Transforming Forces: A Potenzmaschine's demonstration of late eighteenth-century mechanics

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This essay applies Jules David Prown's methodology for the analysis of unknown objects to examine the aesthetic and functional properties of a Potenzmaschine, an instrument that demonstrates the transformation of forces by simple machines, from the founding collection of Deutsches Museum (Inv.-Nr. 1457). Connecting the material evidence to written evidence of lecture-demonstrations by Ildephons Kennedy in Munich, publications on mechanics, and instrument makers' workshops in the late 18th century allows for tentative conclusions about the Potenzmaschine's production as well as its uses. Differently skilled makers likely created the parts, and the Potenzmaschine may have been used for both public lecture demonstrations and school demonstrations.

Keywords: Potenzmaschine, history of physics, lecture-demonstrations, Ildephons Kennedy, Bayerische Akademie der Wissenschaften, Deutsches Museum, Material Culture

Objects as primary historical sources

When embarking on this inquiry into the history of physics through investigating a specific object from the physics collection at Deutsches Museum, I became curious to know the history of studying history through objects. Peter Miller's "History and Its Objects" follows the legacy of antiquarianism from the 1500s throughout the centuries, showing how objects were used as evidence of beliefs, ideas and values. In the 19th and early 20th century, engagement with material culture took place outside of academia "because of historians' total lack of interest in things" (Miller 2017: 33). However, the institutional founding of a master's program at the Winterthur Museum - University of Delaware in 1952 rang in a time of growing academic historical engagement with artifacts, the academic material turn being a rather "slow awakening" (Miller 2017: 33). A reflexivity about artifacts and materiality remains current today, for artists, biographers, designers, and of course for historians to whom objects, in their greater independence from human intentionality, allow an interrogation of the beliefs of a society or group at a given time that may contradict and complement more intentional sources like written documents (Miller 2017: 37–38).

In the 1980s–90s, scholars such as Jules David Prown and Susan Pearce attempted to refine the analytical approaches of E. McClung Fleming and others to the study of material culture (Fleming 1974; Prown 1982; Pearce 1994 [1986]). Prown's detailed methodology for how to engage with an entirely unknown object forms the basis of my approach here. Prown proposes the investigation of an unknown object should begin with a description, including substantial analysis (physical dimensions, material, how its parts were put together), content (decorative designs, inscriptions, engravings), and formal analysis (visual character, 2D and 3D organization). His second step, deduction, includes sensory engagement (texture, heft, touch and adjustments users may have made), intellectual engagement (what it does and how it does that), and emotional response. The final step, speculation, invites theories and hypotheses, leading to a plan for investigating the scholarly questions posed by the material evidence (Prown 1982: 7–10). However, Prown expresses apprehension regarding the application of his approach to "machines, vehicles, scientific instruments, musical instruments, implements", a category of artifacts he called devices (Prown 1982: 3). He explains his apprehension with their externally directed intention of utility, proposing that their aesthetic aspects are relevant for cultural analysis but their functional ones are not (Prown 1982: 14–15). In this essay, I investigate *both* the aesthetic *and* functional aspects of an unknown (to me) artifact from the physics collection of Deutsches Museum, examining the object as a piece of evidence for both cultural and scientific facets of its time and place.

Although following Prown's methodology rigidly proved difficult while directly engaging with the artifact from the physics collection, let alone while writing up my results, the attempt to take seriously the suggestions made by Prown, Pearce and their colleagues does result in a report with a somewhat unfamiliar structure. In the first section, I provide a detailed description of the artifact, discussing only what it is made of, how its pieces were assembled and how it moves. In the second section, I take the object itself as evidence to build on previous research by Deutsches Museum on the making of the artifact as well as its original surroundings, and finally, in the third section, I discuss how the object may have been used. The second and third sections merge Prown's methodological step of imaginative hypotheses and theories with the outcomes of my further research.

Engaging with a mystery object: description and speculation

The object consists of a rectangular wooden ground plate (Fig. 1e) on three ball feet, measuring 45 cm by 20 cm. From the ground plate, two metal rods rise up 14 cm in the shape of decoratively curved arches on one side (Fig. 1c) and then continue straight and parallel, set 4.5 cm apart, to the base of the plate on the other side, with the slope measuring 38.5 cm in length. A short metal bar flanked by two wheels, with a ball weight hanging freely by a hook from its center, rests upon the inclined rods, much like wheels of a train cart sit on railroad tracks (Fig. 2e). Two flat wooden columns, flanking the arched side of the rods, rise vertically above the tip of the metal slope (Fig. 2d). They are mounted by a much smaller horizontal wooden plate at the total height of 53 cm (Fig 1a).

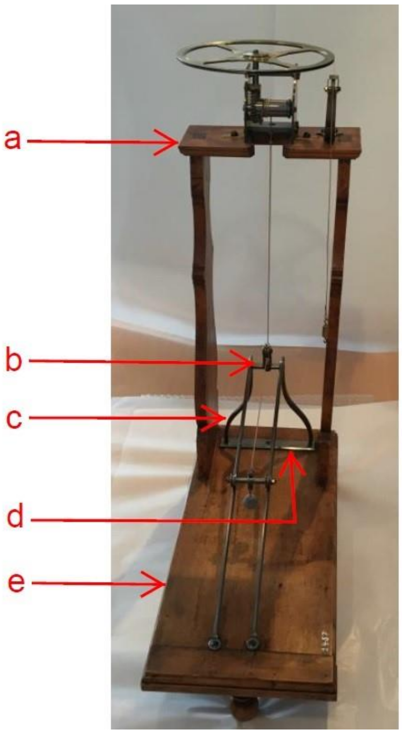

Fig. 2 Frontal view. Source: Deutsches Museum Munich © Granado Torres.

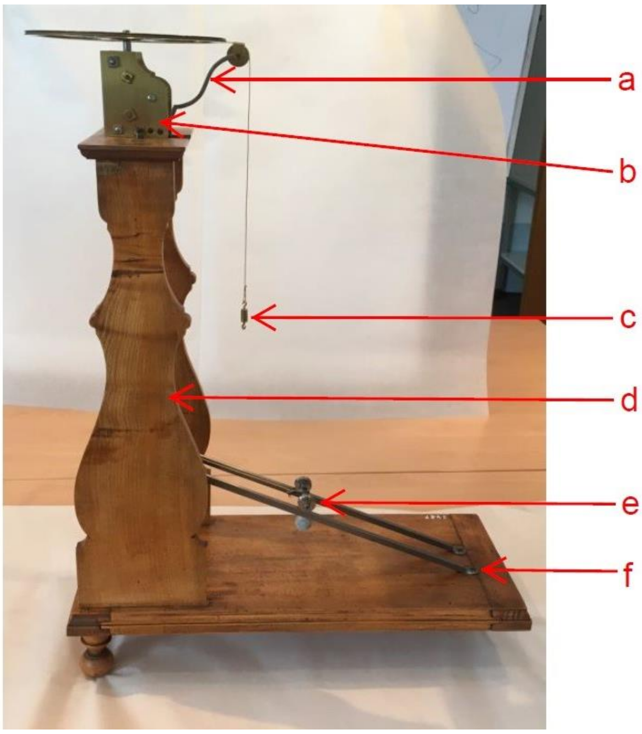

Fig. 1 Side view. Source: Deutsches Museum Munich © Granado Torres.

On the top plate sits a mechanical brass structure that consists of a cylinder (Fig. 3e), a gear, also called toothed wheel (Fig. 3c), and a vertical worm, or screw (Fig. 3b). Vertical brass plates (Fig. 2b) encase the mechanical structure on two sides but it remains open to view from all other sides. The width of these side plates is set apart by a rod at their top (hidden due to the angle of the photos) and by a rectangular piece with an empty drill hole in its center at their base (Fig. 3f). The hole has perfectly regular helical markings. Above this mechanical structure is a brass horizontal disc with four large openings, shaped much like a steering wheel, measuring 16.5 cm in diameter (Fig. 3a). Next to the mechanical structure, a decoratively curved arm, aligned with the edges of the ground plate, rises from the top plate at an angle of approximately 45° (Fig. 2a). The entire mechanical structure on the top plate measures 8.5 cm in height.

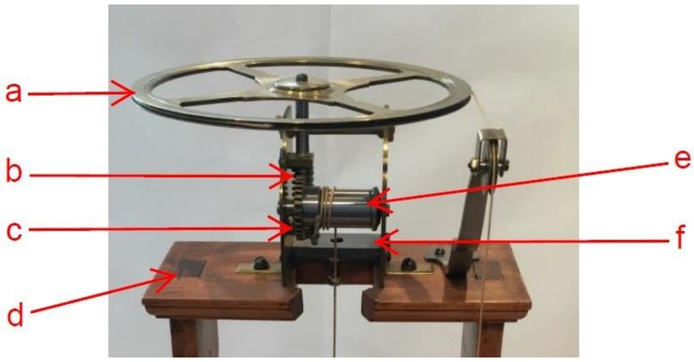

Fig. 3 Upper mechanical structure. Source: Deutsches Museum Munich © Granado Torres.

From the cart on the inclined rails, a thin, stiff, off-white string runs to a pulley[1] at the tip of the rails (Fig. 1b) which directs it upwards to the cylinder where the string wraps around three times. The gear on the end of the cylinder interlocks with the vertical worm. The worm's top is fixed to the disc. The disc's edge has a slit all around in which a second identical-looking string is attached and partially wound up. This top string runs over another pulley at the tip of the angled arm from where it hangs down freely, with a miniature weight with hooks hanging from the neat, small loop at the end of the string (Fig. 2c).

In total, the object measures 62.5 cm in height, 45 cm in length and 20 cm in depth. The metal rails are likely steel, as suggested by their darkened color and magnetic properties. The pulleys, the upper mechanical structure and disc as well as the angled arm and the tiny hooked weight on the top string are all brass. The rough texture and lighter patina of the ball weight suggest it may be lead. The rectangular piece with the drill hole and the rod at the top of the mechanical structure both have a darker color than the brass pieces and, unlike brass, are magnetic. Their material optically resembles nickel, and their magnetic properties do not rule out this possibility.

The ways in which materials were put together in the fabrication include joints, screws, bolts and knots. The steel rails are made from two singular long rods, formed to their particular L-shape and angle. On their decoratively arched side, the rods are set apart by two cross-connections, one at the tip of the inclined rails to which the pulley is attached and one directly on the ground plate (Fig. 1b and 1d). At the center of the connection that rests on the ground plate, a screw holds the entire steel structure in place. On the far side, where the rails directly meet the ground plate again, each rod is slightly flattened at its end and screwed to the wood (Fig. 2f). Those three screws, all alike, can be seen and felt from underneath the ground plate, as their tapered sharp tips almost reach through the clearance holes which have been pre-drilled all the way through the wooden plate. The decoratively arched side is perfectly centered in between the tall columns but on the far side, the rails are off center by 0.85 cm.[2]

A number of differently looking screws and bolts hold together the pieces of the upper mechanical structure. The side plates are not attached directly to the wooden top plate but by two small brass brackets, attached with a bolt to a punched-out hole on the side plate and with a large dark screw to the top plate. In addition, the brass side plates have two unused punched-out holes next to each bracket. Two screws attach the heart-shaped base of the angled arm with the pulley to the top plate. They can also be felt from underneath the top plate but were not guided through clearance holes.

Both the tall, flat columns and the top plate consist of a single piece of wood each. The columns connect the ground plate to the top plate. The mechanism of attachment is the same on each end: a narrow rectangular tenon from the column was interlocked with a through mortise of the plate, so the tenons are visible both from above the top plate (Fig. 3d) and from below the ground plate. No protrusion can be felt as the tenons fit perfectly and are only visible due to their darker color, which likely resulted from absorbing the stain differently. The ground plate was assembled from three individual pieces, one large main piece in the center, and two identical narrow edge pieces. They were assembled with a variation of a tenon and mortise joint as well: the main piece

[1] Pulley simply refers to what is called Rolle or Rad an der Rolle in German, a grooved wheel that can direct a rope or string. A pulley and rope system, however, would be called Flaschenzug.

[2] The distance between the rods remains perfectly the same, 4.5 cm measured from their outer edges. However, the distances from each rod's outer edge to the edge of the ground plate should, if centered correctly, be 7.75 cm. In reality, they are 6.9 cm on one side and 8.6 cm on the other. Accordingly, the very center of the rails is off by 0.85 cm.

has a protrusion along the entire width of 20 cm on each side that interlocks with an elongated stub mortise along each edge piece.[3] Two feet are attached to the bottom of the edge piece on the side of the tall columns and one foot is attached to the edge piece on the other side. No mechanism of attachment is visible. Notably, the cross-connection at the tip of the inclined steel rails is fixed to the rails with a mortise and tenon joint as well, so the technique was applied for different materials in the piece. The knots, which attach the strings in several places, are delicately executed.

The lines where wooden pieces connect, for example the main piece and edge pieces of the ground plate, are black, suggesting the object may have been exposed to dust for extended periods of time. The number 1457 appears three times on the object: once in white, written directly on the edge of the ground plate, and twice on the outer surfaces of the columns, once in pencil and once on a stamped or typed paper label that has been partially worn off and looks dirty with glue residue. Very small black dots appear at irregular intervals on the sides of the steel rails.

The straight edges of the top and ground plates were created with decorative moulding. The rounded shape of the feet, the arched side of the steel rods as well as the styled lines of the columns, brass side plates and angled arm all correspond to one another. The decorative piece has a sophisticated character, with clear, symmetrical lines and curves. Its visual coherence is only interrupted by the crudeness of the rails, although they do still match the over-all aged appearance, and by the eclectic assortment of screws and bolts at the upper mechanical structure, which are difficult to date. All wooden pieces were made from the same type of wood, stained to a warm brown color with shine and visible grain. Together with the shine of the brass, their refined appearance dominates the object's character.

If undisturbed, the object is at rest with the cart and ball weight about half way along the slope of the rails and the miniature hooked weight in the upper half of the distance between the angled arm and ground plate. Before actually trying to manipulate the object, we imagined how it *might* move: turning the disc on top clockwise, or rather, pulling the miniature weight at the end of the top string down would - by in turn moving the worm, toothed wheel, cylinder and string - result in moving the cart upward on the steel slope. We expected this movement to be easily observable. The top string seemed long enough, so we predicted the movement of the miniature weight to be limited by the ground plate, since the position of the string is such that it could not be pulled straight down any further than the ground plate.

The anticipation of movement was quite inviting. The cart can be lifted off the rails but it cannot be pulled further down the rails with gentle pulling at all. The miniature weight on the top string, however, is easily movable. It can be pulled down directly or pulled up by winding up the top string with the flat disc, but it always stays at rest whenever left alone. Pulling it straight down the full distance from the tip of the angled arm to the ground plate causes one entire turn of the flat disc and worm, which in turn moves the gear approximately 2-3 teeth. The movement of the gear and the cylinder is barely visible. The cart with the ball weight moves a maximum of 1-2 mm up the rails, a change so slight, we thought the instrument broken for the first hour of our investigation. Neither longer strings nor different weights at either end would increase the range of movement, since the key relationship for determining relative movement of both

[3] A stub mortise does not go all the way through the piece of wood to which the second piece with the tenon is being attached.

weights is defined by the grooves of the worm and the teeth of the gear. We had expected the movement of the ball weight to be much bigger, revealing our assumption about its use for large demonstrations.

We speculated the object may have been used for demonstrating and teaching mechanical principles, rather than taking any exact measurements since the open construction would allow a group of people to gather all around and observe the moving pieces. The limited range of movement, the off-centered rails and the lack of a measuring scale point away from quantitative precision. Also, the black dots on the rails do not seem to have come from marking measurements since their spread does not correspond to the cart's range of movement. We returned the object to the collection with many open questions regarding the construction of the separate parts and what exactly the object may have demonstrated. I will now discuss the material evidence of the object in the context of previous research at Deutsches Museum to investigate its origin and possible alterations.

Making the Potenzmaschine: possible makers and modifications

Previous research at Deutsches Museum identified the object as a Potenzmaschine. It is part of the museum's founding collection that consisted of the donated scientific instrument collection from Bayerische Akademie der Wissenschaften (BAdW), the Bavarian Academy of Sciences and Humanities. The museum dated the object's construction to 1770–1805 (Bloemer & Mirwald 2015a). The museum project that investigated the founding collection based their interpretation of this particular object on Petrus van Musschenbroek's "*Introductio Ad Philosophiam Naturalem*" from 1762. The physicist and instrument maker depicted and described a machine that is strikingly similar to the upper mechanical structure of this Potenzmaschine. His machine was also constructed of a large flat disc, a worm, toothed wheel and an arm with a pulley, directing a string. However, it was complemented by two dial gauges (Musschenbroek 1762: 139–140; Tab. IX, Fig. 7).

The force, *potentia* in Latin, applied by pulling down the small weight a long distance is being transformed in multiple ways to pull up the ball weight a short distance, hence the name of this type of instrument. According to Musschenbroek's text, this instrument was used for demonstrating the principle of the transformation of forces and for material instructions for artisans and machine builders who were seeking to apply this principle in the construction of new tools and machines (Bloemer & Mirwald 2015a). Given this background information, in the second half of the 18th century, what may have characterized the making and the surroundings of such an instrument in general and this Potenzmaschine in particular?

Since the origin of the object is known to be the instrument collection of the BAdW, I will first consider this context. The BAdW was founded in 1758 (Teichmann, Eckert & Wolff 2002: 333). In his work on the history of the BAdW, Ludwig Hammermayer analyzes a wide range of correspondence and other archival sources to reconstruct the extent and the value of the academy's "Attribute" which most prominently included natural history specimens and the physical-mathematical instrument collection, also known as "Armarium" (Hammermayer 1983: 175), to which the Potenzmaschine would have belonged. Academy secretary Ildephons Kennedy had built up and managed the instrument collection alone until he began to share this responsibility with Franz Xaver Epp in 1774/75 (Hammermayer 1983: 45). Kennedy, a Scottish Benedictine monk, versatile researcher and important member of several councils in Munich, was secretary of the academy 1761–1801 (Hammermayer 1983: 5, 381). Academy member

Franz Xaver Epp who joined in 1774 was a teacher for mathematics and physics at the Munich grammar school (Hammermayer 1983: 114). In expanding the collection, Kennedy and Epp were further supported by the Swiss watchmaker and inventor Michael Artzt who was granted the official title of “akademischer Mechanikus” in 1780 (Hammermayer 1983: 175).

The collection included a wide range of instruments, models, machines and devices. The earliest remaining inventory catalogue, titled “Verzeichniß des physikalischen, mathematischen und chemischen Apparats bey der königlichen Akademie der Wissenschaften in München”, was compiled in 1806, after Kennedy’s time. Kennedy had died in 1804 (Forbes 1981: 93). Names of objects collected in the last three decades of the 18th century, some rather difficult to interpret today, include, to sample a few: “artige Drehmaschine”, “eine Art Windmühle”, “selbstschreibenden Barometer”, and “meteorologische Maschine” (Hammermayer 1983: 175–177). Examples of subheadings in the section that lists the mechanical collection include, for example, “Räder an der Rolle” and “Modelle”.[4]

Several documents point to the value and importance of the collection to both the academy and the Bavarian ruler in the later decades of the 18th century. For example, just after Epp took on the management of the collection, he spoke of a “prächtigen und sehenswirdigen Apparat von philosophischen Instrumenten”[5] (Hammermayer 1983: 18). In 1784, when the 1783 decree of Prince-elector and Duke of Bavaria Karl Theodor that the BAdW move to a different site had caused significant financial strain for the academy (Hammermayer 1983: 171–172), Kennedy and others wrote to Karl Theodor to ask for the refund of moving costs. The maintenance of their “Attribute” was an important argument which the “Hofkammer”, the authority that managed the ruler’s assets, actually repeated in their report for Karl Theodor: in the new location, the collections should be brought up to such a standard that they are presentable to both domestic and foreign distinguished visitors and scholars (Hammermayer 1983: 172). Starting in 1776/77, the Munich grammar schools were also allowed to use the collection for demonstrations, despite the academy’s initial harsh resistance to sharing (Hammermayer 1983: 175). Purchase and maintenance decisions in the late 18th century were determined by the BAdW’s continually precarious financial position (Hammermayer 1983: 178).

Correspondence between Kennedy and others reveals that some of the objects in the collection were offered by the makers and then bought, some were made to order, and some were donated by members and supporters (Hammermayer 1983: 18). Some of the instruments in the founding collection of Deutsches Museum carry instrument makers’ signatures, for example an Atwood machine made in 1795 by Johann Anton Wisenpaintner from Eichstätt, Bavaria (Bloemer & Mirwald 2015b). The Potenzmaschine does not. The markings with number 1457 simply note the inventory number it received in 1905 when entering the museum.[6] So who may have been the maker of the Potenzmaschine?

The object itself can provide some evidence regarding the kind of maker. The upper mechanical structure, aside from the somewhat eclectic assortment of screws and

[4] See p. 3 and 6 in the section “Mechanischer Apparat” of the 1806 catalogue “Verzeichniß des physikalischen, mathematischen und chemischen Apparats bey der königlichen Akademie der Wissenschaften in München”. Scan provided by Dr. Johannes-Geert Hagmann, Deutsches Museum. The examples mentioned above roughly translate to comely lathe, a kind of windmill, self-recording barometer, meteorological machine; the mentioned subheadings are pulleys, models.
[5] Transl.: a splendid apparatus of philosophical instruments worth seeing.
[6] See “Grunddaten-Ausdruck: Potenzmaschine, Inv.-Nr. 1457”.

bolts, looks highly sophisticated. It only differs from Musschenbroek's depiction in that it does not have dial gauges for quantifying the transformation of the applied force by measuring how much the worm and the gear move. Accordingly, the upper mechanical structure may have been a separate instrument, perhaps even made in series by a skilled maker, as a simplified version of Musschenbroek's example. Similarly, the wooden plates and columns are made well. Making the ground plate out of three pieces may have served to prevent warping due to humidity and temperature since the two narrow end pieces function like clamps on the main piece. Also, the decision to set the ground plate on three legs, not four, may have been made with durability in mind, since the object would never wobble. However, three legs make it less stable when someone bumps into it, perhaps pointing to the possibility that not just anyone was allowed to use the instrument. Although different kinds of expertise went into the wooden scaffolding and the upper mechanical structure, a professional instrument maker's workshop would have been able to execute all. Ralf Kern, in his illustrated multi-volume work on scientific instruments throughout the centuries, concludes that a large professional instrument maker's workshop in the late 18th century may have employed up to 30 workers. While they certainly did not mass-produce, they did create some instruments in series and made multi-use parts to be kept on stock (Kern 2010: 396). Perhaps the maker knew Musschenbroek's example or the person ordering the upper mechanical structure brought the plate from Musschenbroek's book to show the maker, ordering a less costly version made up of simple and affordable brass pieces, pulleys, worms and gears mostly kept on stock.

Restricting the earliest possible time of production to 1770, as Deutsches Museum did, makes sense as an interpretation of the Potenzmaschine's stylistic properties. It has none of the intricate, asymmetrical features of Rococo or elaborate, dynamic surfaces of Baroque ornamentation. None of the wood or brass is engraved or shaped with detailed ornaments. The curves of the arched rods, the wood columns and the angled arm only carry a faint reminder of the whimsical volutes on Baroque furniture or instruments. The moulding on the ground and top plates' edges and the ball feet also carry this reference to Baroque style. However, the clarity and symmetry of the neoclassical aesthetic dominate the style of the instrument. While in earlier decades of the 18th century, scientific instrument makers had decorated almost every surface, the simplicity of the surfaces themselves became what made a piece decorative in the later decades (Kern 2010: 264). Nevertheless, stylistic dating of any scientific instruments in the German-speaking countries must be an approximation since styles overlapped and co-existed (Kern 2010: 265).

The refined visual coherence of the Potenzmaschine is disrupted by the crudeness of the steel rails, and especially their attachment to the ground plate. While the joint at the top of the slope is neatly executed and the rails' arched side mirrors the elegant curves of the columns, their attachment with screws that go all the way through clearance holes in the ground plate appears sloppy and unskilled by comparison. The same is true of the screws that attach the angled arm to the top plate. Furthermore, although the inclined rails have a constant slope and the rods remain parallel, the entire plane is askew. While a deviation of 0.85 cm from the center may sound small, it is quite visible to the naked eye. Given the assumption that the structure was meant to be symmetrical, there are two possible explanations for this deviation. Either the holes were drilled in the wrong place and the rods had to be bent to fit the holes, or the steel track was made askew and the holes had to be drilled to fit this shape. Given the low flexibility these rods likely have, I find the second option more likely and conclude that the steel structure was likely produced by a less exact maker. This may have been one of the many people contributing to the instrument maker's workshop, whose subpar work resulted in a sale of the object without a maker's signature, perhaps at a more affordable price. Alternatively, the steel rails may have been ordered separately, from any local blacksmith, raising the question of whether only part or all of the Potenzmaschine came from an instrument maker's workshop.

Lifting the Potenzmaschine reveals how top-heavy it is on one side. An expert instrument maker in the second half of the 18th century would likely have designed the piece to include a counter-weight on the other side. In addition, the circular indentation in the wood around the heart-shaped base of the angled arm suggests there may have been a differently shaped piece attached at one point. In addition, the pulley at the tip of the inclined rails and the pulley at the angled arm have differently wide grooves, so one of them may have been added at a later point. Taken together, this evidence suggests the conclusion that several parts from completely different makers were combined to assemble this Potenzmaschine. An explanation might be that Kennedy, Epp or a donor had envisioned the expansion of the kind of Potenzmaschine depicted in Musschenbroek's work by an inclined plane. They may have purchased the mechanical structure from an instrument maker's workshop but acquired the wooden scaffold with the steel rods elsewhere, perhaps to keep costs lower than if those parts were custom-made in a professional instrument maker's workshop.

However, I cannot rule out the possibility that the Potenzmaschine was altered or assembled much later, never actually having been in its current form during the time frame of creation given by the museum. Given my hypothesis that the Potenzmaschine may have been assembled from several separately made pieces, historical inventories of the collection may contain relevant entries. Internal research at Deutsches Museum during the 1950s attempted to compare the current inventory numbers to the catalogue numbers assigned in the BAdW's surviving catalogues of 1806, 1827 and 1850. A researcher at the museum interpreted the Potenzmaschine with inventory number 1457 to be present as a single item in all three, with catalogue number 47 in the earliest catalogue.[7] In this inventory from 1806, the name of number 47 reads "Ditto [ein Flaschenzug] mit vier Rollen", a pulley and rope system with four pulleys.[8] While the Potenzmaschine does indeed have four wheels – two wheels on the cart, one pulley at the tip of the steel rails, and one pulley on the angled arm – it does not include an actual Flaschenzug, meaning a pulley and rope system that transforms the applied force. Given the reference of Musschenbroek's Potenzmaschine and given that the reversed-digit number 74 in the same inventory is named "Potenzen-Maschin"[9], the museum researcher's allocation as number 47 not just fails to provide a satisfactory answer to the question of assembly, it is even likely to be inaccurate. However, number 74 does not provide a definitive clue either as it may have referred only to the upper mechanical structure. In addition, while the restoration workshop at Deutsches Mu-

[7] See p. 2 of the list "Apparate der mathematisch-physikalischen Sammlung der Akademie der Wissenschaften". Scan provided by Dr. Johannes-Geert Hagmann, Deutsches Museum. The document neither has a date nor does it note an author. However, the internal file where this list was found contains very similar typed pages on the academy collection that are dated with 1953 and signed by R. Poetzelberger.
[8] See p. 4 in the section "Mechanischer Apparat" of the 1806 catalogue "Verzeichniß des physikalischen, mathematischen und chemischen Apparats".
[9] See p. 7 in the section "Mechanischer Apparat" of the 1806 catalogue "Verzeichniß des physikalischen, mathematischen und chemischen Apparats".

seum does not have any record of repairs, cleaning or alteration for the Potenzmaschine[10], the strings look far too clean and uniform, without any discoloration or kinks, to be from the late 18th century.

One possible explanation for the newer string and the remaining mysteries (the odd assortment of bolts, the piece with the industrial-looking drill hole and the rod made from different material on the upper mechanical structure) may be that the upper piece was at one point altered to be displayed on a stand by itself. Perhaps it was detached for repair with some additional bolts and later returned. Alternatively, an entirely different upper mechanical structure may have crowned this Potenzmaschine previously, having been replaced with the current one sometime before entering the collection of Deutsches Museum in 1905. However, considering a Potenzmaschine's purpose of demonstrating the principle of the transformation of forces, it would have likely been a similar piece on the top plate. It is entirely possible that the Potenzmaschine was assembled in this or at least a very similar form in roughly the last three decades of the 18th century. Perhaps it was made to order by Kennedy himself, an academy member, or a donor who, based on their knowledge of mechanics and simple machines, creatively envisioned that previously known versions of a Potenzmaschine could be expanded and improved by the inclusion of an inclined plane.

Using the Potenzmaschine: lecture-demonstrations in the enlightenment

The Potenzmaschine incorporates several types of simple machines to demonstrate the principle of the transformation of forces. I will now investigate the use contexts of objects like the Potenzmaschine to further evaluate the hypothesis that this instrument is an expansion of a Musschenbroek-style Potenzmaschine, assembled from separately made pieces. In the 18th century, physics was being redefined as the science of the observable forces in all of inanimate nature (Lind 1992: 159), entangled with a major shift in didactic approaches that made demonstrative experiments the new standard teaching method (Lind 1992: 152). Teaching science through the method of lecture-demonstrations became institutionalized in universities all over Europe but also in those academies which provided lecture series for the benefit of citizens' education in natural philosophy (Turner 2002: 6). The physical record of different collections and written record of textbooks show that several lecturers developed "composite pieces of apparatus" for their own use (Turner 2002: 8). Accordingly, a composite Potenzmaschine envisioned by Kennedy or Epp would be a realistic possibility. Public science lectures dramatized aspects of natural philosophical theory, employing a communicative strategy of curiosity and surprise (Riskin 2008: 45).

With the Potenzmaschine, a lecturer can point out every redirection or transformation of the applied force, since all mechanical pieces are open to view. The cart sits on the inclined plane formed by the steel rails like on a miniature stage, corresponding to the larger stage of the lecture-demonstration in general. Imaginative possibilities of how an actual demonstration with this instrument may have been performed include adding a certain weight to the hook on the top string to make it travel down at a particular speed. The flat disc's openings allow for easy re-winding of the string, so the lecturer could have hung an even lighter or heavier weight right after, repeating the same demonstration in less time or more time. On the steel tracks, the ball weight's barely observable maximum range of movement (1-2 mm) is dramatic in its smallness, high-

[10] Internal records were checked by Thomas Rebényi, director of the restoration workshop at Deutsches Museum (22.2.2019).

lighting the extreme transformation possible. My own experience while physically investigating the Potenzmaschine reveals a certain spectacle: we were absolutely floored when we realized that the cart *did* move and the machine was in fact not broken, instead working as suspected.

In the specific case of mechanics, enlightenment ideals of practicality come to the fore in Jacob Leupold's "*Theatrum machinarum generale*" from 1724 where he defined mechanics both as a science that teaches how to move objects with advantages of time or effort and as the art to produce machines or tools according to the laws of motion (Leupold 1724: 1). Based on Leupold's categorizations of simple machines, Johann Heinrich Zedler's "Universal-Lexicon" later defines simple machines as those used to compose complex machines: "Hebel, *Vectis*", "Flaschen-Zug, *Trochlea*", "Haspel, *Axis in Peritrochio*", "Keil, *Cuneus*", and "Schraube, *Cochlea*".[11] Zedler acknowledges the co-existence of different categorizations. Some ignore the wedge completely and some classify all simple machines as variations of a lever (Zedler 1931–1951: vol. 19, col. 1907). Also, the lexicon defines "Potenzen, Lat. *Potentia*" as another word for the five simple machines "welche als mechanische Principia angesehen warden"[12], with a cross-reference to the previously mentioned entry (Zedler 1931–1951: vol. 28, col. 1863), illuminating why this type of instrument was named Potenzmaschine, or perhaps more accurately for its time of origin, Potenzen-Maschin.[13]

Since different categorizations of simple machines co-existed, I look to Ildephons Kennedy's work in particular. He had come as Thomas Kennedy from Scotland to Bavaria in 1735, under the supervision of the Benedictine monks at the St. James' Abbey in Regensburg where he studied until 1741, taking the name of Brother Ildephons (Forbes 1981: 93). Next, he studied at the University of Erfurt where Andrew Gordon, another Scottish monk, instructed him in mathematics and physics. When returning to Regensburg in 1747, Kennedy began to teach students in mathematics and physics himself (Forbes 1981: 93). Having been involved as an active supporter of the new academy from its inception in 1758, Kennedy was appointed secretary in 1761, relocating to Munich (McInally 2016: 171). That same year, Kennedy emulated Andrew Gordon's successful communication of natural philosophy to as wide an audience as possible in Erfurt by instituting a demonstration-lecture series in Munich (McInally 2016: 173). The demonstration apparatus for this lecture series which he repeatedly conducted until Franz X. Epp took over and continued this legacy in 1775 (Hammermayer 1983: 114) became the nucleus of the "Armarium" (McInally 2016: 174), or as Kennedy himself called it, of the "*Musaeum physicum experimentale*" (Kennedy 1963: i).

In 1763, Kennedy published a book where he collected and summarized all the major teachings he claims to have demonstrated with experiments during the two-year public lecture series, titled "Hauptsätze und Erklärungen jener physikalischen Versuche welche auf dem Akademischen Saale in München öffentlich angestellet warden". Since there were many further iterations of the lecture series by Kennedy and Epp, the book's contents and structure likely give some indication of mechanics at the BAdW for the next few decades.

Kennedy articulates the principle of the transformation of forces at the beginning of section VII, "Die mechanische Bewegung": "Um soviel Kräfte vermittelst der Maschine

[11] Transl.: Lever, pulley and rope system, reel, wedge, and screw.
[12] Transl.: ...which are being regarded as mechanical principles.
[13] See p. 7 in the section "Mechanischer Apparat" of the 1806 catalogue "Verzeichniß des physikalischen, mathematischen und chemischen Apparats".

gewonnenwerden, um soviel werden an der Zeit verloren" (Kennedy 1763: 22–23).[14] He then differentiates two main categories of machines: the lever (*vecti*) and the inclined plane (*plano inclinato*). He assigns all other simple machines to one of these categories.[15] Kennedy makes special mention of ropes (*chordae*) as a third category since they are used in many different machines (Kennedy 1763: 23). Contrasting Kennedy's classification with that of Jacob Leupold, Kennedy's inclusion of the inclined plane as one of the simplest of the simple machines stands out. Correspondingly, the inclined plane of the Potenzmaschine at Deutsches Museum is quite prominent, even larger than the upper mechanical structure. While this does not prove that Kennedy himself designed the instrument, of course, Kennedy's classification of the inclined plane as a – previously ignored – simple machine does shed some light on why the inclined plane may have been designed to feature so prominently by someone in his circles.

Furthermore, Kennedy's written emphasis on *chordae* draws attention to the strings. Rather than taking the different widths of the pulleys' grooves as evidence that the pieces were assembled later, the grooves may actually have been designed to correspond to differently thick original strings. The top string over the angled arm's pulley with the narrow groove may have been thinner, illustrating the smaller weight, and the string running from the cart with the ball-weight over the pulley with the wider groove may have been thicker, highlighting the larger weight. Both up-close and from further away, the audience would have benefitted from this visual emphasis of the relationship between the two weights of the Potenzmaschine. However, Kennedy's "Hauptsätze und Erklärungen" makes no explicit mention of any particular demonstrations and experiments he conducted to illustrate the principles of mechanics, so no direct textual evidence can be found there.

The Potenzmaschine's current label in the mechanics exhibition room at Deutsches Museum proposes that this Potenzmaschine was built to demonstrate the transformation of forces by showing the equilibrium of a greater weight with a smaller weight.[16] This interpretation aims attention at the fact that the weights are at rest when undisturbed. However, Kennedy makes no mention of equilibria in his theoretical section on mechanical motion and machines. The material evidence in the context of enlightenment ideals and teaching methods points to the conclusion that the display at rest may have been one of its uses but manipulation and movement for demonstration were likely more important.

New instruments, new sociability

The Potenzmaschine from the BAdW is more conceptual and less exact in its demonstrative capabilities than Musschenbroek's, perhaps highlighting artisans' and machine builders' practical application of knowledge as an ideal of the Enlightenment rather than an actual characteristic of scientific endeavors. Nevertheless, the curious visual clash of the steel rails and the elegant brass and wood pieces references the marriage

[14] Transl.: Section VII Mechanical motion: However much force is won through the machine, so much is lost in duration/time.

[15] The simple machines which Kennedy considers variations of the lever are the scale, the reel, and the pulley/ pulley and rope system (Kennedy 1763: 18–34). The wedge and the screw, however, he considers variations of the inclined plane (Kennedy 1763: 37–38).

[16] As of February 2019, the label reads "[…] Das hier gezeigte Gerät benutzt [verschiedene einfache Maschinen] um ein größeres Gewicht mit einem kleineren im Gleichgewicht zu halten", stating that the exhibited apparatus uses several different simple machines to keep a larger weight in equilibrium with a smaller weight.

of academic/scientific knowledge and practical applications in emerging industries. Public lectures with demonstration experiments were important for fashioning “a new interplay between manufacturers, men of science and intellectuals” (Outram 2005: 22). Munich’s social elites, both new and traditional (Outram 2005: 24), would have come together at lecture-demonstrations in the last decades of the 18th century.

It remains difficult to say when exactly the object entered the “Armarium”, who exactly made it or may have altered it until it entered Deutsches Museum in 1905. However, my examination of the aesthetic and functional properties of the Potenzmaschine point towards a creative expansion of Musschenbroek’s Potenzmaschine by an inclined plane, perhaps designed by someone in Kennedy’s circles, and realized by makers of various skill levels in the 1770s or shortly after. Either Kennedy or Epp may have used the Potenzmaschine in their public lecture-demonstrations. Additionally, it may have been used to demonstrate the transformation of forces to the students of the Munich grammar schools. However, the Potenzmaschine has neither a specified maker nor a definite group of users. Consequently, I cannot identify a clear use either.

Further research could attempt to find archival sources regarding Kennedy’s, Epp’s and Artzt’s designs and instrument purchases. This approach may not result in specific conclusions about the creation of the Potenzmaschine either but could allow for a more detailed understanding of the BAdW’s general process for creating new instruments. More importantly, further research could compare the Potenzmaschine to similar instruments with known makers and users from other collections. Their similarities and differences may shed some light on the makers and users of the Potenzmaschine at Deutsches Museum.

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