FROM ARCHIMEDEAN SPIRALS TO SCREW MECHANISMS – A SHORT HISTORICAL OVERVIEW

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ABSTRACT Mathematics forms the common roof for Archimedean spirals on the one side and screw mechanisms on the other side. Moreover, Archimedes was a genius of mechanics and mechanisms and was famous for solving mathematical and mechanical problems. There is also a historical justification for the title of the present paper, because the technical notion "Archimedean water-screw" is well-known to those mechanical engineers who are fond of looking back to the ideas and inventions of some famous protagonists and forerunners in the past and still today want to learn from their successes and failures.

1. INTRODUCTION

Did *Archimedes* (287–212 BC) actually invent the screw, one of the known five "mechanical abilities" or "simple machines" of Antiquity? Apart from the screw we still have the lever, the wedge, the roll or wheel, and the pulley as shown for example by *Guidobaldo del Monte* (1545–1607), Fig. 1 (left). On the right side of Fig. 1 we look at different types of screws (del Monte 1577).

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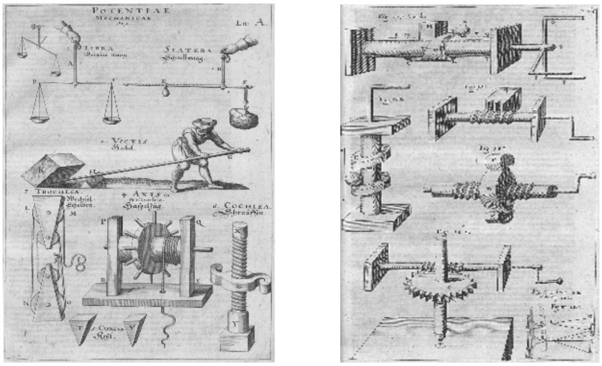


Fig. 1. The five "mechanical abilities" of Antiquity (left) and different types of screws by G. del Monte (right).

T. Beck (Beck 1899) points to the fact that *Aristotle* (384–322 BC) mentions the "mechanical abilities", but the screw is missing. On the other hand, *Heron of Alexandria* (ca. 10–85 AD) describes in chapter 34 of his book "Dioptra" an odometer, a chariot device used for indicating travel distances. It is based on a series of worm gears and may have been inventted by Archimedes during the 1st Punic War, but the reference to Archimedes is missing. So, there is a real chance for Archimedes in the time between to have invented the screw. *Salomon de Caus* (1576–1626) offered a compromise by drawing the two famous protagonists in a common picture, Fig. 2 (de Caus 1615).

Fig. 2. Archimedes (left below) and Heron of Alexandria (right below).

However, in accordance with *W. Treue* (Treue 1954) the historian *T. Koetsier* (Koetsier 1999; Koetsier, Blauwendraat 2004) declares that there is no reliable proof of the claim “Archimedes invented the screw”. But Archimedes undoubtedly knew the screw as a cylindrical helix (a wedge twisted around a cylinder) and also knew its mechanical properties. Furthermore, we surely know that the genius of mechanics and mechanisms (Chondros 2009), mathematics and geometry, namely Archimedes, intensively dealt with spirals and their mathematical properties (Czwalina-Allenstein 1922). He developed numerous theorems and equations for the type of spirals that were named after him, i.e. Archimedean spirals. The Archimedean spiral in the present form is a planar curve and follows the equation

$$x = r \cdot \cos\varphi, \; y = r \cdot \sin\varphi \qquad (1)$$

in Cartesian x-y coordinates, where $\varphi = \omega \cdot t$ (time t), $p = v/\omega$, and $r = p \cdot \varphi$; its curve is generated by a point that moves with constant linear velocity v along a semi-ray starting at the origin O of the coordinate system; the semi-ray itself turns around O with constant angular velocity ω. How can we derive the spatial screw curve from the planar spiral curve? We succeed by adding the third dimension z, i.e.

$$x = r \cdot \cos\varphi, \; y = r \cdot \sin\varphi, \; z = p \cdot \varphi \qquad (2)$$

taking any constant radius r and any constant pitch p. The sign of p marks either a left-hand screw ($p < 0$) or a right-hand screw ($p > 0$).

For technical purposes the screw is applied in form of a regular surface or with simple geometrical cross-sections, as rectangle, trapezium, circle etc., twisted around a cylinder, and thus giving the pitch p, the translation along the screw axis during one full screw rotation. Screws for technical purposes can be roughly classified into “motion screws” and “fastening screws”. In the present paper we shall concentrate on motion screws and neglect fastening screws. Dealing with motion screws reminds the kinematician that screw mechanisms exist and that screw mechanisms once belonged to the group of elementary mechanisms in machinery at the beginning of the period of mechanization in mechanical engineering more than 100 years ago, independent from the fact whether Archimedes actually invented the screw or not. But first we will have a look back to the Renaissance period and its artist engineers.

2. MOTION SCREWS IN THE MACHINE BOOKS OF THE RENAISSANCE PERIOD

The Roman architect and engineer *Marcus Vitruvius Pollio* wrote around 25 BC his ten books under the main title “De architectura” (Beck 1899). From his work we take that the Romans did not only learn architecture and arts from the Greeks, but also mechanics and mechanical engineering. In the 6th chapter of his 10th book about machines Vitruvius describes very precisely the construction and function of a water-helix (Fig. 3, left), however, without mentioning Archimedes. The reference to Archimedes occurs later in the machine books of the Renaissance and the baroque period (15th to 17th century) (Hilz 2008): *Agostino Ramelli* (1530–1590), Italian military engineer from Ponte Tresa, presents a triple Archimedean screw in his famous illustrated book (Ramelli 1588) (Fig. 3, right) which set standards for machine books in this time. The German artist engineer *Georg Andreas Böckler* (1648–1685) demonstrates in a similar way how to use a triple Archimedean screw for the lifting of water (Böckler 1661) (Fig. 3, middle).

Such a water-screw is driven by human muscle power (treading) or by water power, for example by means of water wheels. The early historian *Diodor* (1st century BC) from Sicily also mentions like Vitruvius that water-screws or water-helices were used in Egypt for water supply in cities and military camps near the river Nile. Very probably Archimedes came to know water-screws when travelling through Egypt.

A very interesting survey of the development of Archimedean water-screws is given by *J. Hennze* (Hennze 1992) in the catalogue of the Museum for Screws and Threads of the worldwide acting Würth Screw Wholesaling Company in Künzelsau (Germany).

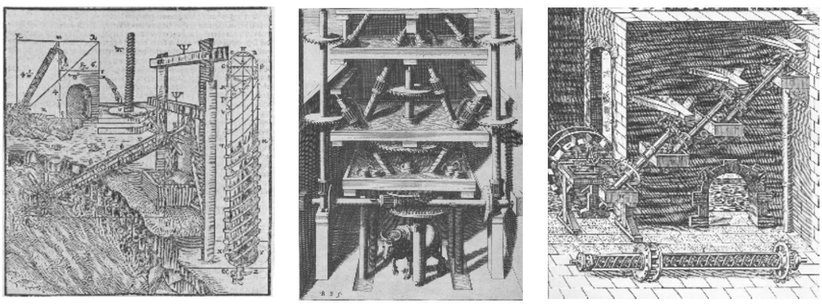
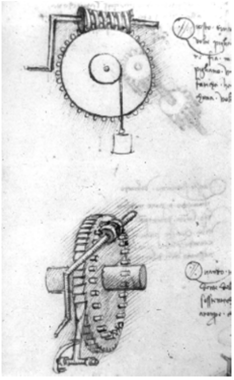


Fig. 3. Archimedean water-screws as recorded by Walter Ryff (German translator of Vitruvius´ books, 1548), Böckler and Ramelli.

Francesco di Giorgio Martini (1439–1501) of Siena was a very gifted designer of machines, architecture and fortifications. In the 7th book of his main treatise "Trattato di Architettura" we also find screws and worm gears (Moon 2007). The second famous artist engineer, contemporary to di Giorgio, *Leonardo da Vinci* (1452–1519) certainly owned a copy of di Giorgio's work. He used the endless screw (helix) as an input unit in numerous mechanical prototypes because of the profitable mechanical reinforcement, often combined with a worm or pin wheel (Fig. 4, left) (Leonardo 1493). But Leonardo also drew machines taking screws as output units, e.g. for setting upright heavy columns (Fig. 4, right) (Hoepli 1894–1904).



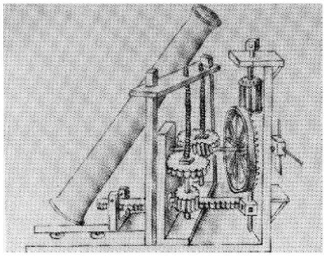


Fig. 4. Screw input units (left) and output units (right) by Leonardo da Vinci.

The idea of using a screw in combination with a lever or in combination with a lever and a gear wheel, single or multiple in series, is taken up by many artist engineers in the Renaissance. The lifting of loads was a very important task in a time of building monuments and fortresses and also of sea trading. *Jacques Besson* (1500–1569), professor of mathematics and natural philosophy at the University of Orléans (France) and one of the successors of Leonardo as engineer and consultant at the French court, presents for example a screw-driven crane (Fig. 5, left) in his famous book "Theatrum instrumentorum et machinarum" and also a lathe for the manufacture of screws (Fig. 5, right) (Hartenberg, Denavit 1956).

Besson also describes a press with three screws in parallel order for pressing grapes, clothes or lather (Fig. 6) (Treue 1954). Variants of presses with one or two motion screws were well-known since Antiquity and spread over in countries around the Mediterranean Sea.

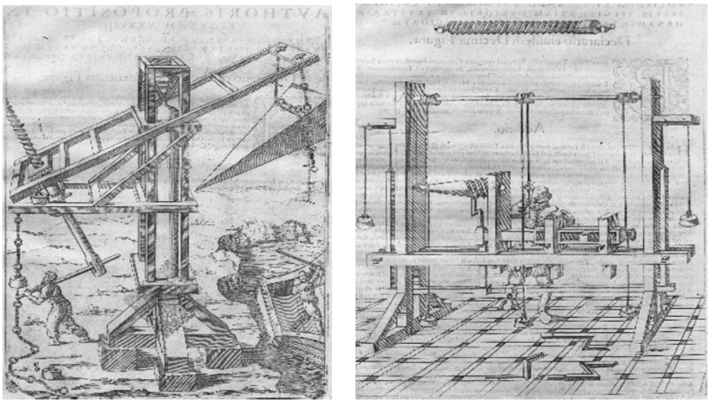


Fig. 5. Screw-driven crane and screw manufacturing lathe described by J. Besson.

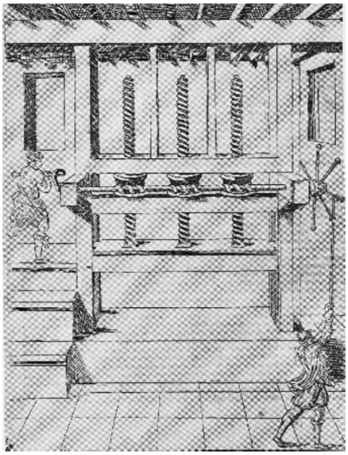


Fig. 6. Press with three parallel screws described by J. Besson.

The invention of the book press in the first half of the 15th century augmented the supply of presses based on screws. The book press mainly originates from *Johannes Gutenberg* (1397–1468) from Mainz (Germany). In Fig. 7 (left) we look at a book press made in Padova (Italy) with screw and long nut, drawn by *Vittorio Zonca* (1568–1602) in his machine book published only in 1621 (Zonca 1621). However, already Leonardo had designed a press for printing wood engravings (Fig. 7, right) (Hoepli 1894–1904). When the upper press board is lifted, the press table rolls down an inclined plane and comes out, so that the printed sheet can be removed easily and another one put on the table. When the screw is turned in opposite direction, the sheet goes back under the press table.

Heinrich Zeising (?–1613) wrote four volumes of a machine book titled "Theatrum machinarum" which were published between 1607 and 1613 (Mauersberger 1993). He took up again an idea of Ramelli concerning a big machine for the horizontal moving of heavy loads by means of multiple pulleys in parallel order (Fig. 8). One or two men are able to operate such a machine using a wheel-screw-combination.

Simpler and also more practicable seems to be a solution from Zeising for the lifting of trunks with a spindle which is operated by two men (Fig. 9).

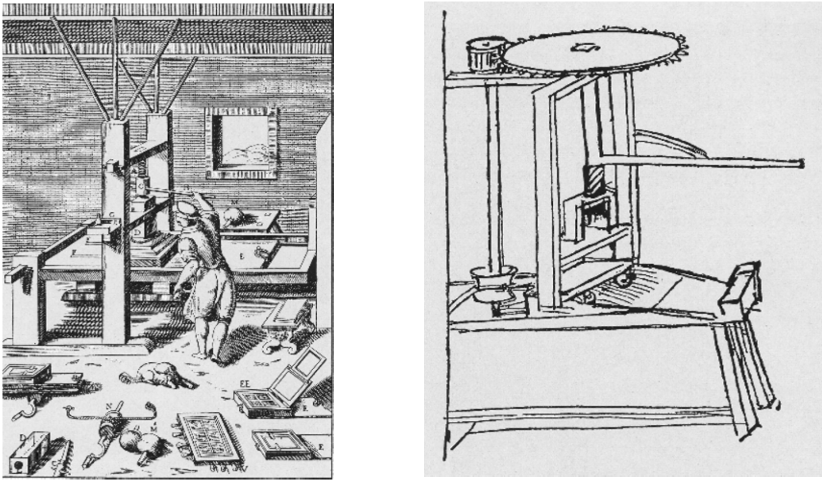


Fig. 7. Book presses by V. Zonca (left) and Leonardo (right).

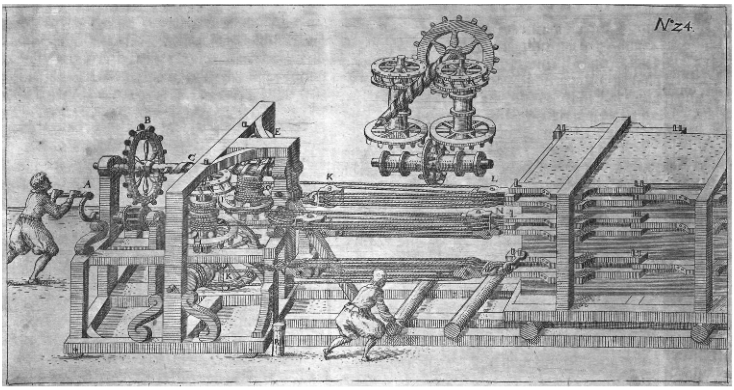


Fig. 8. Machine for horizontal moving of heavy loads by H. Zeising/A. Ramelli.

Fig. 9. Spindle hoist by H. Zeising.

In 1586 Pope Sixtus V called for an engineering congress and invited experts in mechanics to discuss about the following problem: Which mechanical solution could be set into practice for the dislocation of a fragile obelisque of some hundred tons of weight on St. Peter´s place in Rome? This meant an enormous challenge for contemporary engineers. The winner became *Domenico Fontana* (1543–1607), chief architect of the pope. He proposed to use ground winches and pulleys (Fig. 10, left) (A). Other variants are also shown in this figure: Floating bodies (B) as proposed by *Francesco Masini* (1530–1603) following the buoyancy principle of Archimedes, with screws (H), etc.

Years later, the German architect and artist engineer *Joseph Furttenbach* (1591–1667) from Leutkirch also made a proposal to erect an obelisque by means of numerous screws in serial order and of a lever. Fig. 10 (right) shows the mechanically extravagant solution taken from his book "Mannhafter Kunst-Spiegel" (Furttenbach 1663). Viewing and evaluating the variants of solutions in Fig. 10 the fantastic approaches concerning the pure as well as combined applications of the "mechanical abilities" of Antiquity are very surprising. But the mechanical engineer of today immediately discovers that there is a gap between the (virtual) models presented and a possible realization (Kerle et al., 2009). Proper materials were missing; time had not yet come in order to test original machines by means of physical models of minor scales. And there was hardly experience with mechanical energy losses caused by friction and wear, a

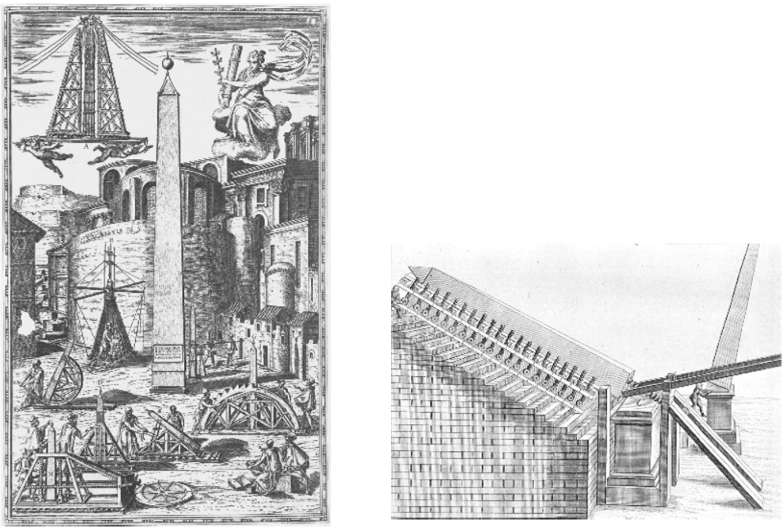


Fig. 10. Solution variants for erecting an obelisque.

severe handicap for many traditional gigantic drafts of machines and mechanisms.

Therefore machinery evolution was waiting for *Jacob Leupold* (1674–1727) from Leipzig, who wrote a ten-volume machine book titled "Theatrum machinarum" (Hartenberg, Denavit 1956). Not every machine in Leupold's books was his own invention, but he added special views of machines whose functions and purposes he had studied and understood. He also drew details of machine parts and machine elements that could help to explain and to build the machine (Fig. 11). Leupold belonged to a new generation of mechanics who did not only want to describe a machine, but tried to dismantle it into its different parts of function and design. Leupold rejected Ramelli's machine for moving heavy loads as shown in Fig. 8, mainly because of the considerable amount of friction between moving parts in counter directions. For the same reasons Leupold was also not fond of Furttenbach's idea (cf. Fig. 10, right) to erect an obelisque by means of a multitude of screws.

Therefore, we can take Jacob Leupold as the last artist engineer of the Renaissance who developed a more modern view of mechanical engineering combining theory with practice and thus opened the door to the pre-industrial age.

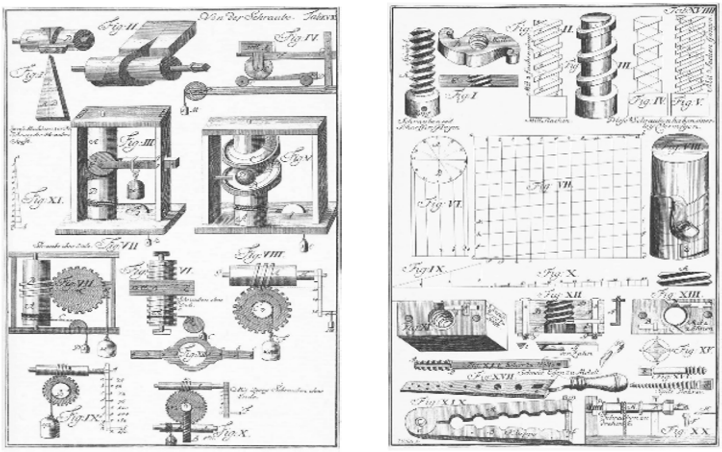


Fig. 11. Some machine element groups with screws by J. Leupold.

3. FROM MOTION SCREWS TO SCREW MECHANISMS

In the 2nd volume of his famous book "Lehrbuch der Kinematik" the pioneer kinematician *F. Reuleaux* (1829–1905) enumerates six typical groups of mechanism drives for use in machines (Reuleaux 1900): Screw, crank, gear, roll, cam and ratchet drives. From the systematic point of view simple (planar) screw mechanism with one DOF consist of three links and three joints/pairs; the complete version of such a screw mechanism consequently has three screw pairs with coaxial screw axes. In Fig. 12 taken from Reuleaux the links are designated by the letters a, b, c and the pairs by the digits 1, 2, 3. Link a is the input link, link b the output link, and link c belongs to the frame or fixed link.

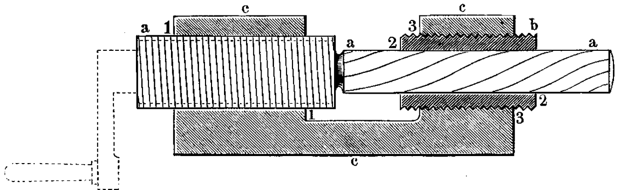


Fig. 12. Reuleaux's three-link coaxial screw mechanism with three screw pairs.

With a screw pair the rotation around the screw axis is coupled to the linear displacement by the pitch p, i.e. the dof of the pair yields one. Screw mechanisms can be treated systematically like planar wedge-slider or prism mechanisms (Beyer 1958).

Instead of actual screw pairs with a finite negative or positive pitch value (p ≠ 0) it is possible to insert simple turning pairs (p ≡ 0) or sliding pairs (1/p ≡ 0). Thus, six different simple three-link screw mechanisms with one, two or three screw pairs are developed, Fig. 13 (Rabe 1958a, 1958b).

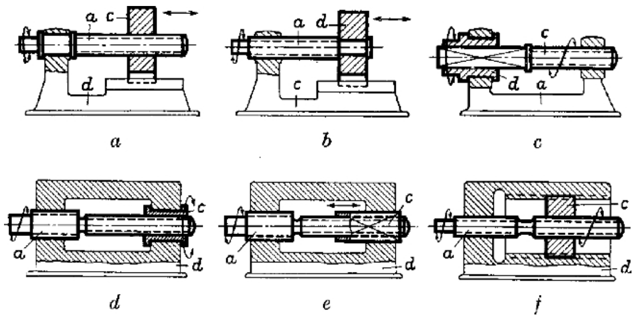


Fig. 13. Basic forms of three-link coaxial screw mechanisms: *a, b, c* one screw pair; *d, e* two screw pairs; *f* three screw pairs.

Most of the machines (and instruments) based on screws and screw motions can be derived from the mechanisms systematically represented in Fig. 13.

In the days of Reuleaux the fastening screw was a very well-known machine element. Screws of bigger size were made on forge machines; especially the heads of the screws being in a red-hot condition were jolted with the help of spindle-friction presses, Fig. 14 (left) (Georg, Ripke 1920). Another example with a crank press for metal parts is given by Reuleaux himself (Reuleaux 1900), Fig. 14 (right). The distance between the punch and its counterpart with the workpiece between can be continuously varied by a screw mechanism of the type *e* in Fig. 13 with two screws having the same pitch, but with different sign.

The following last examples are taken from *A. Widmaier's* catalogue (Widmaier 1954), a collection of mechanical solutions for the generation of motion on the base of mechanism theory. The catalogue was published at the beginning of a new industrialization period in Germany after World War II and was meant to be a practical source of knowledge in kinematics for the designer of machines and machine components, a knowledge that was created by generations of mechanical engineers before.

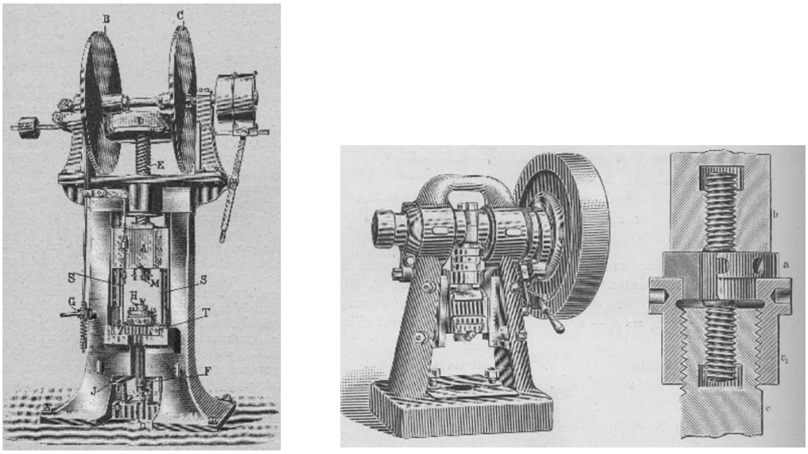


Fig. 14. Spindle-friction press (left) and crank press with a double screw-pair unit for adjustment (right).

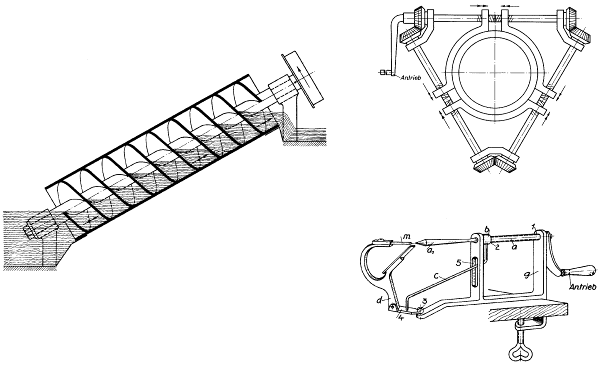


Fig. 15. Three modern mechanism examples based on screws by A. Widmaier.

On the left side of Fig. 15 we find again a screw for lifting fluids (or also powder or grain), it is a double start helix and in contrast to the Archimedean screw a screw surface is used for transportation of the fluid (cf. also Rauh 1939). On the right side of Fig. 15 (above) we look at a clamping device for tubes or cylinders with six screws having the same pitch, but with different signs two by two; below there is a simple machine for peeling potatoes or fruit on a table in the kitchen. The potato is pinned onto the needle a_1 which is turned manually by the crank (Antrieb). During crank rotation the nut b is moved along the screw axis a and makes rotate the knife m around the axis 3.

4. CONCLUSIONS

The screw for transforming rotary motion into linear motion in combination with an input torque around and an output force along the screw axis was one of the five "mechanical abilities" in Antiquity. Motion screws of this kind were used in presses and hoists and could be operated by means of human or animal muscle power. The machine books of the Renaissance partly present motion screws with gigantic dimensions. Most of those drafts of machines never could be set into practice because of energy losses due to friction and wear. Only Jacob Leupold at the end of the 17th century regarded and classified screws as parts of mechanisms (motion screws) and as machine elements (fastening screws) and proposed ways of proper design. His studies were introductory for the later development of compact screw mechanisms in modern machinery inspiring following mechanical engineers like Franz Reuleaux.

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