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Spreading Newtonian Philosophy with Instruments: The Case of Atwood's Machine

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We study how the paradigm of Newton's science, based on the organization of scientific knowledge as a series of mathematical laws, was definitively accepted in science courses—in the last decades of the XVIII century, in England as well as in the Continent—by means of the "universal" dynamical machine invented by George Atwood in late 1770s just for this purpose. The spreading of such machine, occurring well before the appearance of Atwood's treatise where he described the novel machine and the experiments to be performed with it, is a quite interesting historical case, which we consider in some detail. In particular, we focus on the "improvement" introduced by the Italian Giuseppe Saverio Poli and the subsequent "simplifications" of the machine, underlying the ongoing change of perspective after the definitive success of Newtonianism. The case studied here allows recognizing the relevant role played by a properly devised instrument in the acceptance of a new paradigm by *non-erudite* scholars, in addition to the traditional ways involving erudite scientists, and thus the complementary role of *machine philosophy* with respect to mathematical, philosophical or even physical reasoning.

Keywords: Atwood's Machine; Giuseppe Saverio Poli; Newtonianism

Introduction

The XVIII century was characterized by a widespread interest for natural philosophy, driven by public lecture courses and the publication of popular texts in addition to the traditional forms of transmission of knowledge. The scientific societies and academies created during the scientific revolution played an increasingly larger role than universities, thus becoming the cornerstone of organized science (McClellan, 2003; Gillispie, 1980). In England, the presidency of Sir Isaac Newton to the Royal Society from 1703 to his death in 1727 obviously led British science to be dominated by Newtonian ideas and experiments, and the structure itself of Newtonian physics, that is scientific knowledge organized as a series of mathematical laws, became the model for all sciences. However, due to this use of mathematics, very few people—in England and abroad—were able to understand Newton's ideas, so that an army of popularizers, lecturers and textbook writers was required in order to widespread Newtonianism: this occurred precisely in the early XVIII century, continuing for about half a century.

The rapid dissemination of Newton's science came first via the members of the Royal Society, both British and Continental (Feingold, 2004), and an important role was played by Huguenots (Baillon, 2004; see also Gibbs, 1986), i.e. French Protestants who had been expelled from France as early as 1685. In this respect, a key contributor to the success of Newtonian science was John Theophilus Desaguliers, whose work of dis-semination extended well beyond his lectures and publications. Indeed, for example, in 1715 Desaguliers also performed experiments on colors before members of the French Académie Royale des Sciences, thus paving the way to a wider recognition of the validity of Newtons theories in France, and much the same took place before diplomatic audiences from Spain, Sicily, Venice and Russia (Stewart, 1992). The Dutch Willem Jacob's Gravesande was present to the demonstration of 1715, and later became a decisive spokesman of Newtonian science in the Netherlands, a country which already played in the XVII century a significant role in the advancement of the sciences, including Isaac Beeckman's mechanical philosophy and Christiaan Huygens' work on the calculus and in astronomy (Jacob, 1988). The Netherlands became the first Continental country to adopt Newtonianism, with Amsterdam becoming the center of European publishing, thanks, again, to French exiles, while in France the struggle against Cartesianism lasted for some time, the Newtonianism attracting mainly people dissatisfied with French society and the Catholic Church, like Voltaire. A similar, or even deeper struggle, was fought in the Germanic world, where Newton's science contended against the prestige of Leibniz's philosophy, this resulting in the long-lasting Newtonian-Wolffian controversy (Calinger, 1969): in the XVIII century, Germany was always hesitant about the mechanization of nature, and eventually Newton's mechanics was incorporated into the dominant German academic philosophy. Instead, Newton's science filtered quite early into different parts of Italy,

notwithstanding the Inquisition looked with suspicion on these ideas, not least because they came from a Protestant country.

The traditional way to disseminate Newtonian natural philosophy was, of course, through academic courses: before the XVIII century, indeed, science courses were taught almost exclusively through formal lectures. Thus, in the first instance, scientists, mathematicians and philosophers of Holland, France, Germany and Italy read Newton's books and taught the ideas to their students. The structure of courses, however, began to change in the first decades of the XVIII century, when physical demonstrations were added to academic lectures, and popular lectures were introduced in response to the growing demand for science. For example, Pierre Polinière was among the first individuals to provide demonstrations of physical principles in the classroom: he presented experimental demonstrations of his own devising before students at the University of Paris (Hanna, 1972), his lectures proving so popular that in 1722 he presented a series of experiments before Louis XV, King of France. In particular, in physics, such a change coincided with the institutionalization of the course in Experimental Physics (Schettino, 2001).

Now, still in the XVIII century, what we now could call "research centres" of the newborn physics, were not necessarily distinct from the places devoted to the transmission of knowledge, i.e. schools, colleges, etc. The success of a theory also passed through its acceptance by "students", i.e. scholars not yet acquainted with it, who then contributed actively in the dissemination of novel ideas. In other words, if the first acceptance of a given doctrine was disputed at a rather "high" level between leading scientists and philosophers (as a reminiscence of the philosophical disputations of earlier centuries), the definitive one was played in lecture halls before non-experts. An illuminating example of this mechanism is just the general achievement of Newton's mechanics, expressed in his *Principia* (Newton, 1726). While its acknowledgement by leading scholars is well documented in the literature [see, for example (Westfall, 1971); see also (McCormmach, 2004)], the same is unfortunately not true for its thorough acceptance by "students"[1]; in this paper, we will focus just on this last historical case.

If treatises of natural philosophy played a major role in the "high" level debates, the writing and the circulation of practical textbooks for the courses in Experimental Physics (or similar other ones) became essential for the dissemination and acceptance of the novel ideas among "students". In the following Section we then review this issue. Far from being exhaustive, we focus just on the most known scholars and their textbooks in England and in the Continent, by concentrating on the period immediately following that influenced directly by Newton. Instead, in the further Section we enter into the heart of the subject matter hereof, by showing how the invention of a "universal" dynamical machine by George Atwood, described along with the experiments to be performed with it in an accompanying treatise, contributed substantially to the final, general achievement of Newton's mechanics. The invaluable work of Jean-Hyacinthe de Magellan and especially that, much less known, of Giuseppe Saverio Poli in the rapid spreading of Awood's machine outside England is considered in a following Section, where the subsequent key changes and "simplifica-

tions" underlying the ongoing change of perspective are pointed out as well. Finally, in the concluding section, we summarize what discussed in order to provide a rapid overview of the historical case studied.

Newtonian Textbooks of Natural Philosophy in the Post-Newtonian Age

Newtonian doctrines spread in the first quarter of the XVIII century thanks to elementary or complex textbooks by English authors such as J. T. Desaguliers, or the Dutch ones W. J. 's Gravesande and Pieter van Musschenbroek, and the Frenchman Jean Antoine Nollet. The complexity of Newtonian thought expressed itself in several different ways, and in the following we will give a glimpse of such diversity.

Newton's Experimenter Successor

The first English disciples of Newton tried to give an experimental basis especially to ideas that he had not sufficiently formalized (such as that of ether and that of interparticle forces), so that the results obtained by Newton by means of a complex relationship between inductive and deductive reasoning became truths demonstrable directly with experiments.

The Newtonian method underwent a profound remodeling with Desaguliers, a member of the Christ Church College who held popular Newtonian lectures at Oxford, where he had much success in his activity (Hall, 1972). After moving to London in 1710, he was welcomed into Newtonian circles of the capital and was then (1714) elected fellow of the Royal Society, later becoming the *curator* of the Royal Society, a position that was earlier held by Francis Hauksbee. Desaguliers published many works on the *Philosophical Transactions* about experiments on heat, mechanics and electricity. In particular, he correctly realized that the physical quantities then used for describing the motion of a body, i.e. the *momentum* for the Newtonians and the *vis viva* for the Leibnizians, were different concepts, and that the Newtonian one was to be preferred because better supported by experiments.

As curator of the Royal Society, Desaguliers performed experiments that were repetitions of those already described by Newton, although there were more complex experiences such as those aimed at finding a similarity between the electric force and the force of cohesion [for a thoughtful examination of the studies by Newton on the internal structure of matter, see for examples (Thackray, 1970)]. However, Desaguliers' reputation as a scientist was sealed (apart by his three awards from the Royal Society) by publication of a two volume work about *A Course of Experimental Philosophy* (Desaguliers, 1734, 1744), whose first volume was published in 1734, while the second volume's publication came 10 years later in 1744. The first volume deals with mechanics, with an explanation of the basics of Newtonian science, while the second volume contains material oriented toward practical application of scientific findings. Desaguliers contributed significantly to the wide spread of Newtonian-oriented textbooks also by translating Edme Mariotte's *Traité du mouvement des eaux et des autres corps fiuides* (Mariotte, 1718), as well as 's Gravesande's Latin treatise on *Physices elementa mathematica, experimentis confirmata* ('s Gravesande, 1747). In addition, he also wrote several texts, among which we recall *The Newtonian system of the world, the best model of government*: *An allegorical poem* (Desaguliers, 1728) and *A dissertation concerning electricity*

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[1]See, however, the beautiful review by Schaffer on the role of "machine philosophy" in the XVIII century's England (Schaffer, 1994).

(Desaguliers, 1742), which received a prize awarded by the French Académie de Bordeaux.

Instrumental Philosophy in the Netherlands

The introduction of Newtonian science in the Netherlands and, more in general, in the Continent came through's Gravesande (Hall, 1972). Educated at the University of Leiden, in 1714 he had the opportunity to be part of the delegation sent to England by the Dutch States General to congratulate King George I on his accession to the throne, and just during his (one year) stay in London he attended sessions of the Royal Society, later being elected to membership, and made acquaintance of Newton and, especially, Desaguliers. On his return to Holland, 's Gravesande was appointed professor of astronomy and mathematics at the University of Leiden, and in 1720 published the first of the two volumes on *Physices Elementa Mathematica, experimentis confirmata* ('s Gravesande, 1747), already mentioned above.

Written in Latin, this first Newtonian-oriented textbook on natural philosophy was of course accessible to all educated readers in Europe, but the English translation performed by Desaguliers in the same year of its publication certainly contributed to its rollout. In the discussion on the infinite divisibility of matter and on small real particles of which it was composed, Newton's hypothesis on particle different shape and size was not discussed by 's Gravesande, but simply ignored: his position in favor of Leibniz's theses had revived the debate on the *vis viva*. Instead, 's Gravesande agreed with Newton about the role played by short-ranged forces of attraction and repulsion acting on the fundamental particles, the rising of liquids by capillary action being considered as an example supporting the Newtonian theory (such phenomena were treated as *Queries* in Newton's *Opticks* (Newton, 1718). 's Gravesande's treatise displayed a complete adhesion to Newtonian approach, not only about the structure of matter and short- and long-ranged forces, but also on questions of mechanics and astronomy. However, he took no position about ether; rather, on this topic, 's Gravesande showed to follow the ideas of his teacher Hermann Boerhaave, three chapters being devoted to the discussion on the fire and its nature (Thackray, 1970).

In the third decade of the XVIII century, Dutch science enjoyed a period of great splendor with 's Gravesande's successor in Leiden, Pieter van Musschenbroek (Struik, 1979; Kryzhanovskii, 1991), who followed the same approach introduced by his predecessor. The lectures delivered by Musschenbroek, indeed, maintained the excellent reputation that Boerhaave and 's Gravesande earned to the University of Leyden, where students interested to experimentation flocked from all over Europe. The Musschenbroeks were scientific instruments' makers since the seventeenth century, Joost (1614-1693) being the founder. His sons Samuel and Johan continued such activity, specializing themselves in the construction of microscopes, telescopes and air pumps, all of them being typical instruments used at that time. Pieter and Jan were the sons of Johan, and both had an excellent education, his teacher being Boerhaave; however, while Pieter decided to pursue his academic studies, Jan chose to continue the family business.

Pieter van Musschenbroek began his academic career in 1719 in Duisburg, where he taught mathematics and philosophy, and then, after a temporary moving to Utrecht, finally (in 1739) came to Leiden, where he succeeded to 's Gravesande. His lec-tures were characterized by a systematic use of experimental devices, many of them being constructed by his brother Jan. Skillfully designed models, illustrating the use of those machines and the experiments that could be run with them, supplemented the textbooks written by Pieter, among which we find the *Elementa physicae* of 1734 (Musschenbroek, 1734) and the *Institutiones physicae* of 1748 (Musschenbroek, 1748). The large diffusion of these text books also increased the demand for instruments constructed by Jan: both universities and private science amateurs wanted to buy them for their demonstrations. The demand increased to such an extent that the manufacturers of scientific instruments began to reproduce the same models of Jan: it's well known, for example, that the instruments made by George Adams in the cabinet of George III of England were inspired just by those models. The fame of Pieter van Musschenbroek spread rapidly throughout Europe, and his works were translated into German, French and English, in addition to further editions of the *Elementa physicae*, including the Neapolitan one of 1745.

French Newtonianism

The Newtonian science was introduced in France through Dutch scholars. Newton's *Opticks*, considered as a book of experimental physics, was well and quite soon received (a translation into French was published as early as 1720 (Newton, 1720), given the pronounced experimentalism of the Académie des Sciences, while the diffusion of the *Principia* encountered some more difficulty. An initial English corpuscular approach, followed by the experimental Newtonianism in France, gave then way to the typically Dutch fluidic approach, this change being facilitated by some Newton's early reflections on the ether, published only in 1744 (Hall, 1995). This transition from discontinuous to continuous proved very heuristic, especially in the studies about electricity.

Charles-Francois de Cisternai Dufay realized, after many experimental observations, that two different kinds of electricity—the vitreous and the resinous ones—existed: together with his collaborator Jean Antoine Nollet, he proposed to explain electrical phenomena starting from the existence of two opposite fluid currents, gave off by electrified bodies. The success of the fluidic approach was accompanied by the abandonment of the idea on the homogeneity of matter, and fire, ether and electric fluids were conceived as substances different from ordinary matter.

Like many other young scholars from all over Europe, Nollet (Heilbron, 1981) was attracted by the fame of 's Gravesande and moved to Leyden to follow his lectures. On his return from Holland, after a visit to London, where he was admitted into the Royal Society, in 1735 he succeeded to Pierre Polimière who taught at the College of the University of Paris, and in 1740 became a member of the Academic des Sciences. Nollet's contribution to the spread of experimental physics was quite remarkable and his treatises, among which we mention the *Lecons de physique experimentale* (Nollet, 1743-1748), published in six volumes between 1743 and 1748 and often reprinted, enjoyed enormous popularity. This textbook offered many experiments on electricity, and thanks to a very substantial contribution by Voltaire, Nollet could realize many instruments, about 350, with which he performed experiments both during public lectures and in his physics courses.

It was, instead, quite difficult for the Newtonian astronomy,

based on the concept of action at a distance, to be introduced in France, given the wide spread of the Cartesian theory of vortices. Through the reading that the Dutch scholars had made of Newton's works, however, Voltaire reinterpreted the *Principia* along empiricist lines (Arouet, 1738), thus reconciling it with the experimentalism of the French Académie des Sciences. Although in the general scholion of Newton's *Principia* it is shown that the theory of vortices is incompatible with Kepler's law, the conflict between Cartesianism and Newtonianism continued to persist during the XVIII century. Also, a great theoretical debate concerning the theory on the shape of the Earth emerged. The contrast between the Cartesian idea of the Earth lengthened at the poles—as early measurements performed by the astronomer G. Cassini seemed to show—against the idea of Newton on the flattening at the poles due to the proper motion of the planet, found a definitive solution only with the measurements of Earth's curvature at the equator and at the Arctic Circle (de la Condamine, 1751; Clairaut, 1743). This theoretical debate did not find room in empiricist oriented textbooks, but it should be stressed that such studies led later to the development of rational mechanics, carried on by mathematics scholars such as P. L. M. de Maupertuis, A. C. Clairaut, L. Euler, J. B. d'Alembert and the Bernoullis, who were poorly interested in experimenting.

Experimental Science in Italy

Physics textbooks that privileged an empirical approach were inspired, in Italy, by the works by 's Gravesande and Musschenbroek, and the University of Naples, in particular, was among the first to introduce in 1734 the teaching of experimental physics. The sponsor of the institution of this chair was the Grand Chaplain Celestino Galiani, a great supporter of Newtonian ideas, who entrusted the chair to Giuseppe Orlandi (Schettino, 2001). The intent to pursue a teaching based on the inductive method, as practiced in the Dutch universities for over ten years, was clear already from a letter by Galiani to the Grand Chaplain:

"In the beginning, a preface will be present in which I will show how the true way of philosophizing is nothing but by means of experiments; and compare the state of philosophy among scholastics lasted for many centuries with the present, started by so many talented scholars who used to look at the book of Nature and study the characters with which it is written, which are observation, experiments and geometry" [a complete transcription of the letter, in Italian, is in (Palladino, 1985)].

It is evident, however, that in order to perform experiments, as claimed by the followers of empiricism, several machines were required, i.e. instruments by means of which the laws of physics could be inductively derived. For this reason, Orlandi adopted the *Elementa physicae* by Musschenbroek, where the necessary devices were skillfully depicted, but added to it a long appendix on astronomy—*De rebus coelestibus tractatus.* The first Naples edition of this textbook appeared in 1745 (Musschenbroek, 1745), with a long introduction written by Antonio Genovesi under the meaningful title *Disputatio physico-historica de rerum corporearum origine et constitutione,* where the illustrious Neapolitan follower of the Enlightenment attempted to give a first, brief but insightful history of physics from ancient times to XVIII century [about the *Disputatio* by Genovesi and on his attempt to oppose the philosophical interferences encountered in Newtonian oriented textbooks, see

(Torrini, 1994)].

Giovanni Maria Della Torre, entrusted with the teaching of experimental physics in the Royal Archigymnasium in Naples, was the author of a very successful textbook published between 1748 and 1749 in two volumes (Della Torre, 1748-1749). The first volume—*Scienza della Natura generale*—was devoted to general physics, that is Della Torre expounded about "matter, extent, strength, mobility and motion", while in the second one—*Scienza della Natura particolare*—topics related to Earth science were discussed, that is about "Earth's shape and size, internal structure, surface and atmosphere". The Della Torre's textbook was different, especially in the second volume, from the most authoritative ones by Musschenbroek and 's Gravesande, where biology and geology were omitted, as well as almost all of chemistry and meteorology. The historical and critical notes about "ancient conceptions and their links with recent results", though always present in Newtonian oriented textbooks, were so many in the Della Torre's treatise that raised strong debates (Torrini, 1994). In this book, as well as in any contemporary textbook, the use of mathematics was always theorized, but scientific theories were explained without resorting to analytic calculations. This, however, did not mean that theories were not addressed in a rigorous way: for example, in Section IV of the second volume, detailed theorems were present in order to justify the laws of optics and catoptrics. As in the *Lecons* by Nollet, a large part was devoted to the description of instruments, especially microscopes, with fully spherical lenses (invented by Della Torre himself), which limited the problem of spherical aberration. Della Torre acquired such a skill in experimenting with microscopes that was famous throughout Europe: J. J. de Lalande, who traveled in Italy between 1765 and 1766, had him in high regard, and quoted him often in his book *Voyage en Italie* (de Lalande, 1769), and the same applies to Nollet, who had the opportunity to meet him during his stay in Naples in 1750.

Later in the XVIII century, starting from 1770's, a new generation of enlightened scientists, who were educated at the University of Padua, where they had very strong links with scientific circles in England, began to impose in the academies of the Kingdom of Naples (Borrelli, 2000). Giuseppe Saverio Poli was one among these who, having had the opportunity to stay in Cambridge and meet George Atwood (Toscano, 2009), was the first to publish a new, Newtonian oriented textbook (Poli, 1781a) where the novel machine invented by the English scholar was illustrated with a choice of experiments.

Now, however, one step back is needed in order to fully understand the change of perspective that occurred in the last quarter of the XVIII century, and that further influenced the subsequent transmission to "students" of physics results.

Atwood and the General Achievement of Newton's Mechanics

The Atwood's machine changed the way of propagating Newtonian mechanics, and had also a prominent role in the definitive success of Newtonianism, though this fact is not always correctly realized or even considered. In the following we will focus just on this issue, while in the subsequent section, we will show how Poli and others contributed to the widespread use of Atwood's machine (and, in particular, to a specific use of it) in the Continent.

Popular Lecturer in Cambridge

Biographical notes on Rev. George Atwood are scarce, and mainly related to his record in the *Alumni Cantabrigienses* list (Venn, 1922-1958) or other similar records in England [see (Cole, 1970)]. He was the first of three sons (with James and Thomas) by Isabella Sells of Inglesham, Wiltshire, and Thomas Atwood, the curate of the parish of St. Clement Danes, Westminster, where George was baptized on 15 October 1745. After attended the Westminster School, starting in 1759, as a king's scholar, he entered Trinity College in Cambridge on 5 June 1765 as a pensioner (i.e. he paid for his own keep in College), and was then elected to a scholarship on Lent 1766, being also awarded with the Members' prize in the same year. He graduated (as third Wrangler) with a B. A. in 1769, being first Smith's prizeman in the same year, and received his M. A. in 1772. Meanwhile, in October 1770, Atwood became a Fellow of Trinity College and taught there, also becoming a tutor in 1773. His lectures in the observatory over the Great Gate of Trinity College were well attended and received because of their delivery and their experimental demonstrations. He published descriptions of his demonstrations in 1776 (Atwood, 1776), the year he was elected Fellow of the Royal Society: they consisted of simple experiments to illustrate mechanics, hydrostatics, electricity, magnetism and optics. One of the many students who attended Atwood's popular lectures was William Pitt, who later (in 1783) achieved the high office of British Prime Minister. In 1784 Atwood was then hired to a major post in the customs office as part of Pitt's campaign for administrative rationalization: he "rendered important financial services to Pitt, who bestowed upon him a sinecure office, as one of the patent searchers of the Customs, with a salary of £500" (Venn, 1922-1958).

Atwood is now best known for a textbook on Newtonian mechanics, *A Treatise on the Rectilinear Motion and Rotation of Bodies* (Atwood, 1784), published in 1784, where he also describes in detail a machine, now known as Atwood's machine (see below). In the same year he also published a second work, *An Analysis of a Course of Lectures on the Principles of Natural Philosophy* (Atwood, 1784), which is an expanded version of his Cambridge course which he had first given detail in 1776.

Most of other Atwood's published works (Cole, 1970) consists of the mathematical analysis of practical problems, including a *review* for Pitt in which he analyzed the cost of bread and attempted to rationalize the standards for it. A particular mention merit his works on the stability of ships (Atwood, 1796-1798), where he extended the theories of Euler, Bougier and others to account for the stability of floating bodies with large angle of roll, and for which, in 1796, he was awarded the Copley Medal of the Royal Society. Finally, he also wrote on the construction of arches (Atwood, 1801) and on the design of a new iron London Bridge over the Thames at Blackfriars.

Atwood died "unmarried" (Venn, 1922-1958) on July 1807 and buried at St. Margaret's, Westminster, where his brother Thomas had succeeded his father as curate.

A Novel Machine

The name of Atwood is almost entirely related to the dynamical machine he invented between 1776 and 1779: the story of the development of this machine and the spreading of its existence throughout Europe is, by itself, worth-mentioning, and will be considered in some detail here and in the next section. Its scope, according to textbooks appeared since the end of 1700s till recent times, would be just that of conducting experiments proving the laws of rectilinear (and rotational) motion of bodies, with particular reference to motions ruled by gravity. As we will see, such a (reductive) purpose of Atwood's machine was established only *after* the general achievement of Newton's mechanics, that is from the end of the XVIII century onward, but in the Cambridge of 1770s and 1780s it served just to fulfill definitively such achievement before young students and scholars who *later* disseminated the Newtonian paradigm.

The machine is described in Atwood's *Treatise* of 1784 (Atwood, 1784), but its diffusion outside England dates back to the end of 1770s (see next Section). As well known, it consists (see **Figure 1**) just of two balanced cylinders linked by a silk cord suspended over a pulley, where additional weights can be attached (and removed) to either cylinder in order to provide a net (or zero) force acting on the system.

It is quite instructive to follow closely how Atwood devised his ingenious machine, starting from his first considerations about the classical problem of experimenting on the free fall of bodies.

> The most obvious method would be to observe the actual descent of a heavy body, as it falls toward the earth by its natural gravity: but in this case it is manifest, that on account of the great velocity generated in few seconds of time, the height from which the observed body falls must be considerable. […]
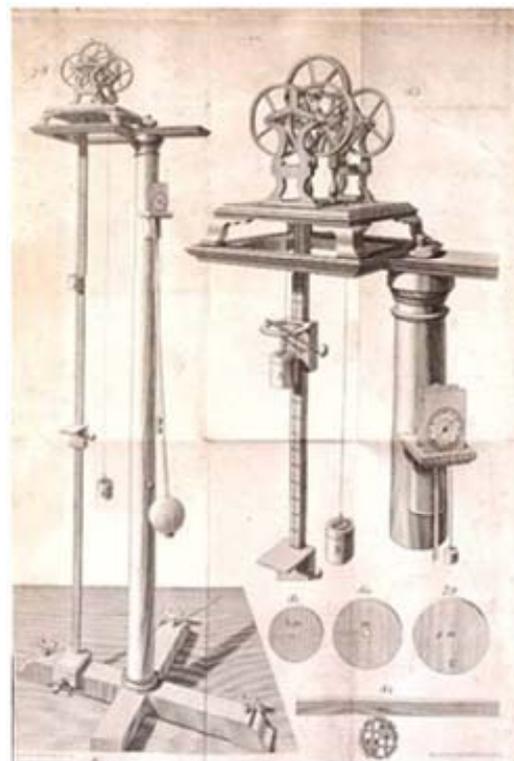

Figure 1.
The plate in Atwood's Treatise of 1784 (Atwood, 1784) with the illustration of the novel machine built by Adams.

If to remedy this inconvenience bodies be caused to descend along inclined planes, according to the experiments of the celebrated author [Galileo] of this theory, by varying the proportion of the plane's height to their lengths, the force of the acceleration may be diminished in any ratio, so that the descending bodies shall move sufficiently slow to allow of the times of motion from rest being accurately observed; and the effects of the air's resistance to bodies moving with these small velocities will be absolutely insensible: the principal difficulty however which here occurs, arises from the rotation of the descending bodies, which cannot be prevented without increasing their friction far beyond what the experiment will allow of (Atwood, 1784: pp. 295-296).

Notably, here the "principal difficulty" is with what theory already knows (as explained in the first half of the book), namely that the acceleration of a rotating body while descending along an inclined plane is reduced with respect to the case where rotation does not occur, and thus gravity is the sole cause of such effect. While this is not accounted for in many modern textbooks, the problem envisaged by Atwood is not the consideration of the effect of rotation (he knew the correct reduction factors: 5/7 for a sphere and 2/3 for a cylinder), but simply the super position of two effects (rotation and gravity) that could cause—in Atwood's mind—not a univocal acceptance of the Newtonian paradigm. This attitude is confirmed one page after in the *Treatise*, where other, different problems with the inclined plane are envisaged.

There are no means separating the mass moved from the moving force; we cannot therefore apply different forces to move the same quantity of matter on a given plane, or the same force to different quantities of matter. Moreover, the accelerating force being constant and inseparable from the body moved, its velocity will be continually accelerated, so as to render the observation of the velocity acquired at any given instant impossible (Atwood, 1784: p. 298)[2].

The first problem is that, with a given inclined plane (i.e. height to length ratio) it is not possible to study the dependence of the force acting upon the body on its mass, thus proving Newton's second law of motion. The second, more involved experimental problem is instead the impossibility to measure the velocity of the body at any desired instant of time, since it continually changes, and thus the impossibility to prove the time law for the velocity in the uniformly accelerated motion.

What is, then, Atwood's aim? Surprisingly enough, he is aware that Newton's second law will be generally confirmed only when considering the effect of *variable* forces, but the inadequacy of the experimental conditions of the epoch forced him to turn to constant forces (as in the free fall or in the motion along an inclined plane). This, however, does not mean for him to make any other concession to the ease of the experiment (again, as is instead the case in the free fall or in the motion along an inclined plane).

Although it might be difficult to reduce the effects of variable forces on the motion of bodies to experimental test, yet the laws observed during the motion of bodies acted on by constant forces, admit of easy illustrations from matter of fact. But in order to render experiments of this kind satisfactory, they should comprehend the properties of the moving forces, the quantities of matter moved, and the velocity acquired, as well as the spaces described and times of description: which general properties of uniformly accelerated motion are not so much considered in books of mechanical experiments as the subject seems to demand (Atwood, 1784: p. 294).

The boundaries of the problem are, thus, well depicted: how is it possible to device a series of experiments with a *single* machine with which force, mass, velocity, distances and times are dealt with? Without previous suggestions by other authors (which is, instead, the case of Desaguliers, as mentioned above, who simply improves Galilei's experiment on free falling bodies), Atwood focuses his attention on pulleys, already worthy of consideration by men of science since many centuries. But here the change of perspective is crucial: a conventional device employed in statics as a simple machine is transformed in Atwood's hands into a carefully scaled *dynamically* device capable of being subjected to mathematical analysis for the illustration of the Newtonian paradigm. In this light, indeed, a consistent interpretation can be given to a number of kinematics and dynamics problems—just theoretical exercises, not directly related to his machine—appearing in Atwood's *Treatise*, most of which not at all considered in subsequent textbooks[3].

In the instrument constructed to illustrate this subject experimentally, *A*, *B* represent two equal weights affixed to the extremities of a very fine and flexible silk line: this line is stretched over a wheel or fixed pulley *abcd*, moveable round a horizontal axis: the two weights *A*, *B* being precisely equal and acting against each other, remain in equilibrium; and when the least weight is superadded to either (setting aside the effects of friction) it will preponderate (Atwood, 1784: p. 299).

The general problems envisaged above (too short falling times—in free fall or on an inclined plane—require very large distances traveled by the falling body, upon which, however, acts a non negligible friction force, the body reaching also too great velocities near the end of its motion) disappear at once: a small mass unbalance induces small accelerations and velocities, thus preventing unnecessary large falling height and, then, neglecting the action of air resistance. But Atwood's aim is a *precise* confirmation of Newton's laws, and if the realization of accurately balanced weights, as well as small while removable additional weights, is leaved to the art of skilled craftsmen, the possible friction developed by the axle of the pulley merits appropriate considerations.

When the axle is horizontal it is absolutely necessary that it should be supported on friction wheels, which greatly diminish, or altogether prevent the loss of motion which would be caused by the friction of the axle, if it revolved on an immoveable surface (Atwood, 1784: p. 338).

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[2]Note that, according to Atwood's terminology, "moving force" is for force, "accelerating force", for acceleration; and "quantity of matter", for mass.

[3]To this regard, it is quite illuminating what writes still in 1922 a reviewer of Atwood's *Treatise*, evidently considered just as a modern textbook: "though written in 1784, some of its pages are greatly superior to those in many of the textbooks now in use in schools, and one is particularly impressed by the stress laid on experimental verification of the various laws of mechanics, and by the extreme care shown in the planning and execution of the experiments proposed" (Hall, 1922).

Such an apparently tricky mechanism, introduced earlier probably by the French clockmaker Henry Sully (Sully, 1726), was installed by Atwood on the top of the cylindrical column of his machine, upon which a weight operated clock is as well mounted in order to perform time measurements, while a ruler with "a scale about 64 inches in length graduated into inches and tenths of an inch" is added on another vertical column to allow measurements of the distances covered by the bodies suspended on the string. The assemblage with the wheels is, interestingly enough, a removable piece of the machine: Atwood was, indeed, creating a device capable of studying rectilinear motions as well as rotation of bodies, to which almost half of his *Treatise* is devoted. The recognition of this important second part of mechanics will be lost in subsequent descriptions of Atwood's machine in textbooks—and further copies of the machine itself will no longer show the *removable* assemblage with the friction wheels—but it should not fall into oblivion the fact that Atwood was originally aimed to conceive a "universal" machine suited for studying both rectilinear and rotational motion. This is clearly testified by a number of interesting and intriguing experiments, proposed in his *Treatise*, to be realized with the aid of additional accessories sketched in figures 84 - 88 of the book (Atwood, 1784). However, while the main part of the machine "was executed with great mechanical skill, partly by Mr. L. Martin, and partly Mr. G. Adams, mathematical instrument makers in London" (Atwood, 1784: p. 337), such accessories, especially the principal one drawn in figure 84 of (Atwood, 1784), were never realized, probably for the change of working interests; see the biographical notes above. Thus, Atwood's machine was subsequently associated only to the studies on rectilinear motion under the action of a constant force.

Displaying the Newtonian Paradigm

How did Atwood obtain a satisfactory illustration of the Newtonian paradigm with his machine? The first step is, obviously, to reproduce the Galilei's law of proportionality between the traveled distances s and the square of the elapsed time t in the uniformly accelerated motion: $s \propto t^2$. Under the "action of the constant force m" (m, here the unbalanced net moving force, corresponds to the weight of 1/4 oz of matter; it is considered as a standard quantity in Atwood's experiments),

if the times of motion be 1 second, 2 seconds, and 3 seconds, the spaces described from rest by the descending weight A in those times will be 3 inches, $3 \times 4 = 12$ inches, and $3 \times 9 = 27$ inches respectively; the spaces described from rest being in a duplicate ratio of the times of motion (Atwood, 1784, p. 318).

The second step is to study the dependence of s on the acceleration a of the descending body, here obtained—in units of the free fall value g—from the ratio of the unbalanced mass to the total mass of the bodies on the pulley (in modern terms, $a/g = \Delta m / \Delta m_{tot}$):

It appears from these experiments, that when the times are the same, the spaces described from rest are as the accelerating force (Atwood, 1784: p. 320)

(recall that "accelerating force" means just acceleration). That is to say, $s \propto a$. What else about the equation of motion regarding the distance traveled? *Obviously*, that $a \propto 1/t^2$:

The latter part of the experiment shows, that if the space described remains the same, while the time description is diminished, the force of acceleration must be increased in a duplicate proportion of the times' diminution (Atwood, 1784: p. 321).

From these three experiments, then, the full time law that, in modern terms, we write as $s = 1/2\, at^2$, is completely derived[4].

Next, Atwood considers experiments suitable for obtaining the law for the velocity, whose measurement with the machine is particularly intriguing (and, mainly, *feasible*). Indeed, let us suppose with Atwood that the instantaneous velocity of the descending body is requested when it passes at a certain height. Then a ring is placed at that height on the column with the ruler, whose ring is designed to remove the additional, unbalanced mass (whose length exceeds ring's diameter) while allowing the passage of the main body upon which it is affixed. In such a way, and from now on, the pulley is completely balanced, and the two bodies continue to move with constant velocity, whose value is easily obtained from the ratio of the distance traveled in a given time. With this trick, the law for the velocity can be tested experimentally even when a constant force is applied to the body, and the first result to be obtained is the proportionality between the instant velocity and the time elapsed: $v \propto t$.

During the different times 1 second, 2 second, 3 seconds, etc. the velocities generated will be those of 6 inches, 12 inches, and 18 inches in a second respectively, being in the same proportion with the times wherein the given force acts (Atwood, 1784: p. 324).

Then:

It appears therefore, that if different forces accelerate the same body from quiescence during a given time, the velocities generated will be in the same proportion with these forces (Atwood, 1784: p. 326)

(again, "forces" means "accelerating forces" or, simply, acceleration), that is to say, $v \propto a$ in a constant time. Finally, as above, the complete law $v = at$ is obtained by means of proportions:

if bodies be acted in by accelerating forces, which are in the proportion of 3:4, and for times, which are as 1:2, the velocities acquired will be in the ratio of 1×3 to 2×4, or as 3 to 8 (Atwood, 1784: p. 326).

The story, however, does not end here, as could be hastily expected. Indeed, other two experiments are described to show that, for bodies accelerated through the same space s, $v \propto \sqrt{a}$ (Atwood, 1784: p. 327) and, conversely, under the action of the same acceleration a, $v \propto \sqrt{s}$ (Atwood, 1784: p. 328). That is to say, in modern terms, $v = \sqrt{2as}$.

Finally, and more importantly, "the moving force must be in the same ratio as the quantities of matter moved," which is Newton's second law of dynamics (Atwood, 1784: p. 328):

Experiments to illustrate this truth may be comprised in the subjoined table.

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[4]According to the introductory mathematical chapter in the *Treatise*, Atwood never uses absolute equations, so that any physical law is always expressed as a proportion. Thus, in the present case, the factor 1/2 does not appear, and the final result is rather written as $s/s' = at^2/a't'^2$. The same applies below, though we will use modern notations for simplicity of explanation.

Moving forces	Quantities of matter moved	Accelerating forces	Spaces described in inches	Velocities acquired in inches in a second
m	64 m	1/64	12	12
3/2 m	96 m	1/64	12	12
3/4 m	48 m	1/64	12	12

From the first three columns it is evident that the "moving force" is equal to the product of the "quantity of matter moved" times the "accelerating force", or, in modern notations, $F = ma$. It is interesting to compare such a result, directly obtained from *experiments*, with the original *Newton's* formulation of the second law in terms of momentum variation rather than acceleration [see the discussion in (Westfall, 1971)].

The accuracy of the conclusions reached by Atwood obviously depends on the sensitivity of his machine and on possible systematic errors primarily related to friction and to the promptness of the experimenter for time measurements. This last point was considered only in broad outline by Atwood, who just warned possible other experimenters to train with the "simultaneous" activation of the pendulum clock with the start of the descending body. This is evidently—a priori—the major source of inaccuracy, and we will back on it in the next Section. The friction issue, including air resistance, has been already dealt with above, but here we mention the fact that Atwood did not limit himself to simply state that "the effects of friction are almost wholly removed by the friction wheels" (Atwood, 1784: p. 316). Indeed, he quantified such assertion by making a preliminary experiment:

> If the weights *A* and *B* be balanced in perfect equilibrium, and the whole mass consists of 63 *m*, according to the example already described, a weight of 1 1/2 grains, or at most 2 grains, being added either to *A* or *B*, will communicate motion to the whole, which shows that the effects of friction will not be so great as a weight of 1 1/2 or 2 grains (Atwood, 1784: p. 316).

Note that a mass of 1 *m* corresponded to 1/4 oz (and thus 63 $m \approx 16$ oz), while 480 grains accounted for 10 oz (and thus 2 grains $\approx 1/240$ oz), so that the sensitivity of the pulley was extremely high. With his device, Atwood was then able to measure accelerations as low as 1/64 of the free fall value (Atwood, 1784: p. 305), an unprecedented accuracy in such studies.

This fact was also the reason for the subsequent fortune of Atwood's machine.

Other Topics in the Treatise

The description of the machine and the discussion of the experiments performed with it occupy only about 10% of Atwood's *Treatise*, so that we cannot leave the issue without even a rapid mention of the remaining topics covered in the book, again aimed at establishing the Newtonian paradigm. The major part of them is devoted to display the theory regarding rectilinear motion, mainly related to the experiments later considered, with few intriguing exceptions.

One of these, which is worth to mention, is the discussion of the resistance opposed to spherical bodies when impinging on given substances. According to Atwood, the resistance force F_R depends, of course, on the substance considered, this effect being parameterized by the penetration depth δ, and is proportional to the square of the diameter *D* of the body; in modern notation: $F_R \propto \delta D^2$ (Atwood, 1784: p. 40).

The only other "exceptions" we here point out regard, instead, the affair related to the concepts of momentum and *vis viva*. Although Atwood discusses at length such issues in Section IX of his *Treatise* (Atwood, 1784: p. 356), he introduces the relevant quantities well before. The momentum $q = mv$ is introduced in the discussion of (a particular case of) what we now call the theorem of momentum:

> The moving force which communicates, and the force of resistance which destroys the motion of bodies in the same time, will be in a compound ratio of the quantities of matter in the moving bodies, and velocities generated or destroyed (Atwood, 1784: p. 36).

In modern notation, for given time interval, $F \propto mv$. Analogously, the *vis viva* mv^2 is introduced in the discussion of (a particular case of) what we now call the theorem of kinetic energy:

> If bodies unequal in quantities of matter, be impelled from rest through equal spaces, by the action of moving forces which are constant, these forces are in a duplicate ratio of the last acquired velocities, and the ratio of the quantities of matter jointly (Atwood, 1784: p. 29).

That is, in modern notation, for a constant force acting for a given distance, $F \propto mv^2$. Echoes of the not yet extinguished polemic with the Leibnizian view of mechanics in terms of living forces are present in Section IX of the *Treatise*, where Atwood considers the "conservatio motus" introduced by Daniel Bernoulli in discussing (one-dimensional) impact of bodies. While we cannot enter here in such an issue, and thus refer the interested reader to the existing literature (see, for example, (Schaffer, 1994) and references therein), we only mention how Atwood posed the physical question. How define the momentum *q* of a body in motion? In terms of *mv* (Atwood, from Newton) or, rather, mv^2 (Bernoulli, from Leibniz)? Atwood's answer was intimately related to the physical properties of (one-dimensional) impact of bodies: according to him, Bernoulli's *conservatio motus* necessarily implied $q = mv$.

The only other polemic present in the *Treatise* is with J. Smeaton about the role of friction. While the natural philosopher Atwood was trying to design frictionless machines, the engineer Smeaton set out to measure friction's effects. The different attitudes are evident: while friction is seen by Atwood as an obstacle to the clear manifestation of the perfect Newtonian laws of Nature, it is instead an important piece of consideration for engineers and engine makers. Additional, interesting details on this polemic, here only trivialized, may be found in (Schaffer, 1994), where a special emphasis is given on what dubbed as social function of friction.

Finally, few words should be said on the second great topic of the *Treatise*, that is rotation of bodies. Indeed, Atwood's book is as well a splendid example of XVIII century's treatise on the mechanics of rigid bodies, with a number of interesting examples and applications, an idea of which may be formed just by looking at the drawings at the end of the book. A clear definition for the centre of gravity is given, together with a discussion of its relevance for rigid body's motion. Also, the concept of moment of inertia is already present in Atwood's *Treatise*, implicitly introduced in the cardinal law for the rotation.

In any revolving system, the force which accelerates the point to which the moving force is applied, is that part of the acceleration of gravity which is expressed by a fraction, of which the numerator is the square of the distance at which the force is applied from the axis, multiplied into the moving force, and the denominator the sum of all the products formed by multiplying each particle of the system into the square of its distance from the axis of motion (Atwood, 1784: p. 345).

In formulae, $a = r^2 F/I$ (I being the moment of inertia), which is just a particular case of the law for the torque M.

Other key, general results for the rotation of rigid bodies are considered and discussed in the *Treatise*, but their punctual reconstruction is here unnecessary: Atwood's main aim of the general achievement of the grandiose Newtonian paradigm has been, probably, well illustrated from what discussed above.

The Spreading of Atwood's Machine: G. S. Poli and J. H. De Magellan

The direct spreading of Atwood's machine outside the borders of England was due mainly to the work of two scholars, who were eyewitnesses of the experiments performed by Atwood with his novel machine: namely, the Portuguese J. H. de Magellan and the less known Italian G. S. Poli.

A Newtonianist in Naples

Giuseppe Saverio Poli was born in Molfetta, Italy where he completed his first studies at the Jesuit College which, together with the Convent of the Dominicans, culturally animated this small agricultural and fishing town [the most recent biography of Poli is in (De Gennaro, 2006)]. In 1764 his family arranged for him to study at the University of Padua, where he graduated in Medicine, and in 1771 moved to Naples practicing as a doctor at the *Ospedale degli Incurabili* and, one year later, he was entrusted with the teaching of Geography and History at the "Nunziatella" Military Academy. It was during this period that Poli resumed his studies (began in Padua) on electricity and, in 1772-3 he published two books on the formation of and effects induced by thunder and lightning (Poli, 1772; Poli, 1773). In the second of these books, Poli described a series of experiments conducted by himself and questioning about one of the main theories of Benjamin Franklin, i.e. about the adiathermanous property of glass (Franklin was the first, in 1751, to suppose that glass is completely impermeable to heat rays). Poli did not know an explanation for some observed anomalies of electrified glass, but noted that they were not justified by Franklin's dominant theory. Nevertheless, to explain with his model also the insulating effect that the glass sometimes displayed, Poli resorted to the existence of two forms of electricity, which he called "by source and by contact" (Schettino, 2000).

As a result of his success within the scientific community in Naples, in 1775 Poli was entrusted with the important task of traveling on behalf of the King of Naples, in order to acquire scientific instruments for the Military Academy and also to study the cultural institutions of the major European capitals. This "scientific" journey lasted five years, but very few details are known about it (Toscano, 2009); some information about his stay in Cambridge and the meeting with Atwood may be, however, deduced from his later textbook (Poli, 1781a).

Meanwhile, spurred by a group of reforming intellectuals, in 1778-1779 Ferdinand IV of Bourbon founded in Naples two important institutions: the Royal Academy of Sciences and Humanities, and the Medical School of the *Ospedale degli Incurabili* (Borrelli, 2007; Borrelli, 2000). Director of the School was Giovanni Vivenzio, who urged the authorities in order to establish in it the teaching of Experimental Physics, with the related "theater" where experiments could be performed according to the Newtonian address. The intention of those reformers was to create a new kind of doctors, updated on the latest scientific results, and Vivenzio was able to obtain that the examinations of Anatomy and Experimental Physics were mandatory, and that students could not graduate without a good knowledge on these subjects.

The teaching of Experimental Physics was entrusted to Poli, who was informed in late 1780, when still in England: this was an opportunity to ask the famous instrument maker Jesse Ramsden (Webster, 1986), encountered in his stay in England, to build the new machine invented by Atwood in order to study the physical laws of kinematics and dynamics.

The Atwood Machine Arrives in the Continent

According to Poli, Atwood's machine he commissioned to Ramsden would have been useful in his teaching to the young students of the Medical School, as clearly highlighted in the inaugural lecture which he held for the start of the course in Experimental Physics (Poli, 1780). Such inaugural lecture was printed by the Royal Printing Office (*Stamperia Reale*), this showing the importance given to that course. The same intention may be deduced from another inaugural lecture, printed in the subsequent year, that for the course in Experimental Physics for the cadets of the "Nunziatella" Military Academy (Poli, 1781b): here Poli laid the foundations for how he dealt with the study of Nature.

In the meantime, Poli had left England and, in this same year, he gave to the press his textbook on the *Elementi di Fisica Sperimentale* (Poli, 1781a), already mentioned above. The particular relevance of this first edition[5] of the *Elementi* follows from the fact that for the first time a plate appears in it, engraved by de Grado, with the illustration of Atwood's machine (note that Atwood's *Treatise* was published only three years later, in 1784). The instrument illustrated in this textbook was the copy ordered to and built by Ramsden; its story, along with those of the other first models of Atwood's machine is quite intriguing.

The copy purchased by Poli for his course at the Medical School and at the Military Academy in Naples arrived in Marseille in October 1782 and was delivered to the countess Zuccheri Stella, who took charge of sending it to Naples so that it could be delivered to Poli:

Dal Sig. Gioacchino Bettalli di Parigi mi fu spedito una cassa contenente istrumenti fisici, e pezzi dell'istoria naturale, la quale lui mi dice avere avuto ordine dal Sig. Cav. Poli di recapitarmela; questa essendomi alla fine giunta, non sapendo io se il d. Sig. Cav. Poli si trova costì, o altrove; e dall'altra parte sapendo per relazione del mio cugino l'Abbate Boscovich, che la d.a cassa deve servire per uso di codesta Università, ho stimato mio dovere spedirla alla direzione di V. S., sicura, che darà ordini, che

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[5]The first Neapolitan edition of 1781 is rarely mentioned in the literature, while the second Neapolitan edition of 1787 is often quoted as the first one.

sia essa consegnata a chi compete [Countess Zuccheri Stella to Marquis Della Sambuca, 19 October 1782, in (Borrelli, 2000)][6].

Some months before, another Atwood's machine, built by Adams, arrived in the port of Genoa: it was delivered to Alessandro Volta in May 1781:

Al mio arrivo qui ho trovato le sei Casse di Macchine provenienti da Londra, ch'io già sapeva da qualche tempo essere giunte in Genova [...] Credo non sarà discaro a V. E. ch'io Le faccia particolarmente conoscere l'indicata Macchina del Sig. Atwood, la quale riunisce i due più grandi pregi di facilità ed esattezza nelle sperienze che si fanno con essa [Volta to Count Firmian, 1 May 1781, in (Volta, 1951)][7].

These are the only two Atwood's machine that reached Italy in 1781-1782. While Poli had been in Cambridge to see Atwood demonstrating his machine, thus deciding to order a copy of it for his course in Naples, Volta didn't. It was the Portuguese Joao Jacinto de Magalhaes, who met Atwood in England, to write to Volta, then teaching at Pavia, and inviting him to subscribe to Atwood's forthcoming *Course of Lectures* [J. H. Magellan to A. Volta, 9 April 1779, in (Volta, 1951)] and, later, to one of the four prototypes of Atwood's machine built between 1780 and 1782, to be addressed to the Physics Laboratory of the University of Pavia [J. H. Magellan to A. Volta, 21 November 1780, in (Volta, 1951)].

Better known to the English-speaking world by the name under which he published most of his works, Jean-Hyacinthe de Magellan (Pierson, 1979) was born in Portugal in 1722 and, at the age of eleven, went to an Augustinian monastery in Coimbra where he spent the next twenty years living and studying. The scientific tradition among the Coimbra Augustinians (who knew and studied the works of Newton) allowed him to become familiar with science, particularly astronomy, and after received permission from Pope Benedict XIV to leave the order, in 1755 Magellan started a "philosophical tour" through Europe, finally settling in 1764 in England. Although he produced no particularly relevant scientific works (the large part of which related to scientific instruments), he is known chiefly for his wide circle of acquaintances and for acting as an intermediary in disseminating new information, mainly about chemistry and experimental physics. Among the people he met during his life, we mention only very few names, including A. Lavoisier and J. J. Rousseau in France, Atwood and J. Priestley in England, Volta and many others. His work and notoriety earned him membership in the Royal Society of London (1774), the Academia das Ciencias of Lisbon (1780) and the American Philosophical Society of Philadelphia (1784), as well as corresponding membership in the science academies in Paris, Madrid, Bruxelles

and St. Petersburg.

Magellan published the letter quoted above to Volta in a pamphlet of 1780 (Villas-Boas, 2000), where he described the new Atwood's machine for studying dynamics, four years before Atwood himself succeeded in publishing his *Treatise* describing all the properties of his device.

Cette machine, dans son état actuel, rend sensible les loix du mouvement *uniformément acceleré*, ou *reiarde*, de meme que celles du mouvement *uniforme*, sans employer qu'un éspace moindre de *cinq pieds & demi*; ce qui la rend extremement commode & tres avantageuse dans un Cours de Physique. La simplicité & l'exactitude avec laquelle cette machine rend ce genre d'expériences a la portée des sens, sont éncore son plus grande mérite: car vous savez que les observations sur la *chute des corps*, & *l'acceleration de leurs vitesses*, démandent des operations très delicates, fort difficiles, & asséz laborieuses: & ce qui plus est, tout-a-fait impraticables dans un Cours régulier de Physique Experimentale (Villas-Boas, 2000)[8].

In the *additions et corrections* to his pamphlet, Magellan stated explicitly that there were four machines that were being built:

Tandis qu'on imprimoit cette Lettre, j'eus occasion de faire les observations et rémarques suivantes, on examinant, comme je vous l'ai promis, Monsieur, la machine qui vous est destinée; & une autre que j'envoyerai aussitot a mon ancien Confrere, les tres-R.P.D. Joachim de l'Assumption, Chanoine Regulier d'un mérite sort distingue, actuellement Professeur de Physique dans le Monastere Royal de Chanoines Reguliers Lateranenses de S. Augustin a Mafra, pres Lisbonne. Ces deux machines sont marquées avec les N. 3 & 4; parcequ'en effet, on n'a pas éncore fait plus, que deux autres machines de cette espèce jusqu'a present, meme en y comprénant celle de l'inventeur (Villas-Boas, 2000)[9].

The same news (evidently taken by Magellan) is reported in the letter by Volta mentioned above: "la Macchina che mi è giunta è la terza appena che sia stata fatta, non essendosene fino ad ora fabbricate più che due altre, compresavi quella dell' illustre inventore" [Volta to Count Firmian, 1 May 1781, in (Volta, 1951)][10].

Contrary to what sometimes appeared in literature (Magellan, 1780), it is thus evident that the first copy of Atwood's ma-

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[6]"Mr. Gioacchino Bettalli in Paris sent out to me a case containing physics instruments and several specimens of natural history. He writes that he was commissioned by Mr. Poli to send me that case. Having arrived such a case, since I do not know if Mr. PoIi is there or somewhere else, while knowing from my cousin, the Abbé Boscovich, that the said case shall serve for use in this University, I have thought it my duty to send it to your lordship, sure that you will give orders that it be given to who be due."

[7]"On my arrival I found the six boxes with the machines coming from London, about which I already knew since some time to be arrived in Genoa [...] I think it will not be displeasing to Your Excellency that I make known to You the aforesaid machine of Mr. Atwood, which combines the two greatest advantages of ease and accuracy in the experiences that we can do with it."

[8]"This machine, in its present form, allows the demonstration of the laws of the *uniformly accelerated* or *retarded* motion, as well as those of *uniform* motion, by using a space less than *five and a half feet*; making it extremely useful and profitable within a Course of Physics. The simplicity and accuracy with which this machine makes this kind of experiments within the reach of the senses, remain his greatest merit, since you know that the observations on *falling bodies and their accelerations require very delicate, difficult and laborious operations*; *and, what is more, all of them is impracticable in a regular course of Experimental Physics*".

[9]"While printing this Letter, I had occasion to make the following comments and observations, when examining the machine that is for you, Sir, as I have promised to you, and another one that I have to send as soon as possible to my former colleague, the very R. H. Don Joachim de l'Assumption, a very distinguished Canon Regular, currently Professor of Physics in the Royal Monastery of Lateran Canons Regular of S. Augustine in Mafra, near Lisbon. These two machines are marked with N. 3 and 4; indeed, we have not yet built more than two other machines of this kind until now, including also that of the inventor".

[10]"The machine that has come to me is just the third to have been made, no more than two others having been produced, including that of the illustrious inventor".

chine—that "marked" with N. 2—was that realized by Rams-den on behalf of Poli.

Intriguing Changes

As recalled above, the major source of errors in the experiments performed with Atwood's machine came from the

As recalled above, the major source of errors in the experiments performed with Atwood's machine came from the possible non simultaneous activation of the pendulum clock with the start of the descending body, such ability being left to the promptness of the experimenter. Poli apparently remedied to such possible inconvenience: indeed, the machine manufactured by Ramsden had a *novelty* compared to those built by Adams, that is a lever that allowed the experimenter just to start simultaneously the motion of the pendulum and the fall of the mass:

> Le parti principali di cui è composta questa nuova Macchina, sono l'asta verticale AB dell'altezza di cinque piedi e mezzo, divisa in 64 pollici; le cinque picciole ruote C, D, E, F, G; i tre sostegni H, I, S, il pendolo K, ed i pesi convenienti. [...] Come in fatti lo stesso Autore mi ha dimostrato, che anche nella massima velocità, che si suol dare al peso 0, la resistenza, che l'aria fa su di esso, a mala pena supera quella del peso di un grano. [...] V'è nell'asta AB una molla, guarnita di un bottoncino P, mercé la cui pressione si fa sì che nel medesimo istante cadano i due sostegni H ed I, e quindi che il Pendolo K ch'era arrestato dal sostegno I, incomincia ad oscillare nel punto stesso, che il grave 0 incomincia a discendere. A codesto picciolo meccanismo si è data la massima perfezione dal felicissimo genio del celebre Ramsden (Poli, 1781)[11].

In **Figure 1**, reproduced here from the Atwood's *Treatise*, we find the original design of the machine: all the models built by Adams conform to such design. In these early prototypes, there are two vertical arms: one supports the pendulum clock for the measurement of time, while the other arm supports the ruler and the latches for the two weights with the gear of the pulley. The machine realized by Ramsden, instead, has a different making: as it is evident from the plate engraved by de Grado for the 1781 edition of Poli's *Elementi* (see **Figure 2**), there is a single vertical arm (parallelepiped-shaped) supporting both the pendulum clock and the latches for the two weights. The trigger mentioned above is as well anchored to the single vertical arm, allowing an easy start of the experiments. Convinced that such a trigger would have reduced the measurement errors, Poli directly spoke of this improvement with Atwood who, however, did not appear entirely persuaded of its effec-

Figure 2.
The plate in the first edition of Poli's Elementi (Poli, 1781) with the illustration of Atwood's machine built by Ramsden.

tiveness, or, rather, was convinced that it would not have improved the measurements. Nevertheless, as a matter of fact, Atwood mentioned this problem—though giving only a broad outline of it—in his *Treatise*, this being probably a reminiscence of Poli's advice (Atwood, 1784: p. 308). Interestingly enough, the machines that were built later (during the XIX century) had all this trigger, though the instrument makers chose to use two vertical arms instead of only one, by keeping separate the pendulum clock from the weights.

The set of five friction wheels was quite immediately simplified: in the 1801 edition of the *Traité eleméntaire de Physique* by A. Libes (Malaquias & Thomaz, 1994), for example, Atwood's machine was already represented with just a simple pulley on the top of a vertical arm with a ruler. Even without resorting to such extreme simplifications, it is nevertheless a matter of fact that, in any of the copies realized in the XIX century, the removable apparatus with the friction wheels in the

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[11]"The main parts that make up this new machine are: the vertical arm *AB* with a height of five feet and a half, divided into 64-inches; five tiny wheels C, D, *E, F, 0, H*; three holders *H, I, S*; the pendulum *K*; and suitable weights. [...] In fact, as the author himself has shown me, even in the case of the maximum speed usually reached by the weight 0, the resistance offered by the air on it barely exceeds that of the weight of one grain. [...] In the vertical arm *AB* there is a spring, provided with a button *P*, through the pressure of which it causes the two holders Hand *I* to open at the same moment, and therefore the pendulum *K*, which was kept idle by the holder *I*, begins to oscillate at the same moment in which the weight 0 begins to descend. The highest perfection of this small mechanism is due to the happy talent of the renowned Ramsden".
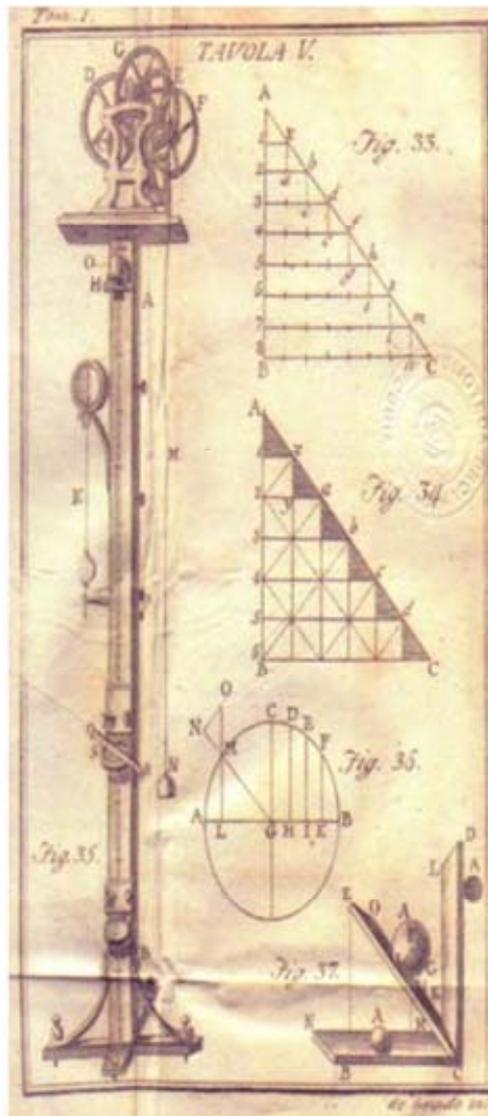
original prototype was replaced by a fixed one: the original intent of a "universal" machine for translational and rotational motions disappeared.

An apparent exception to such boost to simplify is given by Poli's *Elementi* (Poli, 1781) which, in any of its 23 editions (ranging from 1781 to 1837, i.e. well beyond the death of Poli), Atwood's machine is invariably depicted as in the 1781 edition[12], this being evidently related to the original instrument that Poli had at his disposal. It is interesting to note that, although Poli himself gave a simplified presentation in his treatise of Atwood's machine and of the experiments that could be performed with it, as any other author did, nevertheless he stressed his will to revisit the subject in a later work:

> Tutte le rapportate dottrine riguardanti la discesa de' gravi, rintracciate mirabilmente dall'immortal Galileo, render si possono sensibilissime, ed evidenti, mercé di una Macchina inventata, non è molti anni, dal Signor Atwood, Professore di Fisica nell'Università di Cambridge, e mio rispettabile Collega nella Società R. di Londra. Converrebbe scrivere un intiero trattato per dare una compiuta idea di siffatta Macchina, e per indicare la maniera, onde si debbono con essa istituire tutti gli esperimenti. Sarà questo in qualche parte il soggetto di un'altra mia Opera (Poli, 1781).[13]

However, not only Poli did not add a specific chapter on this subject in any of the subsequent editions of his *Elementi,* but he did not publish even any other work regarding Physics, devoting himself in those years to the writing of a major work concerning testaceans (De Gennaro, 2006).

A Different Use

The small (but relevant) changes introduced in the realization of copies of Atwood's machine seen above were, of course, functional to a better operation of the machine, but the "simplification" of it as a whole intervened already at the beginning of the XIX century does not call for a similar explanation. This can be searched, instead, by looking at the use that scholars made of the machine which, as already envisaged in the quotation above from Poli's *Elementi*, was substantially *different* from the original Atwood's intention. Even more explicitly than Poli, the following words by Volta are illuminating:

> V.E. può giudicare di qui se [la Macchina] è novissima: lo è tanto, che non è comparsa ancora l'Opera che il Sig. Atwood medesimo promette di pubblicare sopra questa sua Macchina di Dinamica, dove la descrizione ne sarà più compiuta di quella che or ci dà il Sig. Magellan [...] Ho ripetute io già le principali sperienze propostaci in essa ne' 14 problemi, e le ho variate in più maniere; e sempre l'esito ha corrisposto alla teoria con una preci-

sione, che maggiore desiderar non si potrebbe. Le leggi della caduta dei gravi son messe così chiaramente e distintamente sott'occhio, che anche chi nulla conoscesse della teoria, vi è tosto condotto e le intende a maraviglia. Da qualche giorno che ho messo alla prova la Macchina non so quasi occuparmi d'altro, tanta e la soddisfazione che ne ritraggo [Volta to Count Firmian, 1 May 1781, in (Volta, 1951)][14].

What was the original motivation for the construction of the machine—that of displaying the Newtonian paradigm—has now been changed: its use was quite soon limited just to perform several illustrative experiments on the falling of bodies with a single and accurate device. This is, indeed, the use made of Atwood's machine since the end of the XVIII century until recent times (whereas, sometimes, the experimental study on the falling of bodies is replaced by generic studies on uniform and uniformly accelerated motion).

The reasons for this apparent change of mind are, again, contained in the quotation above: the machine arrived in the Continent well before the appearance of the *Treatise* where Atwood explained its original use, while the description of the experiments that could be performed with it was spread only through the work of the eyewitnesses Poli and, especially, Magellan. While, on the one hand, this implied a rapid fortune of Atwood's machine, given the success of the Poli's *Elementi* with its 23 editions and the indefatigable work as intermediary of Magellan, on the other hand it evidently allowed the subsequent scholars to make (only) a different use of the machine, given the already occurred achievement of the Newtonian paradigm. Furthermore, Atwood himself contributed indirectly to such direction, since he never reissued the 1784 edition of his *Treatise*, having later changed his interests, as recalled above.

Summary

The structure of Newtonian physics is, as well known, based on the organization of scientific knowledge as a series of mathematical laws and, according to early codification by Galilei, such laws require experimental validation. In the XVIII century, physical demonstrations took place in different ways and for different audiences, ranging from academic courses to popular lectures. In the present paper, we have shown how the Newtonian paradigm was definitively accepted in science courses—in England as well as in the Continent—by means of the dynamical machine invented by Atwood in late 1770s just for this purpose. Although being aware that the ultimate test of Newton's mechanics would have come from experiments showing the effect of variable forces, the experimental conditions of his epoch forced Atwood to turn to constant forces, for which he designed a single machine in order to test, in simple experiments, *all* the kinematical and dynamical laws for those

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[12]An irrelevant difference appearing since the second edition concerns only the initial position of the pendulum: in the 1787 edition, it is sketched at the starting of the oscillation, rather than at rest.

[13]"Any result concerning the falling of bodies, as admirably deduced by the immortal Galileo, can be made extremely accurate and evident by means of a machine invented, not many years ago, by Mr. Atwood, Professor of Physics at the University of Cambridge and my respected colleague at the Royal Society of London. It would be appropriate to write an entire treatise in order to give an idea of such a machine and to describe how any experiment could be performed with it. This will be somewhere the subject of another work of mine".

[14]"Your Excellency will judge from this whether [the machine] is new: it is so much new that has not yet appeared the work that Mr. Atwood himself has promised to publish about his dynamical machine, where it will be given a more complete description of what we now have from Mr. Magellan [...] I have already repeated the key experiments proposed by him in the reported 14 problems, having changed them in several ways; the results always conformed to the theory with an accuracy, that you could not desire more. The laws on the falling of bodies are made so clear and distinct, that even those who know nothing of the theory are led to fully understand them. I tested the machine since few days, and I almost cannot take care of other things, so great is the satisfaction I feel with it".

forces, as coming out from Newton's mechanics. Particularly relevant is the mechanism he devised to measure the velocity acquired by the body during its accelerated motion: in Galilei's inspired experiments on the free fall or on the motion along an inclined plane, indeed, only the proportionality between the traveled spaces and the square of the elapsed time could be established. But, probably, the astonishing result was the unprecedented accuracy with which Atwood tested the Newtonian laws of motion, being able to measure acceleration as low as 1/64 of the free fall value. As described in his *Treatise* of 1784, Atwood's original aim was not limited to the mechanical laws of the rectilinear motion, the machine having to serve also for studying the rotation of bodies (in the *Treatise*, a number of experiments are described concerning this topic, with the aid of additional parts, never effectively realized), but such an incredible accuracy catalyzed the interest of any of the subsequent scholars who used the machine in their demonstrations.

The spreading of Atwood's machine outside England occurred well before the appearance of the *Treatise*, where it was described along with the experiments to be performed with it. In fact, some scholars who had the opportunity to attend Atwood's demonstrations in Cambridge in the late 1770s, realized immediately the importance of the novel machine, and disseminate the news, even subscribing (or suggesting the subscription to other scholars) to the acquisition of copies of that machine. Thus, it was the Portuguese Magellan the first to publish (in 1780) a pamphlet where the new machine was broadly described, along with a set of experiments concerning uniform and accelerated motion, in the form of a letter addressed to Volta in Pavia. Instead, it was the Italian Poli to report (in 1781) for the first time an illustration of the novel machine, realized on the copy ordered to the instrument maker Ramsden, in his textbook where a choice of experiments are described as well.

The model manufactured by Ramsden (the second one ever realized, including the original one owned by Atwood) introduced an additional device, suggested by Poli, in order to trigger the simultaneous activation of the pendulum clock and the start of the descending mass. Clearly aimed at a better operation of the machine and, consequently, at a reduction of the measurement errors, this additional lever was always included in later copies of the machine during the XIX century, irrespective of the "simplification" of Atwood's machine (the removable set of five friction wheels was replaced by a fixed set of wheels or even just a simple pulley) that was going on already at the very end of XVIII century.

Such changes which were occurring on the machine are emblematic of the different use made of it. Once Newton's mechanics was definitively accepted in academic courses as the only possible theory of motion, Atwood's machine did not serve anymore as a device displaying the success of the Newtonian paradigm. Its use then changed accordingly: several illustrative experiments on the falling of bodies, or even just on uniform or uniformly accelerated motion may be performed with a single and accurate machine. This is, indeed, the use made of Atwood's machine until now.

The historical case studied here, therefore, allows us to recognize the relevant role played by a properly devised instrument in the acceptance of a new paradigm by non-erudite scholars, in addition to the traditional ways followed by erudite ones (almost exclusively considered in the literature), where mathematical, philosophical or even physical reasoning certainly dominates over *machine philosophy*.

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