The Chemical Balance—From stones to electronics

Jaime Wisniak

Department of Chemical Engineering, Ben-Gurion University of the Negev, Beer-Sheva 84105, Israel

A chemical balance is standard equipment in any chemistry or physics laboratory, but in this electronic age a balance using weights is as odd as a slide rule. Weighing devices made their appearance at the time when human societies started to take root; the early devices were mechanical and developed very slowly until the seventeenth or eighteenth century when science started to set its principles. The next two centuries saw the mechanical balance achieve its final shape until its replacement by electronic devices in the second part of the twentieth century. Here, the history of the development of the balance since the dawn of history until its final mechanical form in the second half of the nineteenth century is being traced.

The history of scientific instruments reflects the history and development of rigor in science. Astronomical instruments were the first to achieve a high degree of accuracy due to their importance for religious, agricultural, and political reasons. Initially the primitive forms of the instruments changed little because lack of enough knowledge about the pertinent physical phenomena and development of their manufacturing techniques. In the beginning they reflected both the mechanical ability of the artisan and his artistic sense; instrument makers had to bring together the arts of different trades, founders, metal workers, armourers, locksmiths and smiths. The quality of the instrument manufactured raw not only on the professional ability of the maker, but also on the quality of the primary materials at his disposal and on the efficiency of his tools.

The history of the development of the balance (or scale), particularly the one used for scientific purposes, also goes along these lines. Its first structure was very simple and it took many years to achieve its familiar form. The latter, as well as the technique for its use, were modified profoundly in the second part of the twentieth century.

Here, the history of the instrument from back in the history of mankind until the radical change brought about by electronics is being traced. To do so in an orderly fashion, the simple definition of a balance as a scale with two pans suspended from the ends of a beam will be adopted. One pan is used for the material to be weighed and the other one for the weights.

Archaeological evidence indicates that about 8000 BCE human settlements in Egypt, Mesopotamia, and the eastern coast of the Mediterranean began the cultivation of grain-bearing grasses and its barter. It can be assumed that originally each community had its own set of measurement and weights for its internal purposes. As communities became dependent one on the other they established, villages, city, states, and eventually empires; this led to the need for more sophisticated measurements and weights. Already by 3000 BCE it was found necessary to devise an official method to measure and weigh to unify the marketing procedure and tax collection. Proper legislation was enacted to avoid non-official individuals and organizations to copy these standards, or to use their own set.

As humanity struggled in his search for the interpretation of physical phenomena, so did the development of the concept of measure and weight. The initial standards adopted were ones that reflected natural or common physical phenomena, such as the palm of the hand, a day's journey, seeds of grain, and simple utensils. Some of these names, such as feet, pound, gram, etc., have survived and remain in use today.

Together with the development of measures and weights was development of the system of equivalence, how to relate length to area, volume and weight. The Bible does not describes the equivalence system used hence, but a hint is given in a verse which expresses acreage in terms of volume of seed requirement: "And with the stones he built an altar in the name of the Lord; and he made a trench about the
altar, as great as would contain two measures of seed" (1 Kings 18:32).

According to Singer et al.\(^3\), the earliest commercial use of weighing was about 2500 BCE, in the pre-Aryan Indus civilization of northern India and perhaps to a limited extent in the Sumerian cities of Mesopotamia. The oldest archaeological findings of a beam balance and weights come from prehistoric graves at Naqada in Egypt. Archaeological findings in Egypt give pictorial evidence of the use of scales for weighing already during the period of the Dynasty V (about 2500 BCE), basically for weighing gold and jewellery. In the paintings of Beni-Hassan, Egypt, a balance is represented in its most simple form: a curved rod, held at its centre by a vertical foot, having at both extremes two hooks, one for the weights and the other for the object to be weighed. Many monuments and funeral papyri (Fig. 1) depict a scene of weighing of the soul in Osiris’ tribunal. In this papyrus, the soul of Hunnafer, superintendent of the cattle of Sati I, 19\(^{th}\) Dynasty, about 1300 BCE, is being weighed down by a feather placed in the opposite scale pan. This use of a scale to represent moral and spiritual reckoning would later repeat itself in different cultures and religions. For example, the Koran (21.47) says: “And We set a just balance for the Day of Resurrection so that no soul is wronged in aught. Though it be of the weight of a grain of mustard seed, We bring it. An We suffice for reckoners”. Similarly, Homer\(^5\) in the Iliad (book 8) talks about the god Zeus as follows: “But when the sun god stood bestriding the middle haven, then the father balanced his golden scales, and in them he set two fateful portions of death, which lays men prostrate, for Trojans..., and Achaians, and balance it in the middle”.

The Etruscans were also aware of the balance, which they adopted from the Greeks, as can be seen in the balance engraved in the Jenkius patera showing the known picture of Hermes holding a balance between his forefinger and thumb.

Until 1450 BCE all weights were made of highly polished stone (diorite, alabaster, basalt, and limestone), first of simple geometrical forms and then adopting other shapes and forms. The Indus people and the earlier Egyptian dynasties down to 1500 BCE used polished blocks of hard stone, cubical in northern India, and flat rectangular with rounded edges and corners in Egypt. Eventually, stone was replaced everywhere by the heavier and less brittle metals. This change was probably to the fact that these weights had less volume and could be replicated more easily.

The ancient civilizations of the Middle East had a weighing system based on eight standards, derived from small units known generally as shekels, the standards of which varied from 120 grains (7.78 g) to 218 grains (14.13 g). Larger units known as minas, and corresponding to 25, 50, or 60 shekels, were established later, except in Egypt where decimal multiplication was used\(^3\).

The verb shql (to weigh) is shared by all Semitic languages; the Semitic people also adopted the same system of weights. Weights were usually made of stones, a fact reflected in the Bible where weights are referred to as even (stones). In some ancient countries, especially in Mesopotamia, the old unit of weight was a seed of grain. The sensitivity of ancient balances was incredibly high and shows the degree of craftsmanship of their builders. According to Singer et al.\(^3\) between 5000 to 1500 BCE the sensitivity of balances ranged from 2 grains (0.13 g) with 100 grains in each pan, to 30 grains with 2000 grains in each pan. Afterwards, and up to the fourth century CE, the sensitivity of the improved balance was one grain with 100 grains in each pan, and 5 grains with 2000 grains in each pan.

With time the ancient empires of the Middle East disappeared or were conquered first by the Greeks and then by the Romans who adopted and modified the standards of weights and measures of the old cultures. The Greek and Roman imposed their systems in most of the countries of their empire and remained as such until the advent of the Islamic empire in the seventh century CE.

Archaeological research has also shed light on the weighing systems used by the dominant cultures in the American continent before the Spanish conquest.
The Inca culture had a weighing system that used instruments similar to those developed in the Northern hemisphere, as showed by excavated specimens of scales made of bones. Interesting enough, the parallel Aztec culture did not possess a weighing system; they sold everything by number and weight. The unit used was the cacao seed, which has a remarkable consistency of weight per unit. As a curiosity, it can be mentioned that although both the Inca and the Aztec cultures knew the wheel, they did not put it to use as a mechanical or transportation element.

**Early balances**

It is not known when the first weighing was carried out but it is reasonable to assume that the first devices were weighing devices having only one pan. This structure was first replaced by the steelyard and then by the two-pan equal-arm scale, or balance (from the Latin bi-lanx, meaning two dishes). The steelyard is an unequal arm balance with counterpoise; it was introduced by the Romans and is usually known as the Roman balance although it originated in Campania, Italy. The steelyard by received its name because it was first used in England by the merchants of the German Hanse who sold steel on the left bank of the Thames.

The equal arm balance of the ancient Near East consisted of a horizontal beam moving freely on a central fulcrum, with the object to be weighed and standard weights suspended at opposite ends in pans or hooks. Initially the beam was suspended at its centre by a cord held by hand and equilibrium was estimated visually. During the period of the eighteenth dynasty in Egypt larger balances were developed, supported by an upright frame resting on the ground. Balances capable of weighing small loads with reasonable precision were in existence thousands of years ago and were used by early jewellers, moneychangers, and metallurgists.

A weighing plummet (mishkolet, II Kings 21:13), suspended from the frame, could be compared with a pointer extending downwards at right angles from the pivotal point of the beam.

The mechanical principle of the balance was probably derived from the yoke of the burden bearer with its two equalized loads: “For thou hast broken the yoke of his burden, and the staff of his shoulder”, Isa. 9:3. Egyptian monuments and papyri depict persons carrying shoulder yokes with containers attached. The workers and their supervisors were certainly aware of how to balance the weights of the containers and how to equilibrate different weights by changing the pivotal point. As shown by early sculptures and drawings, first mechanical balances were small, and were used only for objects of high value in relation to their size, e.g., gold, silver, jewels, spices, etc.

Hand balances and large standing balances are illustrated in many Egyptian reliefs and paintings, the former also on a Hittite relief from Carchemish and the latter on one from ninth century Assyria. Archaeological findings in Israel show a crude sketch of a man holding a pair of scales, incised on the base of a scale-weight of the seventh century BCE. Bible references to the balance are both literal (e.g., “Just balances, just weights, a just ephah, and a just hin ye shall have”, Lev. 19:36) and figurative (e.g., “And weighed the mountains in scales and the hills in a balance”, Isa. 40:12). In the last verse the prophet distinguishes between the weighing devices according to the weight to be determined.

The first Biblical legislation in the interest of general economic righteousness appears in Leviticus 19:35 and Deuteronomy 25:13-16: “Though shall not have in your pouch alternate weights, larger and smaller; you must have completely honest weights and completely honest measures”. The prophets constantly denounced the use of false measures, e.g., “He is a merchant, the balances of deceit are in hand”, Hos. 12:8. Fraudulent weighing is repeatedly denounced in the Bible, i.e., substandard weights (e.g., “Making the ephah small and the shekel great, and falsifying the balances by deceit”, Amos 8:5), different sets of weights for buying and selling (Deut. 25:13), and false balances (Hos. 12:8). Later on, the Levites were made custodians of “all manners of measure and size” (I Chron. 23:29).

Probably one of the most famous books written in this period (1121-1122) on the subject is that of Al-Khāzinī, *Book of the Balance of Wisdom*, where the theory, construction, and operation of a hydrostatic balance are given, as well as its use for discriminating between pure and adulterated metals and between real gems and fakes. This balance had a sensitivity of one part in 60,000 for a weight of about 4.5 kg.

In times of the Roman Empire, official balances were located in all public places of Rome to allow the public to verify their purchases. As the Middle Ages advanced, there was more concern about adulteration and its detection by analysis. Most countries adopted
different measures and controls to restrict these illegal practices. The fight between those interested in bypassing the controls and those interested in making them more strict led to the improved methods of standardization of weights and measures. Official balances can still be found today in certain Chinese markets.

In England the Guild of Grocers had the custody of the Great Beam, that is, of the royal scales, and was also responsible for public food and health. Among their duties was supervising the removal of impurities found in merchandises. Public scales were also present in Parisian markets up to the time of Louis VII (1126-1180) and could only use the weights provided by the royal authorities. One scale was for general use and was called poids-le-roy (the King’s scale). The second type of scales was specifically used for weighing wax for the making of candles (poids de la cire) and was kept in a house called le poids de la chandellerie. Candles and candle making were most important in those days, special scales were used for wax, and for candles in Cologne and Paris. In those days’ candles were not sold by the piece but by weight. Due to their fragile nature they could not be laid in standard pan, thus, the wax scale was provided with special flat pans.

Although, balances are depicted in various alchemist writings they were not considered as an essential piece of equipment as a retort or alembic. Its central use would to have wait until the development of quantitative analytical chemistry and the principle of mass conservation. Weighing was a common operation during metal assay but alchemist and assayers did not pay particular importance to changes of weight. Joseph Black (1728-1799) is usually given credit for the first use of the balance in analytical chemistry. His balance had a beam 42.5 cm long, with pans hanging by cords from its ends by S-shaped hooks.

Assayers fulfilled two major tasks: the examination of ores to determine the possibility of profitably working with them, and the examination of coins and jewellery to determine their quality and to detect fraud. The assayer used three separate balances, which were usually of the same type but of different capacity and sensitivity, the best showing about 0.1 mg³.

**Development of the structure**

For many centuries scale-makers had known how to construct small balances. They were aware that to produce a good balance they had to solve two important problems: the position of the pivoting point in the beam and the attachment of the latter to the stand.

Originally, most scale beams were probably made of wood and this may be the reason that scarcely any early Egyptian and pre-Egyptian examples have survived. For the fine balances used by pharmacists, jewellers, or bankers, the beam was usually made of brass or polished steel to prevent rust. The beams of the so-called Chinese opium scales were made of ivory.

The bearings for the swivel-pin were eventually made of hardened steel but in other respects remained almost unchanged for many years. They were supported by a small chain or silk thread that was held in the hand or fastened to a support screwed onto the lid of the box. Each pan was suspended by three long silk threads to lower the centre of gravity and lessen the oscillations. The instrument could easily be folded and fitted in a carrying box, which also contained weights and tweezers.

An interesting point mentioned by Kisch⁷ is, that, the silk threads (and in many cases the box itself) were coloured green; this colour was supposed to relieve the strain on the eyes of the user.

The method of suspension was also slowly improved; the pin was more carefully shaped; the true knife-edge bearing but did not take the form of a knife-edge of triangular section until the first quarter of the nineteenth century. The pivots of the beam were better cut and the bearings on which the pivots rested were provided with a steel bushing. The suspension wires of the scale pans were lengthened to lower the centre of gravity of the system and were now made of brass to eliminate the influence of variations in the humidity of the atmosphere. The zero point was indicated by a long vertical pointer fixed to the central point of the beam between the arms of the bearings. Finally, placed under a protective glass cover, the balance was fit with a device to check the movement of the pans. The balances were put inside cases to avoid the influence of air currents, as well as to avoid the different expansion of both arms, which could be caused by the proximity of the operator.

One of the oldest known balances for scientific purposes is one of the type known to have been constructed by Francis Hauksbee in 1710 (1666-1713). It had two arms of equal beam with two pans hanging from its extremes. Hauksbee did not invent this type of balance; he was only one of the many instrument builders that adopted it to laboratory
Between 1760 and 1770, the structure of the balance was profoundly modified, the problems of sensitivity and accuracy were carefully studied, and the precision balance as such appeared in its earliest form. A better understanding of the associated phenomena and their problems brought the disappearance of the bearings and resting of the knife-edge on a steel plane carried by a metal column. In addition, the beam was no longer suspended but rested on a stable base. The knife-edge was no longer cut out of the material of the beam, but was built of hardened steel, as a separate piece; it preserved a rounded section and the edge could be cut more finely. The end of the rod carried two curved arms that emerged from the column via two lateral openings and terminated in two forks, which encircled the beam and lifted it up. The lever was activated by means of a small cord, and the operation could be carried out when the doors of the case were closed.\textsuperscript{1,10}

Another problem that was eventually solved was that of wear by mechanical friction. Many factors could result in movement of the parts of a balance even when not in use. This problem was resolved by providing the instrument with an arrestment mechanism, which enabled the components of the bearings to be kept apart except when an observation was being made. The arrestment was usually operated by a knob or lever on the outside of the case, so that the actual weighing could be done under draught-free conditions with the case closed. The first arrestment devices operated as single-action devices that separated the components of the centre bearing. More sophisticated solutions included a separate control to lift the pans, so that the residual loads upon the bearing at the end of the beam were quite small when the balance was out of use. Better instruments had a triple-action arrestment operated by a simple control that arrested the components sequentially. The central bearing was arrested first, followed by the end bearings, and then by the pans. This sequence was reversed when the control was turned the other way to release the moving parts.\textsuperscript{1,10}

John Harrison (1693-1776; famous for the construction of the marine chronometer) is usually credited with having constructed the first analytical balance, which could be first called by this name. It was built about 1770-1775 for Henry Cavendish (1731-1810), on his instructions. Its dimensions were very large: in its stand and case it measured 160 cm long, the beam was 49.5 cm long and the pans, 10 cm in diameter, had a drop of 52 cm from the knife-edges. Harrison’s balance had all the rudimentary characteristics of a prototype and it can be said that it already possessed all the details that would be used later. For example, the beam was supported by a simple metal plate fixed with four screws to a wooden beam inside the glazed case. In order to increase the rigidity of the beam Harrison gave it a triangular section, and adjusted the position of the centre of gravity by means of threaded rods, fixed at the end of the beam, carrying moveable nuts. The knife-edge consisted of a steel prism with side planes and also had a triangular section.

Harrison’s balance incorporated several new details: It had a device for raising the beam while at rest, thin wires replaced the silk threads used for suspending the pans, and a small plate was added below each pan to lessen oscillation. In addition, the index was now fixed but horizontally at one of the extremities of the beam. This modification increased the index amplitude and caused it to move over a graduated arc. The balance was placed inside a glazed cupboard and the table on which it rested had four levelling screws.

Antoine Laurent de Lavoisier (1743-1794) is generally credited with having been the first to use the balance in chemical work. In about 1778 he commissioned the construction of his balance to Nicolas Fortin (1750-1831), with a beam three feet long; this type of balance was first used for the Commission des Poids et Mesures, and Fortin subsequently constructed several others on the same model. Lavoisier was so satisfied by the quality of the scale built by Fortin, that, he wrote in his book Trait\'e de Chimie\textsuperscript{5}: Je ne crois pas, que \`a la exception de celles de Ramsden, il en existe qui puissent leur \'etre compares pour la justesse et la precision (I doubt that except for those built by Ramsden, there exists a balance that can be compared in precision and accuracy). In 1780 Pierre Bernard M\'egni\'e (1751-1807) built two additional balances for Lavoisier. M\'egni\'e understood the need to make the central
knife-edge rest on a hard steel plate placed at the top of a rigid column; its balance it rested on a brass pillar instead of being suspended from bearings. Méginié’s balance was capable of measuring weights between 4 grams and 0.1 milligram. A later balance also built by Méginié for Lavoisier, was capable of weighing quantities of the order of 600 g, down to 5 mg, with a precision of 0.1 grain (1 grain = 64.8 mg). An interesting point is that Lavoisier adopted the weighing method suggested by Jean-Charles Borda (1733-1799).

Jesse Ramsden (1735-1800) produced a balance for the Royal Society, which became very famous. This balance had a beam 61 cm long and consisted of two hollow cones united at their bases and supported at the centre on steel knife edges turning on agate plates. Its sensibility was about 0.5 mg and was capable of supporting considerable weight.

At the close of the eighteenth century the balances constructed by Ramsden, Edward Troughton (1753-1835), and Fortin were most highly thought of and may be considered as the beginning of the era of the balance of high precision.

From the above information it can be seen that the manufacture of more and more precise balances came as the result of the pressure and needs of certain persons and not of a market need.

All the precision balances at the end of the eighteenth century were designed for weighing quantities of the order of a kilogram with an accuracy of about a milligram. In general, they had long beams and large pans suspended by metal attachments. To meet government requirements, scale makers began to make large precision balances, but for laboratories the dimensions of the balances were reduced after the experimental work of Jöns Jacob Berzelius (1779-1848). Berzelius developed improved methods for purification and analysis, determined the atomic weights of some forty elements, and ascertained the composition of many compounds. He demonstrated that it was more convenient and more accurate to weigh small quantities. It is in his time that the chemical balance began to depart from the massive form of many of its ancestors and to take on its modern appearance and capacity.

Berzelius delicate measurements brought to light the fact that sensitivity was the most important characteristic of a precision balance. Although, development of the double weighing procedure by Borda relegated accuracy to a secondary place, balance makers did not forget it. This fact is attested by a balance built by the end of the eighteenth century in which the knife-edges at each end of the beam were mounted on adjusting screws, permitting the regulation of their position.

Mechanical principles indicated that the sensitivity of a balance depended on the relative position of the terminal and centre knife-edges. The theoretical solution was to put the three points and the centre of gravity on the same horizontal axis. Balance makers were well aware of the problem and its answer but did not solve it as required because of practical reasons. They selected instead an alternative solution: to terminate the beam with two upward curving arcs of circles in order to raise the centre of gravity. In this manner the two defects tended to compensate one another.

Small weights were difficult to handle and easily lost. To avoid this problem Berzelius suggested dividing the right side of the beam into ten equal parts and substituting all the centigram and milligram pieces by one weight that could be moved along the beam as needed. This special weight, which was usually made of wire or platinum, was known as a rider and appeared for the first time in a balance made by Collot in 1855. In Collot’s device the riders were placed on the balance beam by a hook manipulated from the outside by a long rod with a milled heat. The rider remained in use until the mid twentieth century. Increasing the number of divisions and thus increasing the precision further improved the idea of the rider.

Christopher Becker, born in Holland, was the first American craftsman to make balances and other scientific instruments, in the early 1850’s. The Becker balance had the beam arrested in such way that the arms pivoted about a common axis of the centre knife-edge and moved through the same arc as the supporting points of the beam.

Oester and Stock have described in detail the balances used by famous scientists such as Black, Cavendish, Priestley, Lavoisier, Dalton, Davy, Berzelius, Liebig, and Dumas.

A very illustrative example of the strong relation between analytical techniques and weighing devices is given by the method of silver assay developed by Gay-Lussac after he took charge of Commission des Monnaies et Médailles (the French Mint). At that time (1829) silver was determined by cupellation; the silver or gold sample was heated in a cupel with lead.
Impurities were oxidized and carried off with the lead oxide. There were many evidences that the method underestimated the amount of silver present. A commission appointed to examine the methods of silver analysis recommended switching to that of Gay-Lussac, which was accurate to within two parts in one thousand. The government economical benefit was to be very large; it would gain about four parts of silver in every thousand in every five-franc piece, which in remelting the entire currency in circulation would represent a net benefit of about six million francs for all coins.

Mechanics of the balance

The mechanical principle behind the balance operation is deceptively simple; it expresses the idea that for a beam supported in one point to be in equilibrium, the vector sum of all the moments must be zero (Fig. 2). Implementation of this idea into a measuring apparatus is complicated by mechanical problems such as rigidity, material properties, alignment, etc.

The Greeks were aware of the physical theory behind the balance; Aristotle (384-322 B.C.E.) in his book Mecanica\textsuperscript{12} established the amplitude relation of the angles swept by the bar before reaching the equilibrium position. He also determined the precision of the measurements and showed it to be dependent of the arm lengths of the balance.

Two important characteristics of a balance are the precision conditions and sensitivity. Precision conditions are the ones that must be fulfilled by the balance so that the beam rests in the same position whenever the apparatus is unloaded. To do so the centre of gravity of the system composed of the beam and the pans should be in the vertical of the hanging point and the two arms should be exactly identical.

The sensitivity of a balance is the tangent of the angle of the deviation produced by addition of a weight \( p \) after the balance has achieved equilibrium having equal weights \( P \) in each pan. The weight \( p \) is smaller than \( P \) and usually taken as one milligram. It can be shown\textsuperscript{13} that for a balance having an angle of \( 2\alpha \) between its arms, the sensitivity is given by,

\[
\text{tg } \theta = \frac{pL \sin \alpha}{(2P + p)L \cos \alpha + \pi d} \quad \text{... (1)}
\]

where \( \alpha \) is the angle between the arm and the vertical, \( \theta \) is the deviation angle, \( \pi \) the beam’s weight, \( L \) the arm’s length \((OA)\), and \( d \) the distance of the gravity centre of the beam to the fulcrum \((O)\) (Fig. 3).

For the case of a straight beam Eq. (1) becomes,

\[
\text{tg } \theta = \frac{pL}{\pi d} \quad \text{... (2)}
\]

Eq. (2) shows that the sensitivity of a balance increases with an increase of the beam length and a decrease of its weight, and the closer the centre of
gravity from the fulcrum. A compromise has to be achieved between these factors because a longer beam will be heavier and will oscillate slowly. For this reason, the beams are constructed of light materials, usually aluminium or magnesium alloys. An additional problem is, that, the beam is not rigid and hence it will bend. Bending will increase with an increase in the load of the pans.

Three procedures were commonly used to determine the weight of a body using a beam balance:

(a) Gauss’ method, which eliminated the possible inequality in arm length by performing two weighings where the weight was put alternatively in each of the pans. If the pertinent readings were $p_1$ and $p_2$, then the real weight was taken to be $\sqrt{p_1 p_2}$ (this expression is easily deduced using the lever rule).

(b) Borda’s method, in which the body to be weighed was equilibrated against a tare (like sand or gunshot), and then substituting the body with weights that equilibrated the tare.

(c) Mendeleev’s method, which was similar to Borda’s, except that the tare was kept constant and the weights were removed until equilibrium was achieved.

Conclusion

Measuring and weighing devices made their appearance at the time when human societies started to take root; the early devices were mechanical and developed very slowly until the seventeenth or eighteenth century when science started to set its principles. The next two centuries saw the mechanical balance achieve its final shape until its replacement by electronic devices in the last part of the twentieth century.

References