FUNDAMENTALS OF THE ANALYTICAL BALANCE

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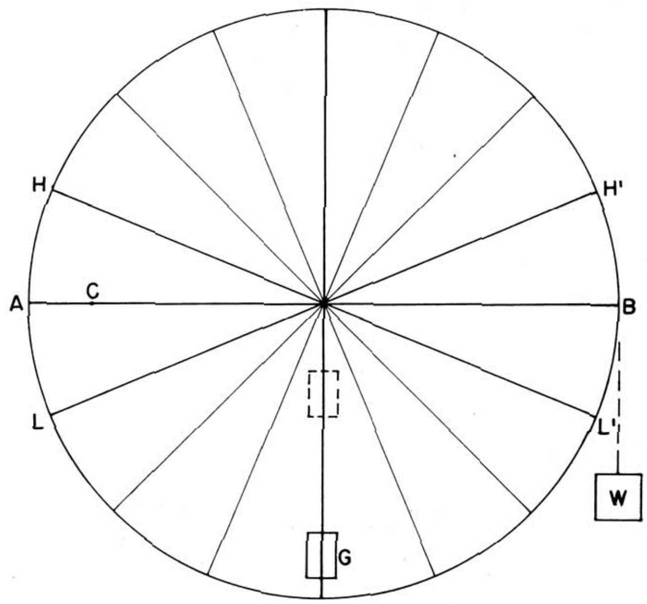
THE analytical balance is one of the important tools in the laboratory. Its usefulness increases when the chemist understands its operation well enough to utilize the full capabilities and to realize the limitations of the balance.

Some chemistry students do not become proficient in the use of the balance because, understandably, they are concerned with so many other and complex instruments and problems. The balance is taken for granted. It may be that, because balances have been used for so many centuries, intuitive knowledge about them is assumed. At the other extreme are those who know there is something precise and presumably delicate about a balance, and so they avoid using one if possible. This is unfortunate because mass, along with length and time, is a fundamental measurement. An example is the use of a balance to prepare standards for the calibration of more specialized instruments. Another important thing about a balance is its high ratio of capacity to sensitivity. Few measurements will yield as many significant figures as a weighing on an analytical balance. Results to six significant and exact figures are ordinary.

Those who have learned about balances by an intuitive process tend to think of them as teeter-totters. Actually a balance is a compound pendulum with complications. The essentials of the operation can be understood easily, however, by visualizing an upright wheel free to turn on a fixed axle.

A weight G clamped around one spoke will cause the wheel to rotate until that spoke finally comes to rest directly under the axle. Then, if a small weight W is



suspended from a string attached to point B, the wheel will turn clockwise and come to rest with B lower than its original position. Two things have happened. A new center of gravity has been established and has sought its place under the axle or point of suspension; and the weight W, descending, has done the work of lifting G to its new position.

Little weight W will cause the wheel to turn more if G is clamped on its spoke near the hub, and less if G is clamped near the rim. Attaching W causes a lateral shift in the center of gravity. This shift represents fewer degrees of rotation when the original center of gravity is near the rim than it would with the center of gravity near the hub. For those not interested in the mental exercise of calculating the forces involved, it is sufficient to get the idea that W has more leverage on G when G is near the axle which acts as the fulcrum.

It is easy to see, too, that small weight W suspended from B will turn the wheel faster if the wheel is light than it would if the wheel were a heavy one. With the wheels of equal weight, the one with a heavy hub and light rim would turn faster than one with a heavy rim and light hub. This is simply a matter of inertia.

The wheel will not turn one way or the other if heavy and equal weights are suspended from both points A and B. Adding the small weight W will make the wheel turn exactly as before. The heavy weights have no effect other than to slow the rotation and to increase the friction against the axle. Ignoring the friction, the rest point will be exactly the same whether or not equal weights are suspended from A and B.

If the heavy weight supposedly at A is really at C, the wheel will turn clockwise *before* little weight W is added. The heavy weight at B has a longer lever arm than the equally heavy weight at C. The addition of weight W at B will make the wheel turn an additional amount.

The heavy weights when suspended from A and B do not affect the rest point because they have equal lever arms and because they do not change the center of gravity. Suppose, however, that the weights are suspended from points L and L' instead of from A and B. This *does* lower the center of gravity, and the effect is the same as lowering G nearer the rim, *i. e.*, weight W attached to point B (or to L') will not cause the wheel to turn as far as before.

Another possibility is that the heavy weights are suspended by strings from points H and H' rather than from A and B. This raises the center of gravity, and has the same effect as raising G nearer the hub. With this condition, weight W will cause the wheel to turn more than when the heavy weights were suspended from A and B. If points H and H' are high enough and the weights suspended from these points are heavy enough in relation to G, the wheel will turn completely over because the center of gravity has been raised to the axle and beyond.

The purpose of a balance is to detect the small weight suspended from B, or to put it another way, to detect an equally small difference between weights suspended from A and B. To do this, the wheel must turn a detectable amount when the total weight on one side is smaller or larger than the total weight on the other side. Moreover, it is desirable that the wheel always turn the same amount whenever the same difference exists between the total weight on the two sides. This makes it possible to interpret the amount of rotation in terms of weight rather than to counterbalance the two sides in order to make a weighing. Also, if the same difference in weight turns the wheel the same amount under all conditions, the smallest difference that can be detected will be the same under all conditions.

Superimposing the concept of a balance beam on the wheel, we see that there are several conditions to be met if the balance is to detect a small weight, or small differences in weight, consistently under various loads.

(1) There must be very little friction in the axle. This condition is met in an analytical balance by supporting the whole moving system on a sharp straight knife edge resting on a flat plane. The only friction is that caused by the knife edge's rocking through a small arc on the plane.

(2) There must be very little friction in the strings which suspend the various weights. If the strings are stiff, they will have the effect of fastening the weights rigidly to the wheel with the resulting complications of having the size and shape of the weight affect the center of gravity. Here again the knife edge and plane are used in analytical balances. The hangers which hold the weights and samples are suspended from planes which rest on the knife edges in the ends of the beam.

(3) The weights must be suspended from points A and B, not C and B. This is accomplished by having the end knife edges of the beam in a balance equidistant from the center knife edge.

(4) Again, the weights must be suspended from points A and B, not L and L' nor H and H'. This means that, in a balance, the bottom of the center knife edge must be in the same horizontal plane as the tops of the upturned end knife edges.

(5) The weight G must be near the hub and not down near the rim. In an analytical balance this requirement is met by using a beam designed so that the center of gravity of the beam and all parts attached rigidly to it are just below the center knife edge.

(6) The wheel must be light in weight. The moving systems of analytical balances are made largely of aluminum and are stripped of all unnecessary attachments.

(7) Most of the weight of the wheel should be near the hub rather than the rim for faster rotation. In a balance this is accomplished again by the design of the beam, and by the use of a shorter beam. Theoretically a longer beam would give more sensitivity, but would slow the swing, and might bend under load if the beam were of light construction.

(8) Two additional requirements of an analytical balance are in the third dimension, and so are not shown by the wheel. The first is that all three knife edges, as viewed from above, must be parallel. The reason can be visualized by assuming that the left knife edge is closer to the fulcrum at its back end than

at its front end. Then if a heavy weight were to be placed on the back of the left pan, any friction in the suspension could throw more of the load on the back end of the knife edge. The effect would be to shorten that side of the beam, like suspending the weight from C instead of A.

(9) Similarly, the knife edges must be in the same horizontal plane all along their lengths. If one end edge is higher at the back than at the front and more weight falls on the back, the effect is that of suspending the weight from H rather than A.

In summary, a balance will weigh accurately without requiring special techniques only if the beam is designed properly and if the three knife edges in the beam are parallel, equidistant, and coplanar. The relative positions of the knife edges cannot be exact. As a practical matter, some tolerance must be allowed. The surprising thing is how small the various tolerances are in modern American balances. In the all-important spacing of the end knife edges, for example, accuracies to a part of one hundred-thousandth of an inch are common.

The important thing to the user is the accuracy in milligrams, not in inches, when the balance is used in various ways. The characteristics of any balance can be determined quickly by means of a few simple tests, and proper allowance for any shortcomings can be made thereafter.

To make the tests, the first step is to find the zero point of the balance when the pans are empty. This can be done by letting the beam swing until it comes to rest, by averaging the swings to calculate the rest point, or simply by using the turning point of the first swing as the reading. The last method can be used only if the pan rests are adjusted so that they do not give the beam a "kick" one way or the other on release. With any method of reading the pointer it will be most convenient to set the balance so that the zero or rest point is the zero line in the center of the pointer scale. This is done with the zero-adjusting rider or other means provided.

To test the sensitivity of the empty balance, a suitable small weight is placed on one of the pans and a reading is taken. A two-milligram weight is suitable for the usual "student" balance with a $^1/_{10}$-milligram rated sensitivity. This little weight will swing the pointer out possibly five divisions and change the rest point approximately $2^1/_2$ divisions. This test shows the lack of friction in the bearings and the height of the center of gravity. (G is near the hub, not the rim.)

To determine whether the two arms of the beam are equal in length, the small weight is removed and two heavy and equal weights are put on the two pans. They should each be 100, or preferably 200 grams for a balance with a 200-gram capacity. If the added weight causes the pointer to move to the left, the right arm is longer. (The weight on the left side is suspended from C rather than A.) It is unlikely that the two heavy weights will be exactly equal so they are exchanged between the pans and another reading taken. The midpoint between the two readings is the result due to inequality in length of the two arms of the beam; the spread between the two readings is due to the inequality of the weights.

For the next test the two heavy weights are left on the pans and the zero point is readjusted to the center line on the pointer scale. Then the same small (two-milligram) weight is placed on one of the pans and a reading taken to show the sensitivity of the loaded balance. If the same small weight swings the pointer farther when the pans are loaded than it does when the pans are empty, the end knife edges are high (at H and H'). Loading the pans certainly has not reduced the friction, so it must have raised the center of gravity resulting in more rotation from the same force. If the swing is less with a load on the pans, the end knife edges are probably low (at L and L'). Loading the pans has lowered the center of gravity. The lesser swing with added load also may be due in part to dull knife edges, the added friction they cause, and the damping action caused by their rocking on a radius which makes the higher arm longer.

To differentiate between low end edges and dull knife edges, the decrease in successive swings is noted. Dull edges decrease the oscillations more rapidly. With sharp edges on a free-swinging balance each oscillation is nearly as large as the previous one whether or not there is a load on the pans.

These four tests, sensitivity empty, change in rest point when load is added, sensitivity loaded, and deceleration of the swing, show the characteristics of a balance and have definite utility to the user. They show the limits of accuracy of the balance when used in a normal manner, and they point to ways of increasing the accuracy of the results by the use of special procedures when required. For example, the sensitivity of the balance at various loads can be charted to show the correct interpretation of the pointer reading with any load on the pans. More important perhaps is that this chart will show how many digits in a weighing are significant. When inequality in the relative length of the two arms of the beam prevents the weighing accuracy required, two solutions are possible. One is to chart the corrections necessary at various loads to compensate for error caused by the comparative lengths. The other is to use the substitution or transposition method of weighing. Techniques or methods cannot increase the accuracy of a balance limited by dull knife edges. Such a balance should be demoted to jobs requiring less accuracy. On the other hand, a well-understood balance, with sharp edges, can be relied on to yield accurate results for a long time.