of the component parts. If looked at from the perspective of the Aristotelian causes, this can be thought to have primarily suggested to a drastic reinterpretation of the notion of formal causality (see (Van Dyck, in press-b) for a detailed treatment of Stevin's mechanics against the background of his own reinterpretation of the Aristotelian causes). A machine's behavior was caused by the structural disposition of its components, but these "formal" features could be visually ascertained and geometrically analyzed, in clear contrast to Aristotelian forms. Sixteenth century texts on mechanics could thus provide striking exemplars for a non-Aristotelian way of theoretically analyzing the systematic behavior of complex material objects. This gave rise to a program of what has been called "structural explanation" of phenomena, which characterizes some of the most exciting work in seventeenth century natural philosophy (McMullin, 1978; Gabbey, 1985; Des Chene, 2001; Roux, 2017) – whether this was explicitly carried out under the banner of mechanical philosophy or not. It is important to notice that this did not necessarily imply an ontologically reductive view of the whole of nature. Structural explanations of, e.g., physiological features could be coupled with an independent role for the animal soul (Des Chene, 2005). They did also often rely on structural features that provided crucial boundary conditions for the behavior to be explained, but that were not in turn reduced to a micro-corpuscular level (see (Hutchins, 2015) for Descartes' explanation of the circulation of the blood, which depended on the presence of pores and fibers and assumed the lengthening of the heart). The latter aspect is especially interesting when looked at from the perspective of the science of mechanics, which also depended on certain structural features of machines that needed to be assumed to successfully carry out its explanatory reductive program, such as the presence of inflexible lever-arms that could transmit forces throughout the system. There is accordingly good reason to assume that using the theoretical treatment of machines as central model did not always sit easily with reductive ontological commitments.

Intimately related to the formal perspective inherent to the theoretical treatment of machines was its implicitly teleological character. A machine was a material artifact designed to fulfill well-determined functions. The structural analysis of its operations was always carried out on the supposition that the machine constituted a unified whole that could be characterized by the goals it served. The discourse on machines typically exhibited a double nature, moving from the structural to the teleological. The illustrations of mechanical dispositions in the theaters of machines were always accompanied by short texts that identified the uses to which the machines were to be put, and which were essential to correctly interpret the visual information (Vérin & Dolza, 2000). The mathematical demonstrations of Guidobaldo and Stevin were embedded in texts that helped the reader to see how the mathematical proportions expressed invariant relations underlying all goal-directed practical operations (Van Dyck, in press-b). Transferring the mechanical explanations to natural systems thus carried along a teleological discourse that outlined the boundaries of the structural features identified. Depending on further philosophical and theological commitments, this discourse could be either embraced as testifying to the divine design of nature (Osler, 2001), or it could be obscured by hiding behind the inscrutability of divine intentions, as in Descartes' case, without nevertheless avoiding its implicit role in identifying the features to be structurally explained (see (Des Chene, 2001) for a subtle analysis).

The efficient causes of effects brought about with machines could have varied origins (human or animal power, water, wind, ...), but conceptually they were always assimilated to the equivalent power that could be exerted by the downward tendency of a heavy body – i.e., its weight. This was the only way to guarantee the commensurability of the cause and the effect (the moving of a heavy load), so that they could be expressed through mathematical proportions. (This dependency can be seen *ex negativo* in the problematic case of the force of percussion, where this commensurability was threatened by the impossibility of assimilating the force of the percussing body (e.g., a swinging hammer) to a weight (Roux, 2010).) This shows that the mathematical analysis of machines intrinsically depended on the assumption of weight as an empirical property present in bodies. For mathematicians with Aristotelian leanings (such as Guidobaldo del Monte), this dependency could be seen as expressing the essential distinction between mechanics and physics: the former only treated artificially caused motions that resulted through the mediation of cleverly disposed mechanisms, whereas the latter inquired into the natural cause of bodies' heaviness (Van Dyck, 2006, 2013)). Other mathematicians (such as Stevin or Galileo) simply treated weight as an empirically given feature of material bodies and choose to remain uncommitted about its origin. And it is precisely because such uncommitted attitude was out of the question for Descartes, that the science of mechanics could only play a secondary role in his mechanical philosophy (Gabbey, 1993; Roux, 2004). Weight was one of the primary phenomena to be explained, and could in no way be assumed as an empirical given. Even if structural explanations were central for Descartes' natural philosophical program, they could not remain too closely tied to the mathematical framework developed within the science of mechanics – which meant giving up one of its main points of attraction (but see (Hattab, 2009) for a subtle analysis of its remaining epistemological and metaphysical role). This uneasy relation between the science of mechanics and mechanical philosophy can be seen to result directly from the surprising fact that efficient causality fell almost completely outside the purview of the theoretical treatment of machines.

Material causes were also typically passed over in silence in theoretical treatments of mechanics. The structural relations were considered to be valid regardless of the concrete materials used, which might be seen as suggestive of the homogeneity of natural matter typically (but certainly not unequivocally) stressed by mechanical philosophers. But we must not overlook the relation of the theoretical treatises to material practice, which was characterized by a keen attention for the diversity of matter. The authors of theoretical texts simply assumed that any practitioner was able to use the proper material to construct actual machines that could adequately perform their function, making sure that lever arms were indeed approximately inflexible and that the presence of unavoidable friction and other concomitant impediments could be appropriately managed. As Stevin put it, the task of the practitioner was to take care that "by closer and more painstaking care one may get as near to the perfection of the theory as the purpose of the case requires for the benefit of man" (Stevin, 1961, p. 619) (see (Van Dyck, 2017, in press-b) for further analysis). Matter constituted no independent object for theoretical reflection because mechanics could proceed on the basis of a relatively stable body of practical know-how that ensured the applicability of the theoretical scheme.

This section has assumed the state of the science of mechanics as it was formulated at the end of the sixteenth century. In the next section, we will have a closer look at how conceptual developments internal to the development of the mathematical science of mechanics could introduce further tensions with the ideals of a mechanical philosophy during the seventeenth century.

3 Forms of mechanical intelligibility

3.1 The double role of the law of the lever

The lever occupied a foundational place in the reductive program expounded by Pappus and revived by Guidobaldo, where it actually played a double role. Firstly, Archimedes had given a rigorous demonstration of the mathematical proportion characterizing its conditions for equilibrium. Secondly, all other so-called simple machines could be explained by reducing their operation to that of a combination of cleverly disposed levers. The second role suggested that the lever was privileged because it provided something like basic intelligibility. The lever appeared as a particularly simple device that directly showed how motion can not only be transmitted but also redistributed, since a smaller weight can move a heavier one through the intermediary of a lever; once a more complicated machine was shown to be equivalent to a combination of lever mechanisms one could claim to have understood its operation ((Bertoloni Meli, 2006, 2010) speaks of Guidobaldo's program of "unmasking", and links this with an approach to empirical knowledge that sought understanding through "thinking with objects" – with the lever one such exemplary object). In its first role, the lever was privileged because it allowed one to see how a mathematical description of the operation of the machines in question could be empirically well-founded (see (Van Dyck, 2013) for Guidobaldo's analysis of Archimedes' demonstration, which had a clear empirical grounding on Guidobaldo's reading, contrary to Mach's later criticism). Guidobaldo put equal emphasis on both roles, which were mutually reinforcing for him, but this double role can be seen to be at the source of a tension that would characterize attempts to further extend the scope of mechanics in the seventeenth century.

Stevin's treatment of mechanical operations differed from Guidobaldo's in a number of ways (see (Van Dyck, 2017) for further comments). Most importantly, it included a successful analysis of the inclined plane, which was not directly based on the law of the lever, but on the exclusion of perpetual motion. This argument is often badly misunderstood, but it can be best interpreted as implicitly appealing to what would later be codified as Toricelli's principle: that the centre of gravity of a combined system always takes the lowest (or highest) position allowed by the external constraints to which it is subject (see (Van Dyck, 2017, in press-b) for details on this line of interpretation). Many authors in the seventeenth century would prefer versions of this more abstract principle (often formulated as a compensation principle between weights and distances passed that is sometimes seen as a precursor of the principle of virtual velocities or virtual work) as the proper foundation for the mathematical science of mechanics (Benvenuto, 1991). In the hands of Christiaan Huygens, who called it the "vera mechanicae fundamenta" (Huygens, 1888-1950, Vol. 19, p. 32), it would become a powerful tool for extending the realm of mathematical treatments of mechanical phenomena. Huygens did not only use the compensation principle to offer what he saw as a superior systematization of existing mechanical knowledge, he also appealed to Toricelli's principle to solve a wide array of new problems which included the establishment of the laws of collision (first discovered in 1652, and partially published in 1669) and the determination of the centre of oscillation of a physical pendulum (published in his *Horologium Oscillatorium* from 1673) (Dijksterhuis, 1928; Gabbey, 1980).

3.2 Solving new problems in mechanics

Earlier attempts to find out laws for collision had typically based their approach on an analogy with the law of the lever (this is one of the running themes of (Westfall, 1971)). As mentioned, one could understand the law of the lever as explaining how the downward motion of a lighter body could put a heavier body in motion by interpreting the lever as a device to virtually redistribute and transmit motion. Given the longer lever arm, the lighter body had to move over a proportionally longer distance than the heavy body in the same time, and it is this larger amount of motion that is transmitted to the load. One could similarly try to interpret collision as an encounter between a moving force and a load, where the outcome was determined by a specific way of redistributing the motion of both bodies depending on their respective bulk. The case of Descartes is especially instructive. He confidently stated that his rules characterizing the outcomes of different cases of collision needed no proof "since they are manifest in themselves" (Descartes, 1964, vol. 8, p. 70) – but this direct evidence can only be taken to derive from their implicit link to the law of the lever as a supposedly transparent scheme showing how motion is redistributed and transmitted (see (McLaughlin, 2001) for a clear exposition of the "schematic" dependence of Descartes' rules on the law of the lever). At the same time, Descartes was strikingly indifferent to the empirical implausibility of his rules, which shows how his approach leaned completely on the second role played by the law of the lever in the science of mechanics to the detriment of the first role. (This is of course perfectly consistent with what we noted in the previous section: that for Descartes the law could only have a limited status if seen as a mathematically exact statement concerning concrete, heavy bodies.) This move was completely unacceptable to Huygens, who used his alternative fundamental principle of mechanics to derive mathematical laws of collision that were empirically well-founded. The lever did not occupy any special place in his conception of the science of mechanics, and he pointedly remarked that one should be careful with its seeming intelligibility in dealing with novel phenomena as "plausible axioms are treacherous" (Mormino, 1993, p. 172).

This does raise important questions about the relation between the science of mechanics and mechanical philosophy in the work of Huygens. According to the mechanical philosophy, which Huygens explicitly adopted, collision was seen as the primary mechanism for the transmission of motion in the world, which also gave it a foundational role in the explanation of weight. But Huygens' use of Torricelli's principle implied that his treatment of collision assumed heavy bodies, which seems to render its place within the program of mechanical philosophy problematic (Gabbey, 1980, p. 183). An adequate explanation of how Huygens tried to navigate the precise relation between his mechanical treatment of collision and the philosophical problem of gravity remains a desideratum (see (Chareix, 2006) for the most satisfying account of Huygens' philosophical stance, which correctly puts him at considerable distance from Descartes). At the very least, it is clear that developments within the mathematical science of mechanics could put further pressure on the idea of mechanical philosophy. Relatedly, if one accepted these mathematical demonstrations, this put an extra constraint on natural philosophical speculations concerning the nature of matter, as these now had to be consistent with the results established.

This is not all. Late in the seventeenth century, a controversy arose around Huygens' use of Toricelli's principle in his determination of the centre of oscillation of a physical pendulum, in which the issue of mechanical intelligibility was put centre of stage (the relevant documents are described in (Huygens, 1888-1950, Vol. 18, pp. 457-466), the following summary is based on a more extensive paper that is currently in preparation). A number of authors criticized Huygens' proof because it was seen as not starting from sufficiently "evident" principles. The most sympathetic of these critics, the Marquis de L'Hôpital, opposed Huygens' "incomparably more learned and more geometrical" proof to an alternative that provided "physical and natural reasons" as it was based on an extension of the law of the lever (Huygens, 1888-1950, Vol. 9, pp. 404, 427). His opponents were thus complaining that Huygens' proof was (at best) only mechanical in the sense of providing an empirically grounded mathematical description, but that it lacked in mechanical intelligibility, required for a proper physical treatment in the new sense broadly defined by mechanical philosophy.

There were at least two points that were seen to be responsible for the lack of intelligibility of Huygens' proof. A so-called physical pendulum consists of different weights that are constrained to move together by rigid connections when swinging around an axis. Huygens' determination of this pendulum's centre of oscillation compared the behavior of these weights when they were moving together and after their mutual connections were supposed to be destroyed (Gabbey, 1980). The application of Torricelli's principle put a bounding condition on the relation between the global behavior of the weights before and after their connection as codified by the positions of their respective centers of gravity, but Huygens' critics complained that it did not give any direct insight in how motion was locally transferred from one weight to the others (and vice versa) when they were constrained to move together. Secondly, it was not considered evident that Torricelli's principle could still be applied to bodies that were no longer connected by any physical ties, as had always been the case in the simple machines in which the principle was initially grounded, but which Huygens had abstracted away from (a move that (Bertoloni Meli, 2010) has called "dematerialization"). Interestingly, both criticisms could have been leveled against Huygens' analysis of collision as well, if Huygens would have published his full demonstrations, which he never did.

In his reply, Huygens denied that the law of the lever could provide any true insight in the transmission of motion beyond its initial scope of application, as he had already done when commenting on the case of collision; and he stressed that Torricelli's principle was nothing but the "great natural principle that heavy bodies cannot rise out of themselves" (Huygens, 1888-1950, Vol. 9, pp. 462-463). Huygens thus claimed that the principle had a more general, "natural", scope than its initial limitation to bodies connected to each other might have suggested, and he simultaneously suggested that this global principle could provide physical intelligibility as it was more than a "geometrical" condition. The developments within the science of mechanics had suggested that it might be seen as providing a different form of intelligibility for understanding nature – one that was grounded in what we could call the passivity of matter, exhibited in the impossibility of a perpetual motion machine, and which put mathematically determinate bounds on all possible phenomena in nature through its implications for a system of bodies' centre of gravity.

3.3 Newton's *Principia*: redefining physical systems

These developments can also help us better gauge the place of Isaac Newton's *Philosophiae Naturalis Principia Mathematica* (published in 1687) with respect to ideals of mechanical explanation. A year after its publication, a critical review was published in the *Journal des sçavans* that brings to mind the, roughly contemporaneous, criticisms leveled against Huygens' determination of the centre of oscillation of a physical pendulum. The reviewer called Newton's book "a most perfect mechanics", that contained the most "precise and exact" demonstrations; but that as a "physics" it was a failure (NN, 1688) (Gabbey, 1992). The meaning of mechanics here was clearly that of a merely mathematical science that could offer no true physical insight. Yet Newton obviously did not agree, and to some extent we can see his position as based on similar grounds as the ones that Huygens appealed to in replying to his critics. The third book of the *Principia* analyzed the "System of the World", and the notion of system that Newton proposed must have been recognizable for someone like Huygens. As in the case of Huygens' analyses of collision and the physical pendulum, a physical system was first and foremost identified through the centre of gravity of its component bodies, which remained invariant (in some sense to be further specified by the treatment at hand) throughout all interactions internal to the system. In Newton's case, this was guaranteed by his three laws of motion, which he identified, taking all three together, with a "passive principle" of matter in Query 23 of his *Optice* from 1706 (Query 31 in the 1717 English edition, see (McGuire, 1968)) – and whose validity indeed excluded the possibility of a perpetual motion machine, as Newton had already pointed out in the scholium to the laws of motion in the *Principia*. And, apparently similar to Huygens, Newton saw no problem in extending this notion of a system to bodies that were not necessarily connected through material links. A "system" in this sense is what the "machine" from the science of mechanics had become by the end of the seventeenth century after successive steps of abstraction (first Torricelli introducing his principle as a more abstract characterization of the principle behind the operation of all mechanical machines; then Huygens showing how to use this principle to solve new problems by abstracting away the necessity of rigid connections between the weights; then Newton introducing his three laws as a still more abstract characterization of the underlying forces responsible for this behavior) (see also (Bertoloni Meli, 2010); see (Machamer, McGuire, & Kochiras, 2012) for a somewhat similar line of argument, but one that stresses continuity more than transformation).

Formulated abstractly, Newton's notion of a physical system would not have been foreign to Huygens, but the latter strongly doubted whether there were good grounds to treat the solar system as such a system. The crucial issue at stake was Newton's application of his third law of motion to objects that at no point interacted directly through contact, such as planets and the Sun (Harper, 2002; Stein, 1990). Newton had defined his notion of impressed force at a level of abstraction that did not build the constraint of contact action into its conditions of applicability, which allowed him to apply the third law while remaining agnostic about the question how the force was transmitted between the bodies. In a way, Newton only radicalized Huygens' own move in applying Toricelli's principle beyond its initial domain of application – and, importantly, the main reason for doing this was also similar, as the mathematical bounds that were imposed on the behavior of the objects by the application of the third law allowed Newton to give a more fine-grained mathematical analysis that lead to the law of universal gravity. But in Huygens' case, the bodies making up the system had interacted directly through contact at one point, even if they did not remain in contact. Applying the law without taking this constraint explicitly into account was physically unacceptable for Huygens. At this point, he gave priority to a norm suggested by the mechanical philosophy over one that could be (more controversially) suggested by the mathematical science of mechanics. Yet, it is important to stress that both Huygens and Newton recognized that the matter ultimately might be settled through empirical evidence, since assuming the law of universal gravity led to different predictions concerning the variations in the shape of the earth due to its rotation (Smith, 2008). The option of settling an issue like this by empirical evidence could only be on the table after one had accepted that the possibility of empirically adequate mathematical predictions provided an overriding norm for inquiry into nature, an idea that had been first suggested by the successful treatment of the simple machines, but that was definitely not unequivocally accepted by all mechanical philosophers, as shown by the case of Descartes.

Newton was probably not committed to straightforward action at a distance between objects like the planets and the Sun (see (Ducheyne, 2014; Janiak, 2008; Kochiras, 2011) for recent assessments of the literature on this vexed issue). He seems to have wavered between a few ways of accounting for the transmission of the action, but it is clear that he saw a crucial role for what he called active principles (McGuire, 1968). The passive principle of matter, laid out in the laws of motion of the *Principia,* provided as it were a yardstick with which to measure both the presence and magnitudes of forces in nature that actively put passive matter in motion. Whereas the earlier science of mechanics had to assume weight as an empirical property, Newton had brilliantly seen how to use the principles suggested by this science to include the properties of weight within the theoretical purview of his new science. This overcame one of the central obstacles to build a natural philosophy on a "mechanical" basis, but in Newton's own interpretation it simultaneously reintroduced active principles squarely within the realm of nature.

4 Conclusion

The Antique sources commenting on Archimedes' quasi-divine feat in building an artificial model of the cosmos left open how this was actually achieved, but Claudian explicitly mentioned the presence of "spirits" as movers for this "living work" (see, e.g., the seventeenth century translation quoted in John Wilkins' *Mathematical Magick* (Wilkins, 1648, p. 165)). Newton's machine of the world was similarly dependent on "a certain most subtle spirit" for its operation (in the expression of the *Principia*'s General Scholium – see (Ducheyne, 2014; Kochiras, 2011; McGuire, 1968) for the relation of this spirit to the cause of gravity). This implies that God could not be considered as a mechanic, whose only action would have consisted in cleverly disposing passive matter and infusing an initial amount of motion in the system. Developments within the mathematical science of mechanics itself had strikingly suggested that understanding nature would involve more than directly scaling up and down from our experience with simple machines.

We should not presume that Newton somehow had the last word on this matter, though. Gottfried Wilhelm Leibniz, who had learned the new developments within the science of mechanics directly from Huygens, is the most obvious contrast case (Duchesneau, 1994; Tho, 2017). The mathematical science of mechanics had introduced a strikingly new delineation of what constituted a physical system, but there could be vehement disagreement about how to make this the starting point for more overarching philosophical projects. There did remain radically different ways to reinterpret the philosophical notions of substance and causality such that they could be used to make sense of the world conceived as a system that was created by an all-powerful and intelligent God.

Cross-References

- Action at a Distance in Early Modern Natural Philosophy
- Boyle's Mechanical Philosophy
- Descartes' Mechanical Philosophy
- Gravitation, Laws of
- Gravity as a Property of Matter
- Huygens, Christiaan
- Huygens' Natural Philosophy
- Law of Action and Reaction, the
- Mechanical Philosophy: an Introduction
- Mechanical Philosophy: Reductionism and Foundationalism
- Mechanical Work
- Mechanics and Mixed Mathematics in Early Modern Philosophy: an Introduction
- Mechanism: Mathematical Laws
- Newton and Leibniz

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