EVALUATING JOHN THEOPHILUS DESAGULIERS' NEWTONIANISM:
THE CASE OF WATERWHEEL KNOWLEDGE IN A *COURSE OF*
EXPERIMENTAL PHILOSOPHY

by

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John Theophilus Desaguliers (1683–1744) was a French-born English Huguenot who made his name as a public lecturer in London and a demonstrator at the Royal Society, writing a very popular introduction to Isaac Newton's natural philosophy, the two-volume *A course of experimental philosophy* (1734–1744). This paper looks at the influence of three French natural philosophers, Edme Mariotte (1620–1684), Antoine Parent (1666–1716) and Bernard Forest de Bézouville (1698–1761), on the account of waterwheel functioning in the second volume of that work. The aim of the paper is to show that, although Desaguliers demonstrated a commitment to Newton's work, his own natural philosophical objectives also led him to borrow ideas from natural philosophers outside Newton's direct sphere of influence. To do this I shall give an account of what Desaguliers appropriated from Newton's *Principia*, how it fitted in with his own project and how he also made use of other natural philosophers' theories in his discussion of fluid mechanics. This will hopefully result in a more nuanced conception of Desaguliers' 'Newtonianism' that takes into account the diverse sources and influences in his work.

Keywords: John Theophilus Desaguliers; Isaac Newton; practical mechanics; Edme Mariotte; Antoine Parent; Bernard Forest de Bézouville

INTRODUCTION

Desaguliers was a demonstrator, lecturer and practical mechanic who contributed to the eighteenth-century transformation of artisanal practices into modern, scientifically informed engineering by linking theory and practice in his work. He helped popularize Newton's *Principia* by putting it at the heart of his practical mechanics, and he worked extensively for Newton during his career. He is widely recognized as a 'Newtonian' in the secondary literature.¹ Recently, however, commentators have moved towards a more fine-grained analysis

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¹ See, for example, Larry Stewart, *The rise of public science: rhetoric, technology, and natural philosophy in Newtonian Britain, 1660–1750* (Cambridge University Press, Cambridge, 1992), p. 213; Carlo Poni, 'The craftsman and the good engineer: technical practice

focusing on the reception or appropriation of Newton's work,² as well as studying the ways in which 'Newtonian' natural philosophers made use of many non-Newtonian sources in their scientific work.³ This reflects a refinement of broad categories like 'Newtonian' or 'Cartesian' towards a more nuanced view of natural philosophers and their influences and appropriations.⁴ This will also be the approach adopted in this paper.

Much scholarly work has already been done on the natural philosophy of the Dutch 'Newtonians', such as Willem Jacob's Gravesande (1688–1742), Pieter van Musschenbroek (1692–1761) and Herman Boerhaave (1668–1738), whereas discussion of early British Newtonians has focused more on their religious and political convictions or their social and financial status—avenues of investigation opened by Jacob's and Stewart's pioneering work.⁵ Earlier work on Newton's influence in the eighteenth century also discussed whether or not Newtonianism, and natural philosophy more generally, was a causal factor in the emergence of the Industrial Revolution.⁶ However, this early debate presupposed a dichotomy between theory and practice that has been rejected in the more recent literature.⁷ As we shall see, all the figures discussed in this paper had some familiarity both with the abstractions of mathematized natural philosophy and with the world of practical mechanics.

and theoretical mechanics in J.T. Desaguliers', *Hist. Technol.* **10**, 215–232 (1993) (<https://doi.org/10.1080/07341519308581847>), at p. 217; and Jean-François Baillon, 'Early eighteenth-century Newtonianism: the Huguénot contribution', *Stud. Hist. Philos. Sci. A* **35**, 533–548 (2004) (<https://doi.org/10.1016/j.shpsa.2004.06.006>), at p. 539.

2 Recent trends in the secondary literature are discussed in Scott Mandelbrote, 'Newton and Newtonianism: an introduction', *Stud. Hist. Philos. Sci. A* **35**, 415–425 (2004) (<https://doi.org/10.1016/j.shpsa.2004.06.001>); Mary Domski, 'Introduction: Newton and Newtonianism', *Southern J. Philos.* **50**, 363–69 (2012) (<https://doi.org/10.1111/j.2041-6962.2012.00127.x>); and Jip van Besouw, 'Out of Newton's shadow: an examination of Willem Jacob 's Gravesande's scientific methodology', PhD thesis, Vrije Universiteit Brussel (2017). Simon Schaffer, 'Newtonianism', in *Companion to the history of modern science* (ed. R. C. Olby et al.), pp. 610–626 (Routledge, London, 1990), provides a historical genealogy of the notion of 'Newtonianism'.

3 See Rina Knoeff, 'How Newtonian was Herman Boerhaave?', in *Newton and The Netherlands: how Isaac Newton was fashioned in the Dutch Republic* (ed. Eric Jorink and Ad Maas), pp. 93–112 (Leiden University Press, Amsterdam, 2012); Steffen Ducheyne, 'Different shades of Newton: Herman Boerhaave on Newton *mathematicus*, *philosophus*, and *optico-chemicus*', *Ann. Sci.* **74**, 108–125 (2017) (<https://doi.org/10.1080/00033790.2017.1304574>); and Anne-Lise Rey, 'The experiments of Willem Jacob 's Gravesande: a validation of Leibnizian dynamics against Newton?', in *What does it mean to be an empiricist?* (ed. Siegfried Bodenmann and Anne-Lise Rey), pp. 71–85 (Springer International Publishing, Cham, 2018) (https://doi.org/10.1007/978-3-319-69860-1_5).

4 See Niccolò Guicciardini, review of Elizabethanne Boran and Mordechai Feingold (eds), *Reading Newton in Early Modern Europe* (Brill, Leiden, 2017), *HOPOS: J. Int. Soc. Hist. Philos. Sci.* **8**, 208–209 (2018) (<https://doi.org/10.1086/696347>); and John Bennett Shank, *Before Voltaire: the French origins of 'Newtonian' mechanics, 1680–1715* (University of Chicago Press, Chicago, 2018), pp. 6–12; as well as Ducheyne, *op. cit.* (note 3); and van Besouw, *op. cit.* (note 2).

5 For the religious and political approach, see Margaret C. Jacob, *The Newtonians and the English revolution 1689–1720* (Cornell University Press, Ithaca, 1976); Anita Guerrini, 'The Tory Newtonians: Gregory, Pitcairne, and their circle', *J. Brit. Stud.* **25**, 288–311 (1986) (<https://doi.org/10.1086/385866>); John Friesen, 'Archibald Pitcairne, David Gregory and the Scottish origins of English Tory Newtonianism, 1688–1715', *Hist. Sci.* **41**, 163–191 (2003) (<https://doi.org/10.1177/007327530304100203>); and Baillon, *op. cit.* (note 1). For commercial issues with Newtonianism, see Larry Stewart, 'Public lectures and private patronage in Newtonian England', *Isis* **77**, 47–58 (1986) (<https://doi.org/10.1086/354038>); Stephen Pumfrey, 'Who did the work? Experimental philosophers and public demonstrators in Augustan England', *Brit. J. Hist. Sci.* **28**, 131–156 (1995) (<https://doi.org/10.1017/S0007087400032945>); and Jeffrey R. Wigelsworth, *Selling science in the age of Newton: advertising and the commoditization of knowledge* (Ashgate, Farnham, 2010).

6 The key texts are A. E. Musson and Eric Robinson, *Science and technology in the Industrial Revolution* (Manchester University Press, Manchester, 1969); Rupert A. Hall, 'What did the Industrial Revolution in Britain owe to science?', in *Historical perspectives: studies in English thought and society* (ed. Neil McKendrick), pp. 129–151 (Europa Publications, London, 1974); and A. E. Musson, review of McKendrick, *op. cit.* (this note), *Minerva* **13**, 633–637 (1975).

7 See, for example, Larry Stewart, 'The selling of Newton: science and technology in early eighteenth-century England', *J. Brit. Stud.* **25**, 178–192 (1986) (<https://doi.org/10.1086/385860>); and Joel Mokyr, *The gifts of Athena: historical origins of the knowledge economy* (Princeton University Press, Princeton, 2002).

DESAGULIERS' APPROPRIATION OF NEWTON'S NATURAL PHILOSOPHY

Desaguliers is known for his popular introduction to Newton's natural philosophy, which used experiments, instead of geometrical proofs, to provide an accessible demonstration of Newton's key ideas.⁸ The natural philosophy developed in Newton's *Principia* served as the foundation upon which Desaguliers built his practical mechanics, which was intended to provide the layperson with useful principles for building, and working with, all kinds of simple and complex machines.

Desaguliers wanted to give an account of the basic principles of natural philosophy—which could be reduced to the constitution of matter, forces and the laws of motion—in order to provide a solid foundation for explaining the functioning of simple and complex machines, while at the same time introducing readers to Newton's natural philosophy. This was characteristic of the eighteenth-century view of the *Principia* as being able to provide a rational foundation for mechanics.⁹

The development of Desaguliers' text was progressive: he started with the definitions of matter and force, before going on to give an account of the functioning of simple machines.¹⁰ Some simple machines required a knowledge of the laws of motion in order to be understood, so Desaguliers discussed these laws at length. Another element that was needed to properly understand the functioning of all machines was a knowledge of the rules governing collisions between bodies. At the centre of his appropriation of Newton's work was the account of the laws of motion, which Desaguliers discussed in chapter 5 of the first volume of *A course of experimental philosophy*.¹¹ I use the word 'appropriation' here because Desaguliers was not only teaching Newton's theories but also transforming them by popularizing them and extending them to make sense of machines. To put it simply, Desaguliers used Newton's work to do something different from what Newton himself was doing.

Chapter 5 served not only as an introduction to the laws of motion but also as a survey of a number of central themes from the *Principia*, with Desaguliers focusing in particular on issues that might have been of interest to the layperson, or which were generating debate in the scientific community, such as the shape of the Earth,¹² the explanation of the tides,¹³ the refutation of Cartesian vortices¹⁴ or the observational corroboration (via the measurement of stellar parallax) of the proof of the Earth's motion.¹⁵ It was quite common to find these topics being discussed in lecture courses of the period.¹⁶ Desaguliers intended this 154-page chapter on the laws of motion to cover not only the first book of the *Principia*, but also topics taken from the second and third books, such as resistance phenomena or the motion of the planets.

8 See the preface to John Theophilus Desaguliers, *A course of experimental philosophy*, vol. 1 (John Senex, London, 1734). I shall develop a fuller account of Desaguliers' project later in the paper.

9 Betty Jo Teeter Dobbs and Margaret C. Jacob, *Newton and the culture of Newtonianism* (Humanity Books, Amherst, 1995), p. 73.

10 Desaguliers, *op. cit.* (note 8), ch. 1–3.

11 *Ibid.*, pp. 293–447.

12 *Ibid.*, p. 446.

13 *Ibid.*, p. 369.

14 *Ibid.*, p. 363.

15 *Ibid.*, pp. 384–385.

16 See Stephen D. Snobelen, 'Selling experiment: public experimental lecturing in London, 1705–1728', MA dissertation, University of Victoria, Canada (1995), pp. 103–105, on William Whiston's and Francis Hauksbee Jr's lecture courses.

Although Desaguliers cited the *Principia* often, he also added very interesting passages to Newton's text in order to make Newton's meaning clearer to readers. This approach was not unique to Desaguliers—public lecturers such as William Whiston (1667–1752) and Richard Bentley (1662–1742) had been popularizing Newton since around the turn of the eighteenth century.¹⁷ For example, he quoted in full Newton's explanation of the third law of motion, but added the example in bold below:

If an Horse draws a Stone tied to a Rope, the Horse (if I may so say) will be equally drawn back towards the Stone : For the stretched Rope, by the same Endeavour to relax and unbend it self, will draw the Horse as much towards the Stone, as it does the Stone towards the Horse, and will obstruct the Progress of the one as much as it advances that of the other. **Suppose, for Example, that the Horse is able to overcome an Obstacle equal to 1,000 lb Weight, pressing against it with his Breast; when the Horse draws a Stone of 100 lb Weight, he will then be able to surmount an Obstacle but of 900 lb the Stone taking away from the Force of the Horse as much as to bring it self forward. We must therefore take care rightly to understand the Term as much and distinguish it from as far.**¹⁸

This tells us that Desaguliers sought to make the *Principia* more accessible to lay readers, in addition to providing an overview of Newton's main conclusions. In his discussion of the laws of motion, Desaguliers drew on the *Principia* to give an explanation of the functioning of simple machines such as the hammer, the sling or the bow, which could not be explained in static terms, and Newton had developed his account of these laws enough for Desaguliers to appropriate them wholesale and fairly easily adapt them to his purposes.

By contrast, Desaguliers' discussions of the other simple machines and the rules for collisions required more work, because Newton had only provided very brief remarks on those topics. In the second corollary to the laws of motion, Newton provided a geometric account of the functioning of simple machines, which he reduced to the law of the lever.¹⁹ He concluded that 'from this are easily derived the forces of machines, which are generally composed of wheels, drums, pulleys, levers, stretched strings, and weights, ascending directly or obliquely, and the other mechanical powers'.²⁰

Although he began from Newton's own premise, namely that simple machines all functioned according to the same principle as the lever, Desaguliers nevertheless did the work of actually deriving the forces of these simple machines. Because of the importance of this explanation of simple machines to his project, he treated the subject with rigour, beginning his discussion with a series of suppositions and definitions on which the subsequent analyses would be based.²¹ The functioning of each simple machine was demonstrated via experiments. He concluded the chapter on simple machines by citing the entire second corollary on the laws of motion from the *Principia*, which was intended to serve as a guarantee of the veracity of his experiments.²²

17 Stephen D. Snobelen, 'William Whiston: natural philosopher, prophet, primitive Christian', PhD thesis, University of Cambridge (2000), p. 27.

18 Desaguliers, *op. cit.* (note 8), p. 356; Newton's text is quoted verbatim. See Isaac Newton, *The Principia: mathematical principles of natural philosophy* (trans. I. Bernard Cohen and Anne Whitman) (University of California Press, Berkeley, 1999; first published 1687), p. 417.

19 Newton, *op. cit.* (note 18), p. 418.

20 *Ibid.*, p. 420.

21 See, for example, Desaguliers, *op. cit.* (note 8), p. 94, for the definitions.

22 *Ibid.*, pp. 129–131.

Desaguliers took a similar approach to the rules for collisions in chapter 6 (the first chapter of volume 2 of *A course of experimental philosophy*), developing his own account out of Newton's brief remarks on collisions in the scholium to the laws of motion from the *Principia*.²³ The rules for collisions were important for Desaguliers because they could be used to explain the functioning of almost any compound machine, and once again he attempted to provide a rigorous account, deriving clearly numbered rules, and various corollaries, from experiments on collisions between both soft and hard bodies. However, as with the discussion of simple machines, he relied more heavily on experimental demonstrations, in contrast to Newton's geometrical reasoning (although Newton did also carry out experiments on pendulums). Desaguliers was one of the most accomplished lecturers to give an experimental account of Newton's *Principia*, which was an approach that had been pioneered by Whiston.²⁴

Desaguliers saw his account of simple machines and the rules of collisions as an extension of Newton's laws of motion.²⁵ In contrast to Newton, he did not only want to show the 'wide range and the certainty' of the laws of motion; he also wanted to apply them to practical mechanics, which is something that Newton had explicitly ruled out in the *Principia* ('my purpose here is not to write a treatise on mechanics').²⁶ So, apart from the popular introduction to Newton's natural philosophy in chapter 5, Desaguliers only mobilized a fairly limited amount of material from the *Principia* in his *A course of experimental philosophy*, with much more space being devoted to providing an experimental elaboration of the principles and rules that Newton himself only hinted at.²⁷

DESAGULIERS' NATURAL PHILOSOPHICAL PRACTICES

Although Newton's *Principia* was hugely important for Desaguliers, his own practical, natural philosophical project was very different from Newton's. His role as demonstrator at the Royal Society was a peculiar position which reflected the division of labour along class lines that dominated English society at the time, with the experimental aspects of natural philosophy still associated with lowly manual labour.²⁸ Our modern view of the experimental scientist is incompatible with that of the late seventeenth and early eighteenth centuries, according to which the experimental work was often done by a designated employee—Hooke is the most well-known case of the poorly treated experimentalist.²⁹ As president of the Royal Society, Newton would have been considered just as much Desaguliers' employer and

23 John Theophilus Desaguliers, *A course of experimental philosophy*, vol. 2 (W. Innys, London, 1744), pp. 2–95.

24 Stephen D. Snobelen, 'On reading Isaac Newton's *Principia* in the 18th century', *Endeavour* 22, 159–163 (1998) ([https://doi.org/10.1016/S0160-9327\(98\)00148-X](https://doi.org/10.1016/S0160-9327(98)00148-X)), at p. 161.

25 Desaguliers, *op. cit.* (note 23), p. 9: 'These Rules [governing collisions] are all Corollaries of Sir Isaac Newton's third Law of Motion.'

26 Newton, *op. cit.* (note 18), p. 430.

27 See John L. Greenberg, *The problem of the Earth's shape from Newton to Clairaut* (Cambridge University Press, Cambridge, 1995), p. 13: 'Whether intended or not, the *Principia*'s density, obscurity and various other drawbacks and inconveniences are advantages or strengths, not weaknesses. At least they seem to me to be what motivated other researchers to a great deal of further work in some branches of mechanics.'

28 Pumfrey, *op. cit.* (note 5), provides a thorough account of the status and role of early demonstrators at the Royal Society.

29 Steven Shapin, 'Who was Robert Hooke?', in *Robert Hooke: new studies* (ed. M. Hunter and S. Schaffer), pp. 253–285 (Boydell Press, Woodbridge, 1989), at p. 263.

superior as his scholarly equal, and Desaguliers ‘could still be admonished, as Hooke had been, for the neglect of his duties’.³⁰

Public scientific lectures had been gaining in popularity since about 1700, when a number of lectures were on offer in London.³¹ In 1712 or 1713, Desaguliers joined this growing and competitive market in lectures on experimental philosophy by placing advertisements in the newspapers.³² This teaching role was quite different from an ordinary university lecturer post because it was oriented towards relatively wealthy laypeople who would have come to the courses with quite different expectations: some wanted to cultivate themselves with general scientific knowledge; others wanted more specific technical knowledge to help with commercial enterprises; many merely wanted to be entertained.³³ However, the budding entrepreneurial culture that was taking hold in Britain meant that Desaguliers’ public was increasingly interested in applications of natural philosophy to their various commercial enterprises.³⁴

In both roles—as demonstrator and lecturer—Desaguliers was fulfilling a newly arisen need in eighteenth-century England for experimental work involving complex instruments, and the structured dissemination of natural philosophical knowledge outside the confines of the university. Further, his relatively lowly status required him to seek the patronage of wealthy benefactors, as well as involving him in commercial projects of his own.³⁵ So, although he was engaged in promoting Newton’s work right from the beginning of his career, Desaguliers’ place in the ecosystem of knowledge production and transmission was very different from Newton’s.³⁶ However, the uniqueness of his scientific output went beyond his status in the scientific community.

I will explore three specific topics where Desaguliers’ practical natural philosophy diverged significantly from that of Newton. First, Desaguliers’ explicit aim was not merely to disseminate Newton’s discoveries, but to *popularize* them. Second, he tried bridging the gap between theory and practice by applying theoretical principles to various practical enterprises, particularly in the field of hydraulics. Third, he actively participated in the ongoing *vis viva* controversy.

Newton’s work was well known to be difficult for all but the brightest mathematicians and natural philosophers of the period, which was why popular lecturers like Desaguliers were needed to convey Newton’s ideas to a broader audience—although it has been suggested that Newton did not always agree with this approach.³⁷ Further, Newton limited himself to

30 Pumfrey, *op. cit.* (note 5), p. 144; Stewart, *op. cit.* (note 1), pp. 218–219, recounts how Desaguliers also got into trouble with his patron, the Duke of Chandos, for neglecting his duties.

31 Stewart, *op. cit.* (note 5), p. 48.

32 Audrey Carpenter, *John Theophilus Desaguliers* (Bloomsbury, London, 2011), p. 28, cites an advertisement from 1712; Wigelsworth, *op. cit.* (note 5), mentions an advertisement from 1713.

33 Stewart, *op. cit.* (note 5), p. 48.

34 Simon Schaffer, ‘Machine philosophy: demonstration devices in Georgian mechanics’, *Osiris* 9, 157–182 (1994) (<https://doi.org/10.1086/368735>), at p. 172.

35 Pumfrey, *op. cit.* (note 5), p. 132; Desaguliers’ interest in commercial ventures was crucial, according to Poni, *op. cit.* (note 1), p. 223: ‘Desaguliers concerned himself, then, not only with the technical efficiency of plants but also their cost and profitability.’

36 Desaguliers, *op. cit.* (note 8), p. x: ‘About the Year 1713 I came to settle at London, where I have with great Pleasure seen the Newtonian Philosophy so generally received ... I have had as many Courses as I could possibly attend; the present Course, which I am now engag’d in, being the 121st since I began at Hart-Hall in Oxford, in the Year 1710.’

37 Larry Stewart, ‘The trouble with Newton in the eighteenth century’, in *Newton and Newtonianism: new studies* (ed. J. E. Force and S. Hutton), pp. 221–238 (Kluwer Academic Publishers, Dordrecht, 2004), at p. 229. See also Rob Iliffe, ‘Butter for parsnips: authorship, audience and the incomprehensibility of the *Principia*’, in *Scientific authorship: credit and intellectual property in science* (ed. Mario Biagioli and Peter Galison), pp. 33–66 (Routledge, London, 2003), on Newton’s difficult mathematics.

theoretical mechanics without attempting to extend his natural philosophy to problems in the practical arts as Desaguliers practised them—what we know of today as engineering.³⁸ And Newton famously did not directly participate in the *vis viva* debate, leaving the work of defending a momentum-based account of the collision of bodies to other natural philosophers of the period such as Desaguliers, Colin Maclaurin (1698–1746) and Samuel Clarke (1675–1729).³⁹ Most importantly perhaps, for Desaguliers, was the fact that Newton's discussion of fluid mechanics was very limited in scope and practical applicability, leading Desaguliers to look elsewhere for knowledge relating to his own work in hydraulic engineering.

POPULARIZING NEWTON'S NATURAL PHILOSOPHY

Desaguliers' methodology and practice of natural philosophy was determined not only by his scientific and commercial aims, but also by his didactic objectives. His *A course of experimental philosophy* was written with the explicit aim of making Newton's natural philosophy available to readers with little or no mathematical expertise, via the use of experiments:

As the greatest Part of my Auditors, at whose Desire I have printed this *Course*, are but little vers'd in *Mathematical Sciences*, the *Lectures* are free from difficult *geometrical Demonstrations* and *algebraical Calculations*; and the same thing is often prov'd by several Experiments.⁴⁰

To do this, Desaguliers devised experiments to be carried out on purpose-built machines, or experimental devices, which demonstrated the principles being discussed.

The increasing mathematization of natural philosophy, which was exemplified by Newton's *Principia*, began to alienate the enlightened public who made up the readership of works in natural philosophy and the journals of the scientific academies.⁴¹ The gap between the mathematically educated natural philosopher and the curious amateur widened, presenting an opportunity for public lecturers to narrow this gap by translating mathematical texts into more accessible formats.⁴² These lectures in turn created a market for associated products such as course manuals and scientific instruments—a business model that was pioneered by Whiston and Francis Hauksbee Jr (1687–1763).⁴³

This approach not only favoured experimental demonstration over mathematical demonstration; it also favoured a degree of simplification that broke complex processes down into easily comprehensible parts. This could often, and most easily, be done using examples chosen from the world of practical mechanics. There was a double advantage here, because, as we have seen, a class of entrepreneurial industrialists was emerging

38 Newton, *op. cit.* (note 18), p. 382, put it bluntly: 'we are concerned with natural philosophy rather than manual arts'.

39 See Carolyn Iltis, 'The controversy over living force: Leibniz to d'Alembert', PhD thesis, University of Wisconsin, 1967, which still provides the most in-depth study of the *vis viva* controversy.

40 Desaguliers, *op. cit.* (note 8), p. xi.

41 Yves Gingras, 'What did mathematics do to physics?', *Hist. Sci.* **39**, 383–416 (2001) (<https://doi.org/10.1177/007327530103900401>), p. 392.

42 Desaguliers, *op. cit.* (note 8), pp. xi–xii, referred to 'common Readers', 'young Beginners', and 'those that are not born with a Genius for Mathematicks'.

43 Snobelen, *op. cit.* (note 24), pp. 161–162.

which was keen to put the new sciences to work in the service of profit.⁴⁴ Desaguliers hoped that his lectures would help to protect investors, by preparing them to properly evaluate the claims of fraudulent practical mechanics who were trying to swindle the public by promising impossibly miraculous machines.

As a result of Desaguliers' intention of popularizing Newton's discoveries, and through his use of practical mechanics, *A course of experimental philosophy* came to embody an encyclopaedic empiricism that brought together the latest experimental and theoretical results in natural philosophy, and detailed descriptions of all kinds of machines.⁴⁵ These machines filled the dual role of illustrating the principles laid out in the text and providing examples of practical applications of those principles. This purpose was made especially clear in the preface to the second volume, where Desaguliers presented his aims:

It is owing to a great Majority of the Subscribers that I have alter'd my first Design, and made my second Volume what it is now. As my curious Friends know, that I have made the Consideration of Water-Engines my Study for many Years; they desir'd that I would fully treat upon that Subject by Rules deduc'd from my Hydrostatical and Pneumatical Lectures, and give a Description of a sufficient number of Engines to make the Practice of so useful an Art easy.⁴⁶

Desaguliers wanted to transmit his own knowledge of hydraulics and practical fluid mechanics to laypeople, and he underlined the utility of such knowledge, especially when it came to discerning between real improvements in waterworks and the exaggerated claims of unscrupulous artisans.

This approach was representative of what Joel Mokyr calls the industrial enlightenment, a period when scientific and technological innovation was channelled into commercial enterprises of all kinds.⁴⁷ Entrepreneurs and industrialists realized that manufacturing processes could be optimized through the judicious application of certain principles of natural philosophy. In reality, the industrial enlightenment was a matter not merely of 'application' of theory to practice, but of the gradual adoption of a scientific approach and vocabulary by industry, and the concurrent opening up of spaces, such as the workshop, where practically oriented theory and theory-inspired practice could develop a mutually beneficial relationship.⁴⁸

But these entrepreneurs and industrialists were incapable of engaging directly with a difficult work like Newton's *Principia*, and, even if they could understand it, they would have struggled to see how it could be relevant to the production of commodities.

44 Margaret C. Jacob and Larry Stewart, *Practical matter: Newton's science in the service of industry and empire 1687–1851* (Harvard University Press, Cambridge, MA, 2004), p. 93, describe this situation well: 'Nevertheless, despite Newton's reservations, there were two important aspects of the fashion in public lecturing that gathered momentum throughout the century: first, the emergence of a rapidly expanding public audience for experiments; and second, the demonstration of mechanical contrivances, from simple machines to steam engines, based on Newton's notions of attraction, repulsion, inertia, momentum, action, and reaction.'

45 This approach bears a close resemblance to the method of 'experimental history' discussed in Ursula Klein and Wolfgang Lefèvre, *Materials in eighteenth-century science: a historical ontology* (MIT Press, Cambridge, MA, 2007), pp. 21–26.

46 Desaguliers, *op. cit.* (note 23), p. vi.

47 Joel Mokyr, *The enlightened economy: Britain and the Industrial Revolution 1700–1850* (Penguin, London, 2009), pp. 139–140: 'If the paradigmatic book of the Scientific Revolution was Newton's *Principia*, that of the Industrial Enlightenment was the great French *Encyclopédie*, full of detailed illustrations of technical matters ... In the late seventeenth and eighteenth centuries, Enlightenment culture glorified and codified the arts and crafts of artisans, farmers, chemists, instrument makers, surveyors, navigators, and others as never before.'

48 See Margaret C. Jacob, 'Mechanical science on the factory floor: the early Industrial Revolution in Leeds', *Hist. Sci.* 45, 197–221 (2007) (<https://doi.org/10.1177/007327530704500206>).

Desaguliers' *A course of experimental philosophy* was intended to make Newton's work accessible to the practically minded entrepreneur and industrialist.⁴⁹ He simplified and demonstrated the basic principles of natural philosophy, and he showed, using a wide selection of examples from practical mechanics, how these principles could explain the functioning of *all* machines. As non-specialists were drawn to mechanics, the content of lecture courses and manuals was increasingly focused on practical applications of natural philosophy, which in turn led to even more public interest.

PRACTICAL HYDRAULICS

Desaguliers had been practising his trade as a public lecturer in London since 1712, and he had filled the role of demonstrator at the Royal Society since 1713, but around 1716–1718 he began to apply his own brand of mechanical philosophy to practical concerns, particularly in the field of practical hydraulics. Attempting to apply Newton's mechanics to practical matters became one of the hallmarks of his research throughout his career: in *A course of experimental philosophy*, which was published near the end of his life (1734–1744), he used Newton's natural philosophy as the cornerstone of a practical theory of machines, which could then be used to verify the claims of practical mechanics who had a tendency to exaggerate the advantage to be gained from using their services.⁵⁰

Of special interest to him during this period (from 1718) was the behaviour of spouting water, because he had been commissioned to build fountains and water features in the gardens of his patron, James Brydges, the 1st Duke of Chandos.⁵¹ At the same time, Desaguliers translated Edme Mariotte's *Traité du mouvement des eaux et des autres corps fluides* (1686) into English. In the supplementary notes to his translation of Mariotte's book, he provided a brief account of some experiments on the friction of water in tubes, carried out in the gardens of the Chandos estate with the help of John Lowthorp (1659–1724), the estate librarian.⁵² Even in this early period of his career, Desaguliers was concerned with the practical applications of theory in the real world, taking Mariotte to task for underestimating the amount of friction in pipes carrying water—a common error caused by excessively simplified models.⁵³ Desaguliers discussed these experiments again years later, both in a report in the *Philosophical Transactions of the Royal Society*, and in the second volume of his *A course of experimental philosophy*, arguing—as a result of further experiments carried out in 1726—that some of the lost motion could be put down to air in the pipes.⁵⁴

This explanation grew out of Desaguliers' effort to help improve the efficiency of Edinburgh's aqueducts in 1721.⁵⁵ The five-kilometre-long pipe supplying Edinburgh with

49 Stewart, *op. cit.* (note 1), p. 220: 'If there was a gap between theory and practice, Desaguliers bridged it.' Dobbs and Jacob, *op. cit.* (note 9), pp. 73–74, also emphasize Desaguliers' practical bent.

50 Desaguliers, *op. cit.* (note 8), p. 182: 'What I have said hitherto in the Three first Lectures and their Notes, is sufficient for explaining the Principles of Mechanicks (strictly so call'd) enough to set People to work, who have a Genius for Practical Arts.'

51 Stewart, *op. cit.* (note 1), p. 234.

52 Edme Mariotte, *The Motion of Water and Other Fluids: Being a Treatise of Hydrostaticks* (trans. John Theophilus Desaguliers) (Senex and Taylor, London, 1718), p. 289. See Stewart, *op. cit.* (note 1), p. 234. Carpenter, *op. cit.* (note 32), p. 134, provides some historical background on these experiments.

53 Mariotte, *op. cit.* (note 52), p. 289.

54 Desaguliers, *op. cit.* (note 23), p. 124; Stewart, *op. cit.* (note 1), p. 235.

55 Stewart, *op. cit.* (note 1), p. 235.

water covered undulating terrain, meaning that there were peaks and troughs in the pipe where air could accumulate and block the flow of water. Desaguliers remedied this by removing air locks from the system and contriving a system of valves or cocks—an apparatus that he called a ‘Jack in the Box’—to periodically release the blocked air that stopped the water from flowing properly.⁵⁶ Two historians of civil engineering have established that Desaguliers relied on Mariotte’s calculations of water flow to determine the flow rate of the pipes.⁵⁷

During the early 1720s, Desaguliers carried out research on water-raising machines, hosting a prototype in his house with which he was able to experiment and, more importantly, which became a demonstration piece that allowed the public to see for themselves how the new water technology worked.⁵⁸ He even thought that this instrument was worthy of an article in the *Philosophical Transactions*, where he discussed its innovative system for sealing the pistons using quicksilver (mercury).⁵⁹ In promoting this water-raising machine, Desaguliers came up against stiff competition from other practical mechanics and promoters such as William Harding and John Orlebar, who also designed, or sometimes merely promised, ever more efficient machines to move water.⁶⁰ Water-raising machines were not only useful for raising water out of mines; they could also work in private gardens, or provide cities with water without requiring a downhill route from the source of that water (as was the case in Edinburgh).

Desaguliers also got involved in engineering projects in London, including a scheme, developed by the York Buildings Company and supported by the Duke of Chandos, to supply water from the Thames to nearby residential areas via a large reservoir into which the water would be pumped. And, at around the same period, he was exploring the possibility of diverting water from Uxbridge into London on behalf of a rival outfit, the New River Company; this was exactly the kind of project that would benefit from water-raising technology.⁶¹

Thus it is clear that Desaguliers was very interested in the practical hydraulics of his day, and his familiarity with specialized research, such as Mariotte’s hydraulics, in addition to a solid grounding in the principles of mechanics, was clearly useful for these projects—as is suggested, for example, by the reports of his experiments on spouting water, which he published in the appendix of his translation of Mariotte’s treatise.⁶²

Desaguliers’ contact with the commercial world made him aware of the dangers posed by dishonest mechanics. Anyone could invent a machine for raising water, make extravagant claims about the machine and convince ignorant investors to waste their money.⁶³ During the same period that he was researching water-raising machines, he published a critical

56 Desaguliers, *op. cit.* (note 23), p. 126; John Theophilus Desaguliers, ‘An account of several experiments concerning the running of water in pipes’, *Phil. Trans. R. Soc. Lond.* **34**, 77–82 (1727).

57 E. H. Winant and E. L. Kemp, ‘Edinburgh’s first water supply: the Comiston Aqueduct, 1675–1721’, *P. I. Civil Eng. Civ. Engng* **120**, 119–124 (1997) (<https://doi.org/10.1680/jcien.1997.29790>), at p. 123.

58 Wigelsworth, *op. cit.* (note 5), p. 105.

59 John Theophilus Desaguliers, ‘A description of an engine to raise water by the help of quicksilver invented by the late Mr. Joshua Haskins, and improv’d by J. T. Desaguliers LL. D. R. S. S.’, *Phil. Trans. R. Soc. Lond.* **32**, 5–15 (1723) (<https://doi.org/10.1098/rstl.1722.0003>).

60 Wigelsworth, *op. cit.* (note 5), p. 105.

61 *Ibid.* See also Stewart, *op. cit.* (note 1), p. 350. Stewart discusses this whole episode in detail.

62 Mariotte, *op. cit.* (note 52), p. 289.

63 Desaguliers had recently been involved in a dispute with two booksellers, which might have provoked some of his scepticism about professional motives. See Jeffrey R. Wigelsworth, ‘Competing to popularize Newtonian philosophy: John Theophilus Desaguliers and the preservation of reputation’, *Isis* **94**, 435–455 (2003) (<https://doi.org/10.1086/380653>).

article about a perpetual motion machine built in Hesse-Kassel by the German inventor Johann Bessler (1680–1745), also known as Orffyreus.⁶⁴ The inventor claimed that this machine could lift a bucket of water without any loss of movement. Although the affair ended in ignominy for those who believed Orffyreus' claims, such as 's Gravesande, it did spur natural philosophers to begin thinking more carefully about how to determine the quantity of motion in bodies, leading 's Gravesande to carry out the experiments on bodies falling into clay that embroiled him in the *vis viva* controversy.⁶⁵

THE *VIS VIVA* CONTROVERSY

Desaguliers was particularly interested in issues in natural philosophy that were the subject of scholarly debate, and the debate which most interested him was the *vis viva* controversy. In the second volume of *A course of experimental philosophy*, he provided a detailed overview of his position in this controversy, which he initially entered into in 1722 to defend what was widely considered to be the 'Newtonian' position, according to which motive force was measured by momentum, not *vis viva*.⁶⁶

The controversy began in 1686, when Gottfried Leibniz (1646–1716) challenged René Descartes' (1596–1650) conception of motive force as the product of weight and speed (what we now call mass and velocity—the basic physical notions evolved as the controversy wore on).⁶⁷ Leibniz subsequently proposed that motive force was actually measured by the product of mass and velocity squared, a quantity which was later transformed into the modern notion of kinetic energy.⁶⁸

The controversy attracted the attention of many of the most important natural philosophers of the period, and no consensus was achieved between the 'old' and 'new' opinions, as they were known, until the nineteenth century. After the waning of Descartes' influence on natural philosophy, 'Newtonians' like Desaguliers took up the defence of *mv*.⁶⁹ They were opposed by continental mathematicians and natural philosophers—mainly from Switzerland and The Netherlands—including Jacob Bernoulli (1654–1705), Johann Bernoulli (1667–1748) and Daniel Bernoulli (1700–1782), and 's Gravesande and van Musschenbroek, who came out in favour of *mv*².

A central point of contention of the controversy was the way in which the moving force of a body should be measured: specifically, whether this measure was proportional to distance

64 John Theophilus Desaguliers, 'Remarks on some attempts made towards a perpetual motion', *Phil. Trans. R. Soc. Lond.* **31**, 234–239 (1721). See Simon Schaffer, 'The show that never ends: perpetual motion in the early eighteenth century', *Brit. J. Hist. Sci.* **28**, 157–189 (1995) (<https://doi.org/10.1017/S0007087400032957>), for an account of this affair.

65 Tiemen Cocquyt, 'Failure, fraud and instrument cabinets: academic involvement in the eighteenth-century Dutch water crisis', in *Cabinets of experimental philosophy in eighteenth-century Europe* (ed. Jim Bennett and Sofia Talas), pp. 79–97 (Brill, Leiden, 2013), at p. 83.

66 John Theophilus Desaguliers, 'An account of some experiments made to prove, that the force of moving bodies is proportionable to their velocities', *Phil. Trans. R. Soc. Lond.* **32**, 269–279 (1722).

67 Gottfried Wilhelm Leibniz, 'Brevis demonstratio erroris memorabilis Cartesii', *Nova Acta Erud.* **5**, 161–163 (1686). For a comprehensive discussion of the controversy, see Iltis, *op. cit.* (note 39); and for a more recent discussion, see George E. Smith, 'The *vis viva* dispute: a controversy at the dawn of dynamics', *Phys. Today* **59**, 31–36 (2006).

68 Gottfried Wilhelm Leibniz, 'Specimen dynamicum', in *Philosophical papers and letters*, vol. 2 (ed. L. E. Loemker), pp. 435–452 (Springer Academic Publishers, Dordrecht, 1989).

69 Newton, *op. cit.* (note 18), p. 404. See also Carolyn Iltis, 'The Leibnizian–Newtonian debates: natural philosophy and social psychology', *Brit. J. Hist. Sci.* **6**, 343–377 (1973), at p. 343, for a discussion of Leibnizians and Newtonians understood as social groups, in the context of the controversy.

(*vis viva*) or time (momentum). The focus here was on determining whether the force of a body moving through a resisting medium should be calculated from the *distance it moved* through that medium before stopping, or from the *time it took* to stop, and different experiments were devised to test these alternatives.

's Gravesande and Giovanni Poleni (1683–1761) had carried out experiments dropping brass balls into clay, and they determined that the depth of the impressions left by the balls varied with their *vis viva* (mv^2), thus proving that *vis viva* was the correct measure of motive force (because the depths of the impressions seemed to be an intuitive way to compare motive forces).⁷⁰ Desaguliers set up a counter-experiment—devised by Newton himself—which involved dropping balls through a series of thin membranes.⁷¹ He used this experiment to show that the *time taken* to make the impression must be taken into account. So, although a faster moving ball might break more membranes, this was not because it had more motive force, but because, according to Desaguliers, 'each Diaphragm has but half the time to resist the Ball, that falls with a double velocity'.⁷² In other words, once time is taken into account, it can be seen that the motive force of a body is equal to the momentum of that body, not its *vis viva*. This became an issue for machines like waterwheels, when it became necessary to decide whether to calculate industrial efficiency in terms of the time taken to carry out an action or the distance covered by that action.

Another crucial issue was whether motive force was always conserved, or whether it could be lost, possibly implying that the Universe was running down like a clock (this would have been problematic for Leibniz).⁷³ Momentum appeared always to be conserved, but *vis viva* was lost in soft-body collisions. This looked like a weakness of the *vis viva* theory, but it came to be seen as a strength later in the eighteenth century, when it was used to explain the inefficiency of certain kinds of waterwheels.⁷⁴

MARIOTTE, PARENT AND BÉLIDOR: THE CASE OF THE WATERWHEEL

As we have seen, Desaguliers developed his own intellectual objectives, focused on popular lecturing, experimental demonstrations and practical mechanics. In the second part of this paper, I shall look more closely at the ways in which he mobilized diverse sources to achieve these objectives. Concretely, I aim to show how he appropriated the work of Parent, Mariotte and Bélidor in his study of waterwheels, focusing on the specific uses to which he put these three French natural philosophers, and how particular aspects of their work responded to specific needs in Desaguliers' discussion of waterwheels in *A course of experimental philosophy*.

70 Willem Jacob 's Gravesande, *Essai d'une nouvelle théorie sur le choc des corps, fondée sur l'expérience* (T. Johnson, The Hague, 1722), pp. 21–23, provides an account of the experiments. See also Giovanni Poleni, *De castellis per quae derivantur fluviorum aquae habentibus latera convergentia* (Joseph Comin, Padua, 1718).

71 The description of this experiment can be found in the postscript to Henry Pemberton, 'A letter to Dr. Mead concerning an experiment, whereby it has been attempted to shew the falsity of the common opinion, in relation to the force of bodies in motion', *Phil. Trans. R. Soc. Lond.* **32**, 57–68 (1723), at pp. 67–68.

72 John Theophilus Desaguliers, 'Animadversions upon some experiments relating to the force of moving bodies; with two new experiments on the same subject', *Phil. Trans. R. Soc. Lond.* **32**, 285–290 (1723), at p. 288.

73 Iltis, *op. cit.* (note 69), p. 353.

74 This is discussed at length in Andrew M. A. Morris, 'John Smeaton and the *vis viva* controversy: measuring waterwheel efficiency and the influence of industry on practical mechanics in Britain 1759–1808', *Hist. Sci.* **56**, 196–223 (2018) (<https://doi.org/10.1177/0073275317745455>).

As a preface to his discussion of practical hydraulics, Desaguliers described the qualities of the natural philosophers who would like to apply themselves to hydraulics: '[T]here are more Qualifications requir'd for Water-Works than People commonly imagine; and yet there are perhaps more Quacks in this Art than any other except one.'⁷⁵ He did not specify which art had more quacks than waterworks—although he was almost certainly referring to medicine⁷⁶—but he did make it clear that the presence of quacks, and fraud more generally, was an issue that motivated him to write and teach on practical mechanics. This was why determining an upper limit for the possible efficiency of a waterwheel was very important to him.

Continuing his summary of the qualities required for working in hydraulics, Desaguliers added:

He that would meddle with Water-Works, should know so much of Mathematicks, as to understand mechanical Principles; be so much a Philosopher, as to be skill'd in Hydrostaticks and Pneumaticks; and be so good a practical Mechanick, as to know the Nature of Materials, and how to put them together in the best manner.⁷⁷

These three figures of the mathematician, the philosopher and the practical mechanic correspond strikingly well to Parent, Mariotte and Bélidor respectively. In the rest of this paper I shall look at these natural philosophers through the prism of Desaguliers' description of the characteristics required to be a skilled practitioner in the art of waterworks. We shall see that Parent, Mariotte and Bélidor responded to needs specific to Desaguliers' own approach to practical hydraulics, in a way that Newton did not.

In Desaguliers' classificatory schema, the mathematician was someone who practised mixed mathematics, applying mathematical techniques to the understanding of water behaviour.⁷⁸ The philosopher was an *experimental* philosopher, who not only carried out experiments but also cultivated a flair for demonstration devices, which could serve to educate and entertain.⁷⁹ And the practical mechanic was to be understood as an artisan who excelled in all types of construction projects and who would put the theory into practice. For Desaguliers, anyone who wanted to embark on waterworks engineering projects would need to embody all these characteristics.

THE MATHEMATICIAN: ANTOINE PARENT

Parent was a French natural philosopher and mathematician who achieved his results on waterwheel efficiency using the recently invented infinitesimal calculus, which had been made available in France thanks to Guillaume de l'Hôpital (1661–1704). L'Hôpital wrote the *Analyse des infiniment petits pour l'intelligence des lignes courbes* (1696) following a

⁷⁵ Desaguliers, *op. cit.* (note 23), p. 414.

⁷⁶ See, for example, Roy Porter, *Quacks: fakery and charlatans in English medicine* (Tempus, Stroud, 2003).

⁷⁷ Desaguliers, *op. cit.* (note 23), p. 414.

⁷⁸ See Peter Dear, 'Mixed mathematics', in *Wrestling with nature: from omens to science* (ed. Peter Harrison, Ronald L. Numbers and Michael H. Shank), pp. 149–172 (University of Chicago Press, Chicago, 2011).

⁷⁹ John L. Heilbron, 'Natural philosophy', in Harrison *et al.*, *op. cit.* (note 78), pp. 173–200, at p. 177; Peter R. Anstey, 'Experimental versus speculative natural philosophy', in *The science of nature in the seventeenth century* (ed. Peter R. Anstey and John A. Schuster), pp. 215–242 (Springer-Verlag, Berlin and Heidelberg, 2005), provides some background to the preference for experiment in Britain.

period of instruction by Johann Bernoulli, who had picked up the calculus from Leibniz himself.⁸⁰ Using the calculus, Parent determined the maximum efficiency of the waterwheel to be when the velocity of the wheel and the velocity of the water were in a ratio of one to three, so that the velocity of the turning waterwheel should be one-third of the velocity of the water propelling the wheel.⁸¹ His conclusions were compatible with Newton's own work because he provided a momentum-based account of waterwheel functioning. So, although Parent, as well as Mariotte and Bélidor, were not influenced by Newton, their work was not *incompatible* with that of Newton.

Efficiency in this context can be contrasted with absolute output. A poorly made waterwheel on a large river will have a greater output than a well-made waterwheel on a smaller stream, but the well-made waterwheel will be more efficient, because it can harness more of the power made available by the source (in this case the flowing water). In other words, calculating efficiency involved a comparison between input and output, whereas looking at output alone did not.

Parent made some assumptions which allowed him to simplify his mathematical model: he assumed that friction was negligible, that the water struck the waterwheel perpendicular to the paddles and that only one paddle was in the water at a time.⁸² These assumptions allowed him to provide a workable model of waterwheel functioning, but they meant that his analysis lacked applicability to real-world waterwheels.

The simplicity of Parent's model is further brought out by his schematic waterwheel diagram (figure 1), which provided an illustration for his mathematics. As we can see, the water flows from left to right, turning the wheel on the left anticlockwise. By means of the cogs, the wheel on the right is turned clockwise, raising the weight at P by coiling the cord around the axle N. Parent depicted the variability of the weight P—represented as three different weights—which determined whether the waterwheel would turn or not: P was the weight that held the waterwheel at rest (i.e. that held the flow of the river in equilibrium); p was the smaller weight that corresponded to the optimum output of the waterwheel, and determining p was the aim of Parent's paper. As the weight of P is reduced to p , the wheel turns faster and faster but at the cost of raising an increasingly small weight; the challenge was to find the optimum value p which would raise the most weight in the least time. The detailed labelling of the diagram allowed Parent to discuss altering the size and gearing of the wheel to increase its efficiency. The gear mechanism and the different heights of the weights also tell us that Parent was working with a dynamic model that measured the efficiency of the waterwheel in motion.

Desaguliers turned to Parent's treatise for a very specific reason: Parent had worked out the ratio between the velocity of the waterwheel and the flowing water that would maximize the wheel's efficiency. This particular result resonated with Desaguliers' practical concerns, not because it paved the way for improvements to waterwheel functioning, but because it provided an upper limit for the efficiency that could be expected of a complex machine:

80 Guillaume de l'Hôpital, *Analyse des infiniment petits pour l'intelligence des lignes courbes* (L'Imprimerie Royale, Paris, 1696). See also A. Rupert Hall, *Philosophers at war: the quarrel between Newton and Leibniz* (Cambridge University Press, Cambridge, 1980), p. 81.

81 Antoine Parent, 'Sur la plus grande perfection possible des machines', in *Histoire de l'Académie Royale des Sciences*, pp. 323–338 (Gabriel Martin, Jean-Bapt. Coignard and Hippolyte-Louis Guérin, Paris, 1745; first published 1704). See Danilo Capecchi, 'Over and undershot waterwheels in the 18th century. Science-technology controversy', *Adv. Hist. Stud.* 2, 131–139 (2013) (<https://doi.org/10.4236/ahs.2013.23017>), at pp. 132–33, where there is a full account of Parent's calculations.

82 Capecchi, *op. cit.* (note 81), p. 132.

Figure 1. Parent's waterwheel diagram. Antoine Parent, 'Sur la plus grande perfection possible des machines', in *Histoire de l'Académie Royale des Sciences*, pp. 323–338 (Gabriel Martin, Jean-Baptiste Coignard and Hippolyte-Louis Guérin, Paris, 1745; first published 1704), at p. 326.

But to prevent any Person from being impos'd upon for the future, in relation to Mills or Water-Works, I shall, in this Chapter, shew the *Maximum* in these cases; that is, shew how much Water can be raised to a certain Height in a certain Time, by such a Stream of Water striking against a Wheel, or by a certain number of Men or Horses. Then People may be assur'd, that whoever pretends to have found out an Engine that shall do more than in such Proportions, either deceives himself, or would deceive others.⁸³

As we can see here, theoretical considerations were sometimes co-opted by broader social concerns.⁸⁴ Indeed, the development of measurements such as horsepower was closely bound up with fraudulent claims about mechanical efficiency, and the empty promise of profits to be made from miraculous machines.⁸⁵ The growing field of practical mechanics needed to find a way to deal with 'knavish Workmen', 'Quacks', 'ignorant Pretenders', and 'Perpetual-Motion men', who used the fashion for mechanical improvements as a way to

⁸³ Desaguliers, *op. cit.* (note 23), p. 416.

⁸⁴ *Ibid.*, pp. 413–416. See Antoine Picon, 'The engineer as judge: engineering analysis and political economy in eighteenth century France', *Eng. Stud.* 1, 19–34 (2009) (<https://doi.org/10.1080/19378620902725174>), on eighteenth-century engineers as impartial judges of public interest.

⁸⁵ See Larry Stewart, 'Measure for measure: projectors and the manufacture of Enlightenment, 1770–1820', in *The age of projects* (ed. Maximilian E. Novak), pp. 370–390 (University of Toronto Press, Toronto, 2008).

exploit investors, according to Desaguliers.⁸⁶ His solution was simple: to determine carefully the greatest possible efficiency that could be hoped for in a machine, and Parent had already provided the maximum for the waterwheel.

Desaguliers appropriated Parent's work on waterwheels because it applied the recently invented calculus to the question of waterwheel efficiency—something that Newton himself did not do—and it provided a handy maximum limit for Desaguliers to teach so that those attending his courses could avoid being exploited by unscrupulous engineers, which, as we have seen, he viewed as a pressing problem. By demonstrating the usefulness of such mathematical techniques, he hoped to initiate the layperson into the importance of these techniques, as well as provide practical guidelines on the kind of efficiency to expect from a waterwheel.

Parent's calculation of maximum efficiency also provided a measurement that could be tested using a demonstration device (figure 2). A physician called Robert Barker suggested his own invention, what has become known as Barker's mill (also known as Segner's mill or Parent's mill), to test Parent's claim that the maximum efficiency of a waterwheel was when the wheel turned at one-third of the speed of the water propelling it. Desaguliers provided a description of the device, as well as remarks about how to use a full-scale version in areas where the water source was small.⁸⁷ Interestingly, Barker's mill also provided a good illustration of Newton's third law, which was the principle that explained why it turned. Desaguliers did not provide any information about actually testing Parent's hypothesis, however, possibly because the instrument was not suitable for that task.⁸⁸

THE PHILOSOPHER: EDMÉ MARIOTTE

Mariotte was a French natural philosopher renowned for taking an experimental approach to natural philosophy.⁸⁹ At the end of the 1660s, he and Christiaan Huygens (1629–1695) carried out experiments on the force of spouting water, very likely working together at the Paris Academy of Sciences in 1669.⁹⁰ Mariotte aimed to reduce fluid impacts to impacts between solids, which is why he looked at collisions between spouting water and plates as examples of soft-body collisions.⁹¹

This was an influential approach that allowed later natural philosophers to view fluid mechanics as the instantiation of the rules for collisions between solids.⁹² Mariotte was well placed to make this connection because he wrote a treatise on collisions in 1673 that

86 According to Schaffer, *op. cit.* (note 64), p. 184, Desaguliers 'was an acknowledged expert in exposing the deceit involved in foreign claims to extraordinary work'.

87 Desaguliers, *op. cit.* (note 23), pp. 459–461.

88 According to Terry S. Reynolds, *Stronger than a hundred men: a history of the vertical waterwheel* (Johns Hopkins University Press, Baltimore, 1983), p. 216, 'It would not have provided experimental proof of Parent's theory.'

89 Sophie Roux, *L'essai de logique de Mariotte: archéologie des idées d'un savant ordinaire* (Classiques Garnier, Paris, 2011), p. 7: 'Mariotte appears ... as the father of experimental method in France.' See also Hunter Rouse and Simon Ince, *History of hydraulics* (Dover, New York, 1963), p. 63; and René Dugas, *A history of mechanics* (Dover, New York, 1988), p. 199.

90 Julián Simón Calero, *The genesis of fluid mechanics, 1640–1780* (Springer, Dordrecht, 2007), pp. 58–64; Reynolds, *op. cit.* (note 88), p. 203.

91 Calero, *op. cit.* (note 90), p. 13: 'Mariotte interprets the phenomena as percussions, and in this sense this appraisal is the first appearance of the "impact theory".'

92 According to Michel Blay, 'Recherches sur les forces exercées par les fluides en mouvement à l'Académie Royale des Sciences 1668–1669', in *Mariotte, savant et philosophe (1684): analyse d'une renommée* (ed. Pierre Costabel), pp. 91–124 (Vrin, Paris, 1986), at p. 109, Mariotte made 'suggestive' use of mechanical models.

Figure 2. Barker's mill, intended by Desaguliers to test Parent's estimation of maximum waterwheel efficiency. John Theophilus Desaguliers, *A course of experimental philosophy*, vol. 2 (W. Innys, London, 1744), p. 459.

Figure 3. Mariotte's apparatus to measure the force of spouting water. Edme Mariotte, *Traité du mouvement des eaux et des autres corps fluides divisé en v. parties* (Estienne Michallet, Paris, 1686), p. 197.

was mentioned approvingly by Newton in the *Principia*.⁹³ This approach also benefited from the structural similarity between spouting water—which involved a fall and subsequent return to the original height of a given quantity of water (friction notwithstanding)—and the swing of a pendulum. This was fully exploited by Daniel and Johann Bernoulli in their works on hydrodynamics.⁹⁴ These discussions were also related to the *vis viva* controversy, because *vis viva* was very useful for explaining the relationship between a body rising and falling under the effect of gravity.

Using the conceptual framework of the spouting water apparatus (figure 3), Mariotte was able to directly interpret the behaviour of fully functioning waterwheels as a collision between two solids. This he did by conceptually transforming the static equilibrium established by the water falling from M and spouting onto the plate at N into a dynamic collision, by equating the *pressure* of the spouting water on the plate to the *weight* at Q held by that plate. By means of this schema, Mariotte was able to make sense of his observations of waterwheels on the Seine in Paris. Although the Marly waterworks had been completed just before the publication of his treatise, Mariotte's research was better suited to the more standard waterwheels on the Seine, which allowed him to measure the river's speed and depth, as well as the rate at which the waterwheel turned. A complex, extravagant machine such as that at Marly would have unnecessarily complicated the calculations.⁹⁵

I will use Desaguliers' own translation of Mariotte's text:

93 Edme Mariotte, *Traité de la percussion ou choc des corps* (Estienne Michallet, Paris, 1673); Newton, *op. cit.* (note 18), p. 425, refers to a book on collision experiments with pendulums by 'the eminent Mariotte'.

94 Daniel Bernoulli and Johann Bernoulli, *Hydrodynamics and hydraulics* (trans. Thomas Carmody and Helmut Kobus) (Dover, New York, 1968).

95 See Thomas Brandstetter, "'The most wonderful piece of machinery the world can boast of': the water-works at Marly, 1680–1830", *Hist. Technol.* 21, 205–220 (2005) (<https://doi.org/10.1080/07341510500103750>); Desaguliers, *op. cit.* (note 23), p. 442, gave an account of the Marly machine that was taken from Bélidor.

The Wheels of the Mills that are upon the *Seine* at *Paris*, betwixt *Pont-Neuf* and *Pont-au-Change*, have at their Circumference but half the Velocity of the running Water that strikes against them; which comes to the same thing, as when a Weight in Motion meets with another equal to it self, that is at rest and sticks to it; for being join'd together immediately after their Congress, they go forwards with only half the Velocity of the impelling Weight; and so you may suppose, that the Resistance from the Friction of the Axis of the Wheel, and that of the Mill, and the Grain that it grinds, is join'd to the Weight of the Mill and its Floats, is pretty near as great as the Resistance of a Weight equal to that of the impelling Water; and consequently they ought to retard pretty near one half of the Velocity of the Water that strikes against them.⁹⁶

Mariotte interpreted the difference between the velocity of the wheel and the velocity of the water as conforming to the rules for collisions between soft bodies, which led him to 'suppose' that the weight represented by the resistance of the watermill machinery and the work done by the mill was equal to the weight of the water striking the waterwheel paddle.⁹⁷

According to the rules for collisions between soft bodies, if a soft, or non-elastic, body strikes another body of the same mass that is stationary, both will move off with half the velocity of the striking body. This rule played a major role in the *vis viva* controversy because, although momentum was conserved in soft-body collisions, *vis viva* was lost. As John Smeaton (1724–1792) later discovered during his experiments on model waterwheels, this loss of *vis viva* in soft-body collisions, which could be attributed to the work expended changing the shape of the bodies (turbulence, in the case of water), was what explained the difference in efficiency between overshot and undershot waterwheels.⁹⁸

DESAGULIERS' USE OF MARIOTTE

After enumerating momentum-based laws governing collisions in *A course of experimental philosophy* as part of his discussion of the *vis viva* controversy, Desaguliers proposed an illustration in order to demonstrate the practical utility of such laws. He argued that the functioning of all machines, not only those that are moved by wind or water, but also those machines that involved percussion, could be understood using the rules for collisions.⁹⁹ He provided a list of these machines, also suggesting that many new machines could be built that functioned according to these principles.

If improvements in the efficiency of waterwheels were to be made, then a working knowledge of the rules for collisions would be useful, although Desaguliers' lectures were

96 Mariotte, *op. cit.* (note 52), p. 136. The translation is faithful, as we can see for ourselves: 'Les roues des moulins qui sont sur la Seine à Paris entre le Pont-Neuf & le Pont-au-Change, n'ont à leurs extremités que la moitié de la vitesse de l'eau courante qui les choque, ce qui revient à la mesme chose que lors-qu'un poids en mouvement en rencontre un autre immobile de mesme pesanteur & qu'il s'y attache; car estant joints ensemble, ils n'ont incontinent après le choq que la moitié de la vitesse de celui qui a choqué, & ainsi on peut supposer que la resistance du frottement de l'essieu de la rouë, de celui de la meule & du grain qu'elle brise, joint au poids de la rouë & de ses pallettes, vaut autant à peu près que la resistance d'un poids égal à celui de l'eau qui choque, & parconsequent elles doivent retarder de moitié à peu près la vitesse de l'eau qui les choque.' From the original text: Edme Mariotte, *Traité du mouvement des eaux et des autres corps fluides divisé en v. parties* (Estienne Michallet, Paris, 1686), p. 217.

97 Mariotte, *op. cit.* (note 96), p. 217.

98 For an account of Smeaton's role in the *vis viva* controversy, see Morris, *op. cit.* (note 74), and Larry Stewart, 'A meaning for machines: modernity, utility, and the eighteenth-century British public', *J. Mod. Hist.* 70, 259–294 (1998) (<https://doi.org/10.1086/235069>).

99 Desaguliers, *op. cit.* (note 23), p. 35.

Figure 4. Desaguliers' waterwheel diagram, inspired by Mariotte. Desaguliers, *A course of experimental philosophy*, vol. 2, p. 39.

more likely aimed at people who would pay someone else to make those improvements. To provide more detail, he proposed the example of the waterwheel: 'I will here shew how the Water acts upon the under-shot Wheel of a Water-Mill by the rules of the Congress of Bodies.'¹⁰⁰ His account bears a close resemblance to that of Mariotte, written 58 years earlier, and which he translated 26 years earlier.¹⁰¹ For this reason it is worth citing Desaguliers' own words:

Now let us suppose the Work to be done by the Wheel, the Friction of the whole Machine, and Resistance of the Air, to be equal to the Weight w , equal to 806 lb. hanging at the Circumference of the Wheel: What else will be the Operation of the Water upon the Wheel, but the Congress of two Bodies without Elasticity, as mention'd in the Congress of the Balls A and B, in N° (32) of this Lecture, *Plate 2. Fig. 6.* for here the Wheel is as a Body of 806 lb. suspended at D, and the Water is as a Body of the same Weight moving from A to B with a certain Degree of Velocity. After the Shock, both go on with half the Velocity of the Percutient.¹⁰²

Basing his account on Mariotte's, Desaguliers estimated the resistance of the waterwheel at rest to be the sum of the work done by the apparatus (the mill, for example) attached to the waterwheel, the resistance of the air, and any friction in the system. This is represented in figure 4 as the weight w hanging from D. He then suggested that we should 'suppose', just like Mariotte, that this resistance was equal to the weight of the water flowing from

¹⁰⁰ *Ibid.*

¹⁰¹ Mariotte is not cited in this part of Desaguliers' textbook. According to Poni, *op. cit.* (note 1), p. 219, Desaguliers 'was an active translator of French works, particularly in the period 1711–1718, and made frequent, though not always explicit, references to the work of the French scientists of the Paris Académie des Sciences'.

¹⁰² Desaguliers, *op. cit.* (note 23), p. 35.

left to right and hitting the paddle of the wheel at B, which he calculated from the size of the aperture and the height of the column of water W.¹⁰³ In other words, the water was to be viewed as a moving body of weight w striking a stationary body of the same weight w . The collision between the water and the paddles was thus reduced to an instantiation of the rules for collisions between soft bodies by equating the pressure exerted by the water with the weight held by that water.

Compared with Parent's diagram, Desaguliers' Mariotte-inspired schema is very much simpler. We can see that the waterwheel was reduced to a static equilibrium between the water flowing against the single submerged waterwheel paddle B and the weight hanging from D. This is in line with Mariotte's account—which Desaguliers translated while working on fountains—according to which the static equilibrium between the *pressure* of spouting or flowing water and the *weight* of a body is reconceptualized as a dynamic collision between two soft bodies of equal weight.¹⁰⁴

By means of this reconceptualization, Desaguliers was able to reduce the waterwheel to a collision between two soft bodies of equal weight. His simplified diagram does not feature the gearing or variable weights seen in Parent's representation, nor is the weight w intended to move vertically, as it does in Parent's case. Desaguliers did not depict a functional waterwheel, because the weight w was attached directly to a paddle, meaning that it would go around the wheel instead of being raised, if the wheel were set in motion. This feature was taken straight from Mariotte, who also believed that measuring the force of a river consisted in determining the weight that would be held in static equilibrium by the force of the current of water against a paddle.¹⁰⁵

As we have already seen, Parent took this model further by setting the waterwheel in motion. This he did by reducing the weight held by the wheel (in Desaguliers' diagram, figure 4, this is the weight held at D), allowing the pressure of the flowing water to overcome the resistance of the weight and set the waterwheel in motion. In fact, Parent explicitly contrasted his dynamic model with the static model—adopted by Mariotte and Desaguliers—by starting his discussion with a weight directly attached to the waterwheel paddle (this can be seen at D in figure 1), before moving on to describe the gear mechanism that would allow the wheels to turn.¹⁰⁶

These differences in levels of abstraction in the waterwheel diagrams tell us that Desaguliers used each approach to do something different. Parent's more complex diagram (figure 1) reflects his more sophisticated approach, which provided Desaguliers with a limit beyond which waterwheels could not be more efficient. This was explicitly linked to raising a weight, meaning that Desaguliers saw Parent's waterwheel as a *tool* designed to do *work*. Importantly however, his readers did not need to understand the mathematical demonstration of this maximum limit.

On the other hand, Desaguliers' simpler schema (figure 4), which he took from Mariotte, was used to illustrate the significance of momentum as the correct measure of motive force: he used Mariotte to defend the 'Newtonian' position in the *vis viva* controversy. In order to do

103 *Ibid.*

104 The confusion between statics and dynamics, as well as between pressure and force, was common during this period. See Jip van Besouw, 'The wedge and the *vis viva* controversy: how concepts of force influenced the practice of early eighteenth-century mechanics', *Arch. Hist. Exact Sci.* 71, 109–156 (2017) (<https://doi.org/10.1007/s00407-016-0182-3>), at p. 139.

105 Mariotte, *op. cit.* (note 96), p. 222. See also Calero, *op. cit.* (note 90), pp. 12–13.

106 Parent, *op. cit.* (note 81), p. 325 (my translation): 'We hang in the middle of the paddle D a weight P sufficient to stop the effort of the fluid EB, and hold the mill stationary.'

this, he needed an intuitively accessible schema that was easier to grasp than Parent's calculation of maximum efficiency, and which could be easily reduced to a straightforward collision between two bodies. Unlike Parent's waterwheel, however, Mariotte's waterwheel was not sophisticated enough to actually do any work.

Mariotte's experimental approach was well suited to Desaguliers' courses on experimental philosophy, even though it had been surpassed by more sophisticated accounts, because it simplified complex processes like waterwheel functioning, making them accessible to the layperson as illustrations of the rules governing collisions. This simplification also allowed Desaguliers to link waterwheels to the *vis viva* controversy because waterwheels involved the same conservation of momentum as in soft-body collisions. By binding explanations of waterwheel functioning to the debate over motive force, Desaguliers paved the way for Smeaton, whose work on waterwheel efficiency (which explicitly challenged Desaguliers' view) made a decisive contribution to the dispute about the nature of motive force.

THE 'PRACTICAL MECHANICK': BERNARD FOREST DE BÉLIDOR

Bélibor's *Architecture hydraulique* (1737–1753) was also an important source for Desaguliers' *A course of experimental philosophy*. Bélibor was a military engineer who was moved to write a manual of practical hydraulics—what we now call hydraulic engineering—in order to supply practical artisans with the theoretical tools that would allow them to carry out their work with the greatest accuracy. He recounted in the preface that one day, when in the process of constructing a machine for raising water, he found himself unable to calculate the dimensions of the machine because he lacked the theoretical tools to do so.¹⁰⁷ This, he wrote, inspired him to compile a work which combined both theoretical analysis and practical instructions for the building of hydraulic machines. This project was very successful, and *Architecture hydraulique* served as an engineering manual well into the nineteenth century, being republished with extensive notes by the influential engineer and mathematician Claude-Louis Navier (1785–1836), in 1819.¹⁰⁸

On the subject of watermills, Desaguliers included almost five pages of Bélibor's work, citing unapologetically from *Architecture hydraulique*.¹⁰⁹ He was particularly interested in Bélibor's descriptions of working watermills, and began a long excerpt with Bélibor's reasoning as to the worth of describing watermills: 'A Great Many persons may imagine that it is hardly worth while to write about so common a thing as a Corn-Mill; but the Commonness of it shews its Usefulness.'¹¹⁰

Bélibor's project shared many similarities with Desaguliers' work, and he covered both practical waterwheel design and theoretical calculations of waterwheel efficiency.¹¹¹ He

107 Bernard Forest de Bélidor, *Architecture hydraulique, ou l'art de conduire, d'élever et de ménager les eaux pour les différents besoins de la vie. Première partie. Tome premier* (Charles-Antoine-Jombert, Paris, 1737), p. vi.

108 Olivier Darrigol, 'Between hydrodynamics and elasticity theory: the first five births of the Navier-Stokes equation', *Arch. Hist. Exact Sci.* **56**, 95–150 (2002) (<https://doi.org/10.1007/s004070200000>), at p. 107.

109 Desaguliers, *op. cit.* (note 23), pp. 427–431. This material was selectively taken from Bélibor, *op. cit.* (note 107), pp. 277–293.

110 Desaguliers, *op. cit.* (note 23), p. 427.

111 Alexandre Guilbaud, 'À propos des relations entre savoirs théoriques et pratiques dans l'Encyclopédie: le cas du problème de la résistance des fluides et de ses applications', *Rech. Diderot Encyclopédie* **47**, 207–242 (2012) (<https://doi.org/10.4000/rde.4948>), suggests that Bélibor had taken the first steps to overcoming the theory/know-how divide, and that his account was far superior to that found in the *Encyclopédie*, which maintained the schism between theory and practice. Moritz Epple, 'The gap between theory and practice: hydrodynamical and hydraulic utopias in the 18th century', in *Philosophies of technology: Francis Bacon and his*

Figure 5. Bédidor's watermill drawings. Bernard Forest de Bédidor, *Architecture hydraulique, ou l'art de conduire, d'élever et de ménager les eaux pour les différents besoins de la vie. Première partie. Tome premier* (Charles-Antoine-Jombert, Paris, 1737), p. 321.

discussed exactly how the corn was ground between two millstones, how the wear of these millstones reduced their mass and thus their efficiency, the names of all the parts that went into making a real watermill, and the appropriate materials to be used.¹¹² This emphasis can be seen in some of his diagrams (figure 5). For Bédidor, the choice of materials or the wear and tear of the grindstones were essential to understanding the functioning of a watermill—and even his focus on *watermills* rather than mere *waterwheels* was indicative of a methodological position at odds with that of Parent, for example. Bédidor's sketches were much less schematic than those of Parent and Desaguliers. He put much greater emphasis on the materiality of the waterwheel, and the uses to which it was to be put. Thus, on the left of Bédidor's sketch, the waterwheel is an overshot wheel, which, although fairly common, was more difficult to conceptualize in the eighteenth century. On the right, we can see the power transmission mechanism and more accurately drawn, angled paddles. So Bédidor's drawings were more realistic and included contextual information about the milling they were designed to power, in contrast to the idealized approach which represented the waterwheel as a standardized tool used for raising weights (see figure 1). His sketches more closely resembled engineers' technical drawings than the simple abstract models presented by Parent and Desaguliers.

Bédidor was also one of the first practically oriented natural philosophers to give an account of waterwheel functioning that was intended not for readers who wanted to understand how a waterwheel worked, but for readers who *wanted to build their own*. Desaguliers cited Bédidor so liberally because Bédidor, unlike Parent or Mariotte, provided concrete instructions for building watermills, which helped put the more abstract

contemporaries (ed. Claus Zittel, Gisela Engel, Romano Nanni and Nicole C. Karafyllis), pp. 457–494 (Brill, Leiden, 2008), at p. 470, however, claims that Bédidor's attempted mathematization of practical hydraulics was a failure.

112 Bédidor, *op. cit.* (note 107), pp. 277–293. On Parent's influence, see Reynolds, *op. cit.* (note 88), p. 207.

waterwheel theory into practice.¹¹³ As we have seen, this turn towards practical applications grew out of Desaguliers' attempt to popularize Newton's natural philosophy.

Another feature of Bélidor's work that appealed to Desaguliers was the descriptions of actual working watermills. In the annotations, Desaguliers compared the performance of an undershot watermill described by Bélidor with that of an overshot watermill observed by Henry Beighton (1687–1743) at Nuneaton in Warwickshire.¹¹⁴ Desaguliers took the opportunity to compare the relative efficiency of overshot and undershot mills by directly comparing Bélidor's mill with that observed by Beighton. He concluded that, although the undershot mill ground 2.5 times more corn than the overshot, it used 24 times more water, and so was much less efficient.¹¹⁵ Here Desaguliers partially anticipated the results of Smeaton's experiments on waterwheels in the 1750s, which aimed to demonstrate whether, and to what extent, the overshot waterwheel was more efficient than the undershot waterwheel.¹¹⁶

CONCLUSION

Desaguliers was drawn to experiments as a way of avoiding complex mathematics, and his use of practical examples of common machines not only suited his practical interest in commercial ventures, but also helped make his lectures more accessible. As a staunch defender of Newton's natural philosophy, he took part in contemporary polemics such as the *vis viva* controversy, pushing him to come up with Newton-inspired explanations on topics that Newton himself only briefly touched on.

The main conclusion of this paper is that, although Desaguliers took much from Newton's *Principia*, his project—focusing on popularization and practical applications—led him to carry out his own research, and to appropriate the work of other natural philosophers. In the case of his discussion of the waterwheel, I have provided evidence for his appropriation of work in hydrostatics and hydraulics developed by Parent, Mariotte and Bélidor. Desaguliers used these three natural philosophers to help flesh out his account of waterwheels, employing their different perspectives—that of the mathematician, the experimental philosopher and the practical mechanic—to provide a balanced and informative account that he hoped could be of practical use to the layperson who might be considering building a waterwheel, or employing someone else to build one.

The intention of this paper was to look at other figures who played a role in shaping Desaguliers' practical mechanics, without minimizing Newton's crucial influence on him. I hope to have shown, in the case of Desaguliers, that eighteenth-century 'Newtonianism' was not indebted to Newton alone, but incorporated diverse strands of seventeenth- and eighteenth-century thought and practice. By exploring avenues of research opened up by his extension of Newton's mechanics to practical machines, Desaguliers was drawn to other practically oriented natural philosophers—all of whom combined theoretical and

113 This was why Bélidor tried to distil his theoretical conclusions into handy maxims that could be learnt by artisans without formal mathematical training. See Antoine Picon, *L'invention de l'ingénieur moderne: l'Ecole des Ponts et Chaussées 1747–1851* (Presses de l'École Nationale des Ponts et Chaussées, Paris, 1992).

114 Desaguliers, *op. cit.* (note 23), p. 531.

115 *Ibid.*

116 See John Smeaton, 'An experimental enquiry concerning the natural powers of water and wind to turn mills, and other machines, depending on a circular motion', *Phil. Trans. R. Soc. Lond.* **51**, 100–174 (1759) (<https://doi.org/10.1098/rstl.1759.0019>).

practical concerns in different ways in their own work. For Desaguliers, 'he who would meddle with water-works' needed to be a hybrid figure, equally at home in the abstraction of Newton's *Principia*, in a laboratory surrounded by scientific instruments or in the dust and noise of a working watermill.

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