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INTRODUCTORY

I. Method of treatment indicated by title.

In the title "Suggestions for a series of experiments illustrative of the fundamental principles of chemistry," the introduction of the terms 'suggestions' and 'illustrative' has been intentional and deliberate.

1. Suggestions.

In the first place the word *suggestions* is intended to convey that in the great majority of experiments dealt with, the method adopted and the experimental procedure to be followed will be indicated in outline only, minor details and elaborate descriptions of apparatus being avoided. It is hoped that the figures, which generally are at least approximately to scale, together with the tabulated records of the experimental work involved, will convey *per se* a considerable amount of information as to the nature, size and arrangement of the apparatus employed, the special kinds and quantities of materials used, and the degree of accuracy aimed at in the various measurements involved, thereby supplementing the intentionally restricted amount of verbal direction and description. Moreover, it is assumed that the students have access to standard manuals of practical work (such as Clowes' *Practical Chemistry*, Clowes and Coleman's *Quantitative Analysis*), and that they will be encouraged to consult these whenever the instructions given in this book do not suffice to make clear, *before* the experiment is begun, the principle and the technique of what it is proposed to do: how to obtain an answer, as satisfactory and conclusive as is possible under the circumstances, to the definite question about to be put to Nature. The additional information required will vary in amount according to the average attainments of the class and the individual needs of specially backward or specially advanced students; how much of this must be given by the teacher and how much can be left to the pupil's individual effort depends, of course, on the special conditions. Obviously the greater the call on the learner's independence, originality and ingenuity, the better.

In each experiment, with the object of accomplishing a desired effect, directions are given for the carrying out of certain processes; the word *suggestions* is used in order to convey the fact that the apparatus depicted, the procedures described, do not represent the only or even the best possible means of accomplishing this effect, but merely that these schemes of work lend themselves to the obtaining of results such as those quoted, and that they have been selected because of their simplicity. It will tend to increase the efficiency of the work all round if variety is encouraged, some members of the class, guided by books and their own ingenuity, carrying out the experiment with modifications in detail or even in principle. Thus, for showing the increase in weight of iron on being heated in air (*post*, pp. 55 and 86), one student could use finely divided iron held by a horseshoe magnet suspended from a hook of a balance, while another could pursue the more common plan of placing the iron in a dish, crucible or open tube; or again, the means of collecting for purposes of measurement the hydrogen evolved by the action of magnesium on dilute acid can be made the subject of a competition, the pupils being set to discover how many different simple methods they might employ.

2. Illustrative Experiments.

In the second place, the substitution of 'illustrative experiments' for the current term 'experimental proofs' is intended to define from the outset the attitude of strong disapproval taken by the author towards the use of the words *research, discovery, proof* in connection with the work done and the results obtained by the average student working in a school or college laboratory.

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(1) It is considered of the utmost importance to impress on the students that the result of one experiment, or even of three or four fairly concordant ones, does not constitute a *proof* unless the amount of preliminary work, the nature of the relation investigated, the precautions taken, the prestige due to the personal skill and experience of the experimenter, have, separately or conjointly, created a special and exceptional case. 'Special cases' of that kind actually occurred in Lavoisier's experiment with mercury calx and in Pasteur's experiment by which laevo-tartaric acid was produced, but even in those realms of scientific research where the giants reign, such instances are rare. These two examples so well emphasise the point that they are worthy of fuller description.

(*a*) Lavoisier, by *one* experiment, involving the quantitative synthesis and complete analysis of mercury calx[1], supplied irrefutable deductive proof of the true nature of combustion, including the elucidation of the part played by the air and the composition of air.

(*b*) When Pasteur first announced that, starting from racemic acid, he had been able to prepare a substance in every way identical with ordinary tartaric acid, except that it rotated the plane of polarisation to the left instead of to the right, he was required to produce *proof* of this unexpected and startling phenomenon by making a specimen of the new laevo-tartaric acid under the personal supervision of Biot, at that time the *doyen* of French scientists, who himself supplied all the necessary materials. This episode in the history of Pasteur's great discoveries deserves to be told in detail, with such explanations as are necessary for the proper understanding of the points at issue.

Tartaric acid and racemic acid are both obtained from grape juice, and are substances which even before Pasteur's classical research had already played an important part in the development of chemical theory. As far back as 1829 Berzelius had shown that these two substances, though differing in important physical and chemical properties, had the same

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[1] Freund, *Study of Chemical Composition*, pp. 51 *et seq.*; Muir, *Heroes of Science, Chemists*, pp. 87, 88; Lewis, *Inorganic Chemistry*, 1907, pp. 243, 244.

composition, *i.e.* contained the same constituent elements—carbon, hydrogen and oxygen—united in the same ratio. This was one of the fundamental observations from which was built up the doctrine of isomerism. Later on it was shown that the differences between tartaric acid and racemic acid extend to their optical properties, in that whereas a solution of tartaric acid rotates the plane of polarisation to the right, racemic acid is optically inactive. Pasteur, who in 1848 took up the study of these acids and their salts, found the property of optical activity definitely related to the crystallographic property termed 'hemihedrism,' which consists in the exhibition by the crystal of a number of faces all turned in the same direction, either all to the left or all to the right (fig. 1).

Tartaric acid and all its optically active salts exhibited hemihedrism, the crystals showing a number of faces all turned to the right, whilst optically inactive racemic acid and its salts showed no signs of such unsymmetrical crystallographic development. But the generalisation thus arrived at from the study of a large number of salts seemed at first to break down when applied to the double salts sodium-ammonium tartrate and sodium-ammonium racemate. Experiment showed that the optically active tartrate was hemihedral, but that, contrary to expectation, the optically inactive racemate was hemihedral also[1],

> ...Only, the hemihedral faces which in the tartrate were all turned the same way, were in the racemate inclined sometimes to the right and sometimes to the left....I carefully separated the crystals which were hemihedral to the right from those hemihedral to the left, and examined their solutions separately in the polarising apparatus....The crystals hemihedral to the right deviated the plane of polarisation to the right, and those hemihedral to the left deviated it to the left; and when I took an equal weight of each of the two kinds of crystals, the mixed solution was indifferent towards the light in consequence of the neutralisation of the two equal and opposite deviations.
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> The announcement of the above facts naturally placed me in communication with Biot, who was not without doubts regarding their accuracy.... He made me come to him and repeat before his eyes the decisive experiment. He handed over to me some racemic acid which he had himself previously studied with particular care, and which he had found to be

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[1] Sodium-ammonium racemate is inactive and the crystals are symmetrical (fig. 1 (*f*)), but when crystallised from water at ordinary temperatures it splits up into dextro and laevo tartrates, the former identical with ordinary sodium-ammonium tartrate, the other the new substance discovered by Pasteur. From these salts the two corresponding tartaric acids (fig. 1 (*c*) and (*d*)) can be prepared.

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perfectly indifferent to polarised light. I prepared the double salt in his presence, with soda and ammonia which he had likewise desired to provide.

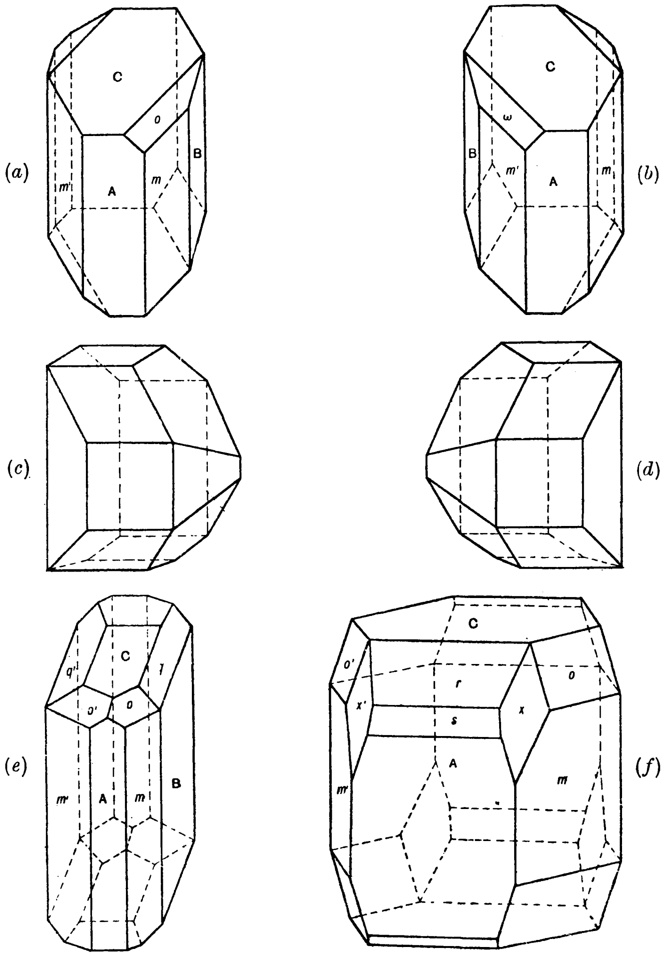

Fig. 1.

(*a*) and (*b*). Dextro and laevo sodium ammonium tartrate tetrahydrate (Pasteur). Note in fig. (*a*) the presence of a face *o* between **C** and *m* and the absence of such a face between **C** and *m′*. (*b*) is the mirror image of (*a*).

(*c*) and (*d*). Dextro and laevo tartaric acid (Pasteur). The crystals are mirror images of one another.

(*e*) and (*f*). Potassium racemate dihydrate (Pasteur) and sodium ammonium racemate monohydrate (after Scacchi). In these two crystals the faces *m*, *o*, *q*; *m*, *x*, *o* are symmetrically arranged on either side of a plane at right angles to the faces **A** and **C**.

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The liquid was set aside for slow evaporation in one of his rooms. When it had furnished about 30 to 40 grams of crystals, he asked me to call at the *Collège de France* in order to collect them and isolate before him, by recognition of their crystallographic character, the right and the left crystals, requesting me to state once more whether I really affirmed that the crystals which I should place at his right would deviate to the right, and the others to the left. This done, he told me that he would undertake the rest.

The dramatic *dénouement* is thus described:

Then the illustrious old man, who was visibly affected, took me by the arm and said: "Mon cher enfant, j'ai tant aimé les sciences dans ma vie, que cela me fait battre le cœur."
(*Researches on Molecular Asymmetry*, Alembic Club Reprints, No. 14.)

(*c*) Another striking illustration of the meaning carried by the words *proof* and *discovery*, when these terms are applied correctly and legitimately, is afforded by a chapter in the history of that youngest and most marvellous of all the sciences, radio-activity. When Sir William Ramsay and Mr Soddy first demonstrated the spontaneous production of the element helium from the element radium, this transmutation was not accepted as *proved* until the same result had been observed by others working in different places, with different apparatus and with different samples of material.

The production of helium from radium was soon confirmed by a number of investigators. P. Curie and Dewar placed about 400 milligrams of radium bromide in a quartz tube. The salt was heated to fusion, and the tube exhausted to a low pressure and then sealed off. The spectrum of the gases in the tube was examined 20 days later by Deslandres, and gave the complete spectrum of helium. This experiment showed conclusively that the presence of helium in old radium preparations could not be due to its absorption from the air.
(Rutherford, *Radio-active Substances and their Radiations*, 1913.)

(2) A tendency which set in a few years ago, and which unfortunately still dominates much of the school teaching of chemistry, would have us believe that in the course of some couple of hours' work the average pupil can definitely correlate an observed effect with its cause, can *discover* the nature of a chemical relationship, or can prove a law. We are told that "the composition of water is *discovered* by burning the hydrogen obtained by the action of acids on metals"..."the girls should be *discovering* the composition and properties of soap." Compare and contrast with this the true evaluation of the work of pupil and teacher in the acquisition of scientific knowledge as given by Ostwald. In the most delightful of

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elementary text books[1], the main facts of inorganic and physical chemistry are dealt with in the form of dialogues between a teacher and a pupil. The method is heuristic in the truest and best sense, but there is no make-believe, no pretence about what the pupil really accomplishes himself and what is done for him. Thus in the investigation of the effect of varying pressure on the volume of a definite quantity of air confined over mercury, a number of corresponding measurements are made in the usual way[2] and the results recorded in tabular form.

Pupil. What is the use of that?
Teacher. I want to show you *how to discover a law of nature.*

And when, after a number of explanations, directions and trials, the relation $pv =$ constant has been formulated:

Teacher. Right. Now you have found the law which connects the pressure and the volume of air with each other, or makes them dependent upon each other.
Pupil. I should never have found that out without your help.
Teacher. I quite agree.
Pupil. I say, did *you* find it out by yourself?
Teacher. No. An English physicist named Boyle discovered it more than 250 years ago, and it goes by the name of Boyle's Law.

Moreover, explicit and emphatic protests come from teachers of high standing and experience, who in the strongest possible terms condemn an attitude which, regarding the learning of elementary science as the making of a series of discoveries, is nothing better than a make-believe fraught with grave intellectual danger.

> The discovery of physical laws by the average pupil seems to me an achievement quite outside the range of the possible; no heuristic process can do away with the prerogative of genius. Of course we can arrange matters so as to produce in the pupils the delusion that they have newly discovered an old truth; but by such a practice we are deliberately deceiving them about matters so fundamentally important as the growth of knowledge, the nature of research and their own abilities. (P. Johannesson, *Die physikalischen Uebungen am Sophienrealgymnasium zu Berlin.*)
>
> It is of the utmost importance that in the school teaching of chemistry, especially in its elementary stages, the interpretation of complicated processes should be avoided; otherwise the result is almost bound to be the encouragement of loose thinking and megalomania on the part of the pupils. This is a very real danger, because again and again we are confronted by a pedagogical requirement which indicates a very low standard

[1] Ostwald, *Schule der Chemie.* Authorised translation by E. C. Ramsay, entitled "*Conversations on Chemistry,*" pub. by Wiley and Son, New York.

[2] Glazebrook, *Hydrostatics*, 1904, pp. 159 *et seq.*

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of psychological insight. "The pupils must themselves discover the causes of chemical phenomena, they must devise experiments suitable for attaining this object, and must themselves elaborate the details of these experiments." Well, if the pupils were capable of doing all this, they would need no teaching, nay, they would in mental ability excel a Faraday, a Bunsen. What humanity through the foremost of its representatives has laboured at painstakingly for centuries, young people are now to play at discovering in the course of a few lessons....[All that] can be accomplished in the school teaching of science is practice in logical thinking, the pupils being *made* to follow lines of thought similar to those traversed by the great discoverers. Note, *similar* lines, not by any means *identical* lines. We guide our pupils along roads which might have led to great discoveries, and at all stages we must tell them as facts a great deal of what has been found by mere fortuitous trial and not as the result of any thinking process, simply because these special facts are outside the scope of logical inference. What logical considerations could suggest the heating of mercury calx[1], when the calces themselves are produced by heating in air? Where does logic come in when in testing for acids and bases we use litmus, a substance unknown to the majority of people? (R. Winderlich, *Logik in der Chemie.*)

Surely, therefore, the more honest, intellectually more bracing and eventually more fruitful course is to sweep away all delusions as to what the pupils can discover for themselves, and further to impress on them at as early a stage as possible the fundamental difference between the 'illustrative experiments' they perform and real research work. In the practical working of the so-called "research method" of teaching, what really happens is: under the direction of somebody who knows (practically always through other people's work) how a certain desired result can be brought about, a certain favourable combination of conditions is created, the effect thereby produced on some specific kind of matter is observed in its qualitative aspect and measured in its quantitative aspect, and the *assumption* is then made that, except for those intentionally modified, all the conditions under which the action proceeds exert no influence on the final result. And finally, whatever may be pretended about 'discovering' and 'proving,' the result so obtained is compared with that *expected* according to the standard work on the subject, accepted when it agrees with it, rejected when it differs. And yet it is only by the judicious use of apparent failure, only when some serious attempt is made to trace the cause of deviation from the standard result, that the element of discovery comes within the scope of the work. But as

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[1] See *ante*, p. 3.

things are, the attitude of many teachers of elementary chemistry who are considered most progressive and most truly scientific has much in common with that of the Alchemists of an earlier age. They cry now as then, "Follow Nature"; but then, as now, it was a following in which "the vision was seen before the following began."

II. Fundamental difference between students' illustrative experiments and research work.

What is it, then, which characterises work intended to lead to and culminating in real discovery, real proof, real standard measurements? For one thing, as many as possible of the conditions under which the experiment is carried out are tested as to their influence on the final result: the experiment is performed a considerable number of times, varying those conditions which are thought uninfluential, and making agreement of the various results obtained a criterion of the legitimacy of this assumption. Even so, in research work many deliberate assumptions are made, but always with the limitation that what is assumed has itself been the subject of previous investigations at least as trustworthy and accurate as those of the special research just being done. The best way for the student to realise in its full extent the difference between an 'illustrative experiment' and a 'research' would be to read some good original paper and to compare it with the corresponding experiment adapted for students' use as described in any good text book of practical chemistry. A fundamental difference exists between the two, and though what begins as an 'illustrative experiment' may of course at any time develop towards a 'proof' or really become one, this necessitates a fundamental change of method and procedure. Good opportunities for learning to appreciate this fundamental difference are supplied by the following cases:

(1) The demonstration by synthesis and by analysis of the qualitative composition of water.

Compare and contrast the directions for students' experiments contained in the ordinary text books with Cavendish's account[1] of his own work which culminated in the statement:

> When a mixture of inflammable and dephlogisticated air [our hydrogen and oxygen] is exploded...the condensed liquor...seems pure water, without any addition whatever;

and the complementary achievement of Sir Humphry Davy[2] summarised by him in the words:

> Water chemically pure is decomposed by electricity into gaseous matter alone, into oxygen and hydrogen.

But in certain syllabuses we are told: "The composition of water is *discovered* by"—etc., leaving the impression that the achievement of such a discovery is well within the reach of the average pupil of school age.

(2) The determination of the gravimetric composition of water.

The short abstract contained in *Nature*[3] of Morley's work on this subject should be read side by side with the directions usually given for the use of Dumas' method in a students' experiment[4].

(3) The determination of the normal density of hydrogen chloride, *i.e.* the weight in grams of 1 litre of the gas at 0° C. and 760 mm.

This being an experiment which is quite frequently done by students towards the end of their school or the beginning of their college course, it may be useful to deal with it in somewhat greater detail under each of the two aspects which it is intended to contrast.

(*a*) Students' illustrative experiment.

The necessary instructions for the experimental procedure are given on p. 11, and a suitable apparatus is shown in fig. 2[5].

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[1] *Experiments on Air* (Alembic Club Reprints, No. 3); Thorpe, *Essays in Historical Chemistry*, 1911, pp. 92 *et seq.*

[2] *Study of Chemical Composition*, p. 10.

[3] *Nature*, **53**, 1896, p. 428.

[4] Ramsay, *Experimental Proofs of Chemical Theory*, § 38; Lewis, *Inorganic Chemistry*, p. 48.

[5] The appendix at the end of this chapter gives a description of an arrangement which in the writer's practice has been found to work extremely well, and to repay fully the somewhat greater trouble involved in the setting up.