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SOME INTRIGUING ITEMS IN THE HISTORY OF SCIENTIFIC BALANCES

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The short survey covers the development of the balance since its invention in the Neolithic era. Scales have been used most probably first as tools in trading, but already in Old Egyptian papyrus its use in techniques is documented. Its theory was cleared by Aristotle and Archimedes and at least at that time it was used as a scientific instrument. Today the balance is still the most widely used instrument in science and there are still improvements.

Keywords: *balance, Egypt, load cell, spring balance, vacuum, history*

Introduction

The balance is the oldest real measuring instrument [1, 2]. Length measurements could be carried out using parts of the body. For volume measurements tools are needed, but for gravimetry complex instruments and even some scientific apprehensions are required. The balance is still the most widely used instrument in science and it was always one of the most sensitive instruments.

Early antiquity

The origin of the balance is obscure. Neolithic society's people settled in the eastern Mediterranean regions about 9000 BC and townships were founded about 5000 BC. Commerce and trade started in those societies. Trade was first purely barter but later on the measurement of quantities like volume and mass was required. In trade quantity corresponds to value. Therefore until now we have some identical designations for mass and money. As far we know, for thousands of years only the equal arm type balance was used. The oldest balance beam made of limestone (Fig. 1) was found in Upper Egypt and is attributed to the pre-dynastic Naqada II period 3900–3300 BC [3, 4]. Most astonishing is the small size of the balance beam of 85 mm. That means that it is not a balance for trade of usual market goods and we don't know the purpose of weighing. Likewise an early representation on a Hethitic bas-relief ~2000 BC shows such a small object (Fig. 2). We have many weights of those times from the Eastern Mediterranean region (Fig. 3) and since about 2600 BC from the Indus valley [5]. Weight division was down to milligrams. Also in Middle and South America balances were invented independently but certainly far later.

Trade with far regions required standardisation. A tablet in the tomb of Hesire in Saqqara shows two balance beams and sets of weights and cylinders (Fig. 4) [6]. Hesire (Fig. 5) was the most important scientist and highest dentist under the 3rd Egyptian dynasty's pharaoh, Netjenkhet Djoser (2630–2611 BC). The balance beams depicted were of the same shape as those about a thousand year's older Naqada object. Such scales of technically unfavourable design could resolve

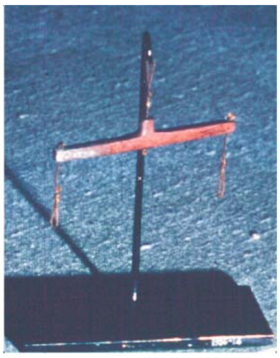

Fig. 1 Model of the oldest balance beam, reddish limestone. The ropes are added for demonstration. Pre-dynastic Naqada periode 3500 BC, Upper Egypt. Science Museum, London, UK. Original in the Petrie Collection, London

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Fig. 2 Hethytic weigher, bas-relief ~2000 BC. Kahramanmaraş, Turkey. Musée du Louvre, Paris

Fig. 3 Weight in the form of a duck, Hethytic

mass differences of 1 g and had a relative sensitivity of about 10^{-2}. Within the 3000 years pharaonic period in Egypt the balance was improved to a relative sensitivity of 10^{-4}.

Many drawings of balances were found in Egyptian tombs of the 18th Dynasty ~1539–1295 BC and later. Papyrus drawings and wall paintings represent weighing scenes in commerce, tribute payment, metal techniques (Fig. 6) and in burial rites. A heart weighing ceremony is depicted in Fig. 7. The dead wife stands before the balance. Her heart is placed on the balance pan and its mass is compared with an ostrich feather representing Maat, the goddess of truth, justice and harmony [7]. The jackal-headed Anubis, tutelary god of the embalmers calms the balance by grasping the suspension cords and touching the plummet. On top of the stand a baboon (identical with Thot) is sitting as a symbol of measure. He controls the operation. (Sometimes his penis is part of the indicator system [8].) The balance beam must come to equilibrium in a horizontal position, thus showing that the life of the dead person has been in harmony with the world. If this was not the case, the Devourer, a combination of hippopotamus and crocodile pounces upon the deceased. If the ibis-headed Thot, lord of the moon, god of learning and inventor of writing, reports a favourable result, Osiris, the emperor of the West, decides entry to eternity.

Fig. 4 Tablet with two balance beams, weights and cups. Tomb of Hesire, Saqquara, Upper Egypt

Fig. 5 Hesire, high officer under Pharaoh Netjenkhet Djoser (2630–2611 BC). Chief of the royal writers, Governor of Buto, Highest dentist and physician, Highest of the Ten of Upper Egypt

The balance used of a man's height is of special equal arm type, characterised by a plummet as part of the indicator system. Furthermore four cords are bedded within both ends of the wooden tubular balance beam, fed latterly and dragged down by the balance pans. Thus, the ends of the beam serve as knife edges. This type of balance (without or with modified indicator system) was used until modern age in Mediterranean countries. We reconstructed such a balance in order to determine its sensitivity and to understand its operation [7]. Such a scale having the height of a man, had a capacity

Fig. 6 Weighing of metal in an Egyptian workshop

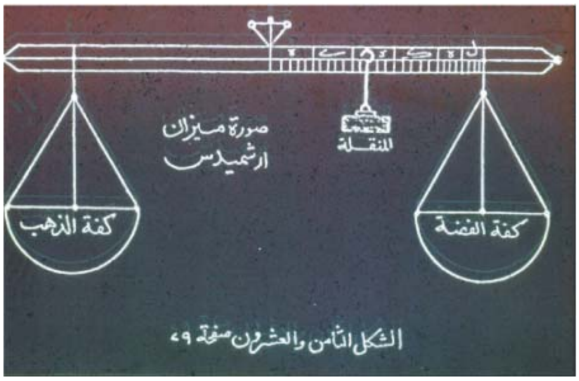

Fig. 8 Hydrostatic Balance of Archimede

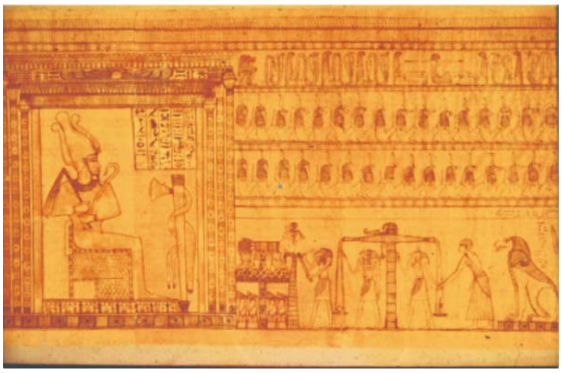

Fig. 7 In front of Osiris, Anubis and Horus weigh the soul of the deceased against the feather of Maat. The Ape Hapi (symbol of science) sitting on top of the balance controls the measurement and Thot records the result. If the balance is in equilibrium the deceased can enter eternity. Otherwise the Devourer is ready to annihilate her. Papyrus Milbank, Oriental Institute, Chicago

Fig. 9 Al Chazini's Balance of Wisdom, Model, Arabisches Institut J. Goethe-Universität, Frankfurt am Main. Al-Chazini: Book of the Balance of Wisdom. 1120, Merw

of about 30 kg and was able to resolve 1 g. So indeed the Old Egyptians could weigh an ostrich feather 2 g in mass and thus find out the soul's mass to about 2 g.

Antiquity

At Seldcuk (nearby the conference place Izmir) are the remains of the Artemis temple, one of the Seven Wonders of the World. Such a temple constituted not only a sacred precinct but also market place and cultural centre. Some temples had in addition a banking function [8], priests controlled masses and balances and likewise the mass standards had been there. The Artemis temple was closed 391 and finally destroyed 401.

Aristotle (384–322 BC) cleared the theory of lever [9]. Now it was possible to design balances with asymmetric beam or of variable length. The use of iron allowed remarkable improvement of the sensitivity and quite new constructions like steelyards. Archimedes (285–212 BC) used the balance for density determinations of solids (Fig. 8) [10]. Presumably the first gravimetric record of a chemical process was performed by Vitruvius in 27 BC by observing the loss of mass during lime-burning [11]. The masterpiece of a hydrological balance was Al Chazini's 'Balance of Wisdom' built about 1120 (Fig. 9) [12]. Its relative sensitivity achieved $2\cdot10^{-5}$.

In Roman times only minor improvements in details and adaptations of balances for special tasks, e.g. for weighing of coins, were made. Further improvement of the balance proceeded very slowly. From Pompeji we have a first painting of a balance factory of 79 (Fig. 10).

Modern times

Balances were improved decisively when a group of scientists with Antoine Laurent de Lavoisier (1773–1794) founded modern chemistry (Fig. 11). At that time, at the end of the 18th century, the French revolution took place. Lavoisier was beheaded, but

Fig. 10 Wallpainting with Erotes producing balances. House of Aulus Vettius Conviva and Aulus Vettius Restitus at Pomeji, Italy. Destruction by the eruption of the Vesuv 79 AD

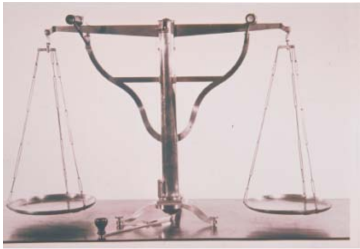

Fig. 11 Balance Fortin de Lavoisier

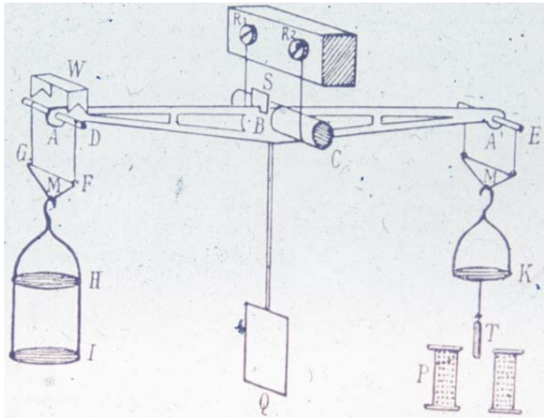

Fig. 12 Electromagnetic Microbalance of Ångstrøm

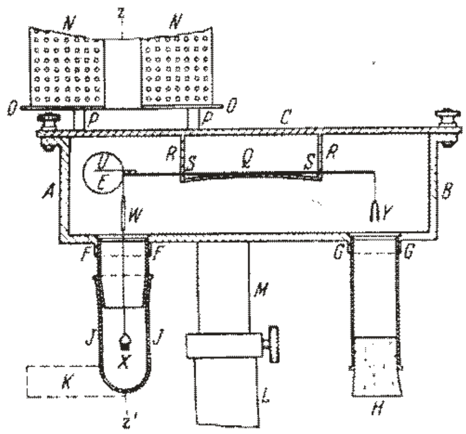

Fig. 13 Emich's electromagnetic vacuum balance

his work survived, including the introduction of the new metric system of units [13]. To weigh the mass of prototypes highly sensitive balances were needed. At the end of the 19th century metrological balances for the kilogram prototypes achieved a relative sensitivity of $2.5\cdot10^{-9}$, a value hardly improved by novel constructions. The Bunge transposition balance was used for more than 80 years up to 1951 and is now in the museum of the Bureau International des Poids et Mesures at Sèvres, France [14].

An important progress was obtained by applying Lorentz forces to compensate the deflection of the balance beam [15]. The first microbalance of that type was designed by Ångstrøm (Fig. 12). The prototype of electrodynamic vacuum microbalances (Fig. 13) was from Emich in 1912. Its measuring range was extended down to the nanogram range. The principle of mass comparison by means of a double-armed balance beam was left in the favour of electric sensing, in particular of self-acting electrodynamic compensation of the beam deflection as developed by Gast [16].

In 1665 Robert Hooke invented the spring balance [17, 18]. Its simple design provides advantages, e.g. for experiments in corrosive surrounding (Fig. 14). A spring body (load cell) with strain gauge sensing of the bending is applied today in many industrial scales and even in laboratory balances (Fig. 15).

Suspension of a sample at a balance by means of a permanent magnet within a controlled electromagnetic field was applied first by Clark [19] and Beams [20]. In 1959 Gast [21] constructed a suspension balance for investigations in a controlled atmosphere. Today an improved type is offered commercially [22, 23]. In 1909 Ehrenhaft and Millikan [24] determined the ratio of electric charge to mass of suspended particles. That method was modified by Straubel and used to measure water adsorption isotherms on suspended particles in the range of 0.1 nanograms [25].

In 1957 Sauerbrey [26, 27] and most probably independently Warner und Stockbridge [28] and Wade und Slutsky [29] invented the oscillating quartz crystal balance (QCM). Using high frequencies, the method is restricted to measure mass changes of samples which are firmly connected to the sensor surface, but it is also used to measure adsorption in liquid surrounding [30]. Metal bodies and bands of various materials oscillating at lower frequencies are applied for measuring dust concentrations. Those mass sensors create its own accelerating field which is by far stronger than the terrestrial gravitational field [31, 32]. Observing the frequency shift of oscillating carbon nanotubes, recently mass changes in the femtogram [33], attogram and zeptogram range could be observed [34–36]. A nanomechanical resonator has

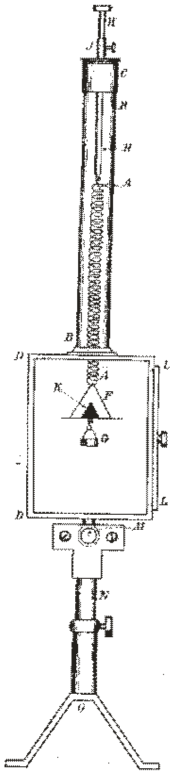

Fig. 14 Emich's spring balance

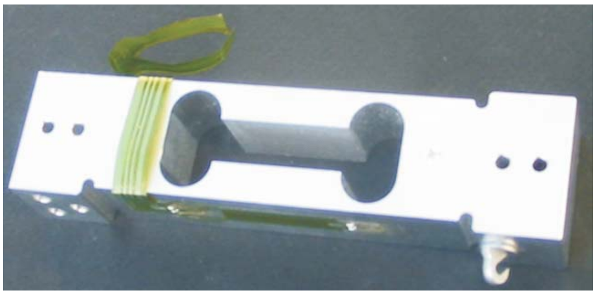

Fig. 15 Load cell with strain gauge

been used to measure quantum effects of thermal Brownian motion [37, 38]. By means of oscillating silica nanorods it was possible to weigh discrete gold dots [34], a single virus [35] and clusters of a few atoms [36]. Aligned ZnO nanowires and nanobelts can be used for converting mechanical energy into electrical signals and reverse. Further possibilities provide the combination of the techniques of atomic force microscopy (AFM) with oscillating elements [39].

Conclusions

The balance was the first real measuring instrument in science. Its sensitivity could be adapted always to the requirements of tasks of the respective era. New developments demonstrate the necessity to proceed with our series of microbalance conferences.

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