

Critical Thinking

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In 1995, in response to the many messages that Chemistry departments were then receiving from employers about the skills they required from graduates, we put together a second-year module designed to improve IT and communication skills amongst our students. The course runs for 12 weeks, at 4 hours per week. For one of the sessions, designed to promote group working and critical thinking about chemistry, we have for some years used a selection of the exercises in *A Question of Chemistry* by J Garratt, T Overton, and T Threlfall. I actually started using this material some years before the publication of the book, having been introduced to it in a preliminary form at a Variety in Chemistry Teaching meeting in York.

For the session the class is split into groups of about 5 students, each with a designated 'leader' chosen at random. Each exercise is presented to the class, they are given a few minutes to discuss the task, and then each leader presents the group's conclusions, justifying their choice. The session thus meets at least two objectives: critical thinking about chemistry and teamwork.

The student response to this activity is overwhelmingly positive. Some of their comments are appended, under headings reflecting the two main objectives mentioned above. All but one student assessed the session as 'useful'.

Critical Thinking:

Makes you analyse and justify statements.
Helps one think more about chemistry.
Useful exercise in analysing information.
Useful exercise in critical thinking.
Nice way to discuss chemical problems.
Increased awareness of the need to think about what one is reading.
Helped learn how to summarise complicated material.
Good to see that people have different ways of discussing chemistry and how such differences may alter meaning.

Group Working:

Group discussions are very important because communication is the key to enlightenment.
Good to encourage group discussion.
Helps get to know other members of the class better.
More useful than just working on one's own.

Other comments:

Should do more of these.
A good way to combine chemistry and teamwork.
Improves individual confidence.
Important lesson: sometimes it is best to stick to one's instincts.
Be open-minded - don't follow others like sheep.

Clearly, the students find this exercise stimulating, and they all take part enthusiastically even though it is the one section of the course that does not contribute to their marks!

I can recommend this approach to colleagues.

Teaching experimental design

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Garratt and Tomlinson in their paper 'Experimental design – can it be taught or learned?'¹ elegantly demonstrate that even experienced, practising scientists may slip up in their experimental design when faced with an unfamiliar situation or subject matter. The paper presents the arguments for the essential feature of a scientific hypothesis: the need to formulate it in such a way that it can be disproved.

While this approach to experimental design is undoubtedly applicable in many cases, it has been argued² that Popper's methodology is not a complete account of how all of chemical research is done. Neither much of analysis, nor much of structure determination or synthesis is done by the formulation of a hypothesis and subsequent testing to try to refute it. Therefore I would question the value of any instruction in scientific method (whatever that is) that is anything other than the encouragement of students to carry out varied types of chemical experiments of increasing sophistication and independence, combined with

careful and guided analysis of what they are doing, why they are doing it and what the results may or may not mean.

Good experimental design is difficult; we have all read scientific papers in print or while refereeing, and spotted flaws in the experimental design that invalidated the conclusions claimed. And this was in papers by experienced scientists writing after careful consideration about their area of expertise and refereed by other experts.

There were two examples in recent years where flaws in the experimental designs of senior and experienced scientists were exposed very publicly indeed. These were ‘cold fusion’³ and Pusztai’s report on nutritional problems with genetically modified potatoes.⁴ Both topics are so important that the investigators must have known their results would be subjected to the closest scrutiny, so they must have believed they had got their experimental design and the derived conclusions right. However, in both cases the people reported results from fields on the edge of their expertise. This kind of case strengthens my belief that, in addition to clear thinking, it is necessary to have an intimate knowledge of the subject being investigated if one is to design reliable experiments producing valid conclusions.

So, we have to accept that all of us are fallible. However, this needn’t stop us preaching the importance and teaching the skills of good experimental design, since if we don’t, who will? But I believe this has to be done by example and with a case-by-case approach, in areas of the subject we each know best. Even the most mundane expository experiment can be used, with well-designed pre- and post-lab activities,⁵ to get students to think about what they did, how they did it, why they did it that way and what it means as a piece of science.

References

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Calculating oxidation numbers of carbon in organic compounds and balancing equations of organic redox reactions

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We have observed two specific problems encountered by our students concerning oxidation numbers of organic compounds:

- They often have difficulty identifying whether reactions are oxidative, reductive, or non-redox.
- They cannot readily balance organic reactions; often this is not important, but is required whenever the stoichiometry of the reaction is important.

The currently accepted oxidation number method and ion-electron (half reaction) method for balancing inorganic reactions can be applied to balance organic reactions.¹⁻³ This approach also reinforces the concept of using oxidation levels to identify redox reactions, whilst its application to half reactions allows equations to be balanced simply and rapidly. However, although there are a number of published methods of determining oxidation numbers of carbon,^{4,6} we have found them to be generally unwieldy for students, thereby limiting their value.

We present here an equation that we have developed for rapidly determining the oxidation number of carbon in organic compounds, and extend this to offer a rapid and convenient method for balancing equations for organic redox reactions. Our equation is an easy-to-use expression of the general formula:

$$\text{Oxidation number of carbon} = 4 - (C + 2E + N)$$

Where C = number of C–C bonds.

E = number of bonds to ‘more metallic’ atoms (see below).

N = number of nonbonding electrons (zero for carbon, but relevant for heteroatoms such as nitrogen in nitro/amine – see below).

In general, E applies to ALL less electronegative atoms such as H, P, B, Si and to metals, but must be qualified to exclude all elements in the non-metallic region of the periodic table running down diagonally from carbon to iodine (thereby excluding Se and I). This generates a rule that is

applicable in virtually all examples that undergraduates are likely to encounter.

In the application of the oxidation number method for balancing equations of organic reactions,¹ we suggest that the determination of electron gain and loss for C directly (instead of first calculating the change in its oxidation number) is a useful short cut; students should be reminded that this is appropriate when only carbon changes its oxidation number, but they need to be aware of O/N/P sometimes doing so (e.g. peroxy, nitro, P^{III/V}). Breaking or formation of each C–H (or another less electronegative atom) bond means one electron loss or one electron gain for C, respectively. However, breaking or formation of each C–O (or another more electronegative atom) bond means one electron gain or one electron loss for C, respectively. By determining the net change in the number of bonds attached to C, the number of electrons ‘lost’ or ‘gained’ by C can be easily found in the oxidation or reduction of organic compounds. We exemplify these approaches with the dichromate oxidation of ethanol to ethanoic acid:

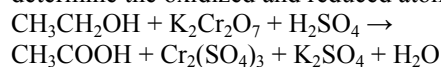
Oxidation numbers of the carbon atoms carbon in the starting material and the product:



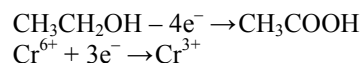
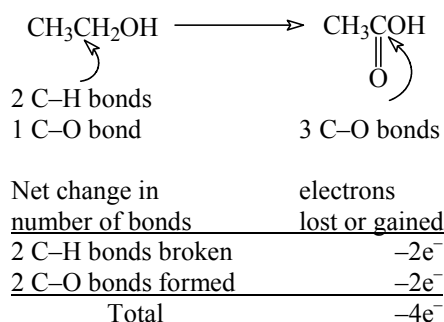
$$\begin{array}{ll} \text{C1: } 4 - (1 + 2 \times 2) = -1 & \text{C1: } 4 - (1 + 0) = 3 \\ \text{C2: } 4 - (1 + 3 \times 2) = -3 & \text{C2: } 4 - (1 + 3 \times 2) = -3 \end{array}$$

To balance the oxidative redox equation, electrons ‘lost’ or ‘gained’ by carbon atoms can also be found by determining the net change in number of bonds to carbon atoms (step B) instead of using oxidation numbers of carbon atoms.

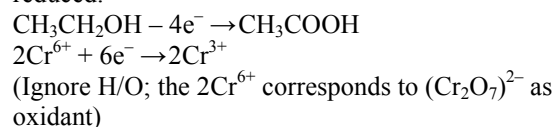
Step A: Write the unbalanced equation and determine the oxidized and reduced atoms.



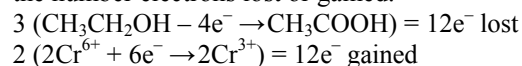
Step B: Write two partial equations. For the oxidized and the reduced C atoms, find the number of electrons ‘gained’ or ‘lost’ by determining the net change in number of bonds.



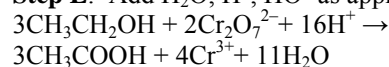
Step C: Balance the number of atoms oxidised and reduced.



Step D: Add coefficients to balance the change in the number electrons lost or gained.



Step E: Add H₂O, H⁺, HO[–] as appropriate:



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Administrators undermine degrees

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Following my recent experiences as an external examiner and on assessment panels, I fear that university administrators are undermining the quality of our undergraduate degrees, and we are acquiescing in this! In order to forestall potential criticisms of unfairness by external assessors (e.g. QAA) or students (litigation), universities are devising degree regulations that attempt to pin down precisely what is meant by the various classes of degree. As a consequence, many chemistry departments are required to follow strict marking and classification guidelines. The educational argument in favour of this approach is a powerful one:

- Surely, they say, we have identified the intended learning outcomes.

- Thus, we ought to be able to set and mark an exam to test for these.
- Hence, if the examinations and the marking process are fair, it is inappropriate to classify students on other criteria (e.g. the whim of external examiners moderating borderlines, or the performance of a student in an oral examination).

This, however, misses the point. Whilst it is easy to set exams that can be marked very precisely, such exams are not appropriate for testing many of the skills at honours degree level. The Chemistry Benchmarking document¹ identifies an excellent set of criteria for achieving various standards but, unlike in most subjects in the humanities/social sciences, it is possible in our discipline to set questions with a specific 'right' answer, thereby responding to the pressure to have precision in our assessment processes. However, I EXPECT questions to be set for which there are several possible answers, and these particularly test the 'key skills' that Dearing² and employers^{3,4} have identified as vital characteristics of high quality graduates (e.g. communication skills, critical thinking, etc.). In my experience, the rules imposed by many universities are leading us to set less demanding exam questions. Far better, surely, to set the exams we really think are appropriate at honours degree level, and ask respected fellow academics to comment on the exams and then provide moderation once they have seen how the whole of the assessment process has been conducted (i.e. the exam paper itself, the answers given, the marking process, the balance of assessment procedures, and any special factors).

Whilst one would rarely expect the classifications to vary greatly from pre-set guidelines (e.g. 70% = 1st, 60% = 2i, etc.), oral examinations offer an additional chance to correct for the imprecision of marking at this level, for students just missing a higher degree classification. Sadly, several institutions are now discontinuing oral examinations on the grounds that they discriminate against some students (don't all exams do that?), and because the assessment process 'ought to be

sufficiently accurate using the prescribed criteria'. It is my view that the orals not only help to ensure fairness just below the borderline, but that they help external examiners to assess the degree standards compared with elsewhere in the UK, and to provide more feedback for improving the courses.

Whilst I clearly have an old-fashioned view of the best way to maintain standards, it is ironic that I think the traditional approach is the most appropriate way of assessing the results of the very best and most innovative of teaching. One change I would advocate is that one external examiner should always be allocated from a pool of assessors (i.e. not chosen by the department), in order to ensure consistency. Although trained assessors were considered (but rejected) by the QAA about four years ago, the simpler procedure of drawing from a pool of experts (*cf.* EPSRC Colleges) has merit. In the long run, the assessment procedures have a profound effect on how courses are designed and delivered and therefore on how students learn, and on the skills they develop; I believe that we have a responsibility to ensure that we really do assess our students in ways that we believe are appropriate at degree level in Chemistry.

References

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