Crossing the borders: Chemical education research and teaching practice

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1. Crises in current chemistry education

In many European countries, chemistry education faces a number of important recurrent difficulties. At the *secondary school level*, many students have a rather negative view of chemistry. They think of it as a rather dirty discipline and they experience difficulties in understanding key concepts and rules. Common student complaints are of the kind 'I know this chemistry formula by heart, but I do not understand its meaning'. Many teachers complain that repeated explanation and demonstration are not very effective and frustrate the teachers as well as the students. Coupled with this negative attitude, students' interest in chemistry as one of the chosen final examination subjects has decreased to a rather low level.

At *university level*, the number of first-year chemistry students is also decreasing. Students complain that laboratory courses involve many boring 'cookbook' problems instead of challenging tasks to explore new areas of chemistry. However, lecturers complain that many students are not able to connect lecture courses with laboratory courses and, for that reason, cannot apply (theoretical) knowledge of chemistry in the context of practical work.

Another category of problems concerns the *chemistry curriculum*. Well-known complaints involve the overload with factual material, the vague course structure and a lack of modern topics. Furthermore, the connection between the chemistry curriculum at secondary level and at tertiary level is rather weak.

Tackling the current crisis requires, among other measures, *the use of research*[1]. Unfortunately, many teachers and researchers point out that there is a gap between chemical education research and the implementation of the research findings in college and classroom teaching.

2. A gap between research and teaching

Those teaching chemistry, whether at university or at school, often feel dissatisfied with chemical education research. Their complaints can be summarised as 'much chemical education is not readily accessible to the teaching practitioners and, in any case, research outcomes seem to be either not very useful or are difficult to translate into useful teaching and learning activities for college and classroom practice'. However, chemical education researchers also complain about a gap between research and teaching. I suggest that there are three main reasons for the origin of these complaints.

First of all, an important cause of such complaints might be mere *survival*. Chemistry lecturers, as well as school teachers have to survive, which means that they cannot find time for reading research articles because they are already too busy with their existing teaching. Even if they have time for reading, they need extra time to translate and integrate the content into their teaching practice, and this is a skill they may not have been able to develop well during their period of teacher training or their career. Chemical education researchers also have to survive, which means that they have to publish in high-ranked journals read by only a few lecturers and teachers. Of course, researchers are free to publish in journals intended for university lecturers and school teachers, and indeed some of them do. However that does not provide rewards in terms of 'research' output.

A second reason might be the *differences in expectations*. Lecturers and teachers might be inclined to think that research ought to provide them with solutions for their teaching difficulties. Researchers might be inclined to believe that teachers are able to transform the reported research outcomes into useful ideas for teaching at college and school level. Unfortunately, both expectations are too high and not very realistic.

Finally, the gap may result from the choice of the *research paradigm* that is used. For many years (including the present), the (theoretical) frameworks of chemistry education research have been strongly influenced by general psychological theories about teaching and learning. Some decades ago, the leading theory was called 'descriptive behaviourism', which includes stimulus-response models about shaping behaviour by operant conditioning (a very common method for training dogs!). This perspective promoted an interest in the use of programmed instruction in chemistry courses (i.e. teaching which involves providing a series of tasks with direct feedback to the answers of individual learners). In the last two decades, another leading theory arose, called cognitive psychology. This approach stimulated an interest in chemistry courses based, for example, on theories about guided discovery learning and theories about conditions of learning. In my opinion, the value of both approaches for improving chemistry teaching and learning is restricted. The conclusions of research which has been carried out in the context of such psychological theories tend to be too general to be helpful for designing courses in specific chemistry topics. The weak relationship between general educational theories and specific teaching practices can also be explained as follows. Course developers use (often implicitly) basic conceptions of chemistry and chemistry education during the process of designing new teaching strategies. Their specific preconceptions of teaching a particular chemistry topic will often be more influential than their knowledge of rather general models of teaching and learning.

In conclusion, much research has focussed on aspects of teaching and learning which are essentially 'content-free' and refer to general problems of teaching and learning. However, teachers are faced with content-related difficulties in teaching and learning. They want to understand the reasons why these specific problems arise. But much research is not concerned with content-related information, and therefore does not help to bridge the gap between theory and practice. We need research which specifically takes content into account. In the language of educational researchers, such studies will have a strong 'domain-specific character.[2]

3. The line of domain-specific research

During the last decade, there has been increased interest in studies of the teaching and learning of specific chemistry topics. This domain-specific research is strongly stimulated by the current leading theory of knowledge acquisition: *constructivism*. According to this perspective (see e.g. Bodner,[3]), learning is a dynamic and social process in which learners actively construct meaning from their actual experiences in connection with their prior understandings and the social setting. Knowledge and learning are considered to be dependent on the situation. Cognition is in part a product of the activity, the context and the culture in which it is developed and used. A major implication for chemistry teaching is the idea that chemistry teachers should have an insight into students' (pre)conceptions of chemistry topics and should facilitate chemistry learning by creating conditions enabling conceptual change[4].

Many *domain-specific studies* were focused on students' conceptions of chemistry concepts and rules[5]. These studies often involve qualitative methods for collecting and analysing research data. This often involves analysing records of interviews, think-aloud monologues or classroom discussions. Think aloud monologues can be stimulated by inviting students to say what they think while they are performing a certain task (introspection), or by asking them (after finishing the task) to describe what they were thinking during the task (retrospection). An interesting example of the think-aloud method is presented by Osborne and Gilbert[6]. Their approach involved interviewing students who were presented with a set of simple line-drawings on cards depicting instances or non-instances of a particular science concept. Students were asked to categorise the picture on each card and then asked to explain their reasons. It appeared to be possible to explore students' *understanding* of a particular science concept beyond their *knowledge* of its formal definition.

In my opinion, domain-specific research is a very important tool for improving chemistry education. However, its value depends on the nature of the research instruments. Records of interviews and think-aloud monologues can be used before or after classroom instructions, but they are not very fruitful for investigating the teaching and learning of chemistry as it actually takes place in the laboratory or classroom. For that kind of research, it is particularly useful to produce records of discussions between students and their teachers in educational situations.

It is important to recognise that the quality of any final record is influenced both by the audiotaping of the original discussion and by its transcription.

The *audiotaping* of students and their teacher requires the presence of one or more tape recorders in the laboratory or classroom. One can be placed on the teacher's desk. Others can be placed on students' desks, especially when students have to work on tasks in small independent groups. If the teacher has the habit of walking around the room a lot, a portable tape recorder can be very useful. In all cases, it is important that the presence of recorders does not influence the behaviour of students or teacher. Only then, is it possible to record spontaneous discussions. It is my experience that students and their teacher quickly accept the presence of recorders and, after one or two sessions, ignore the equipment entirely.

Once the audiotape has been made, it must be transcribed into a record. One method consists of transcribing all recorded statements. Although this approach takes a lot of time, all statements are on paper. A second method consists of selecting a number of episodes for transcription, after first scanning the discussions on the tape. The selection involves making judgements about which episodes are most relevant to the formulated research questions. Although this approach saves time by reducing the length of the record, there is a certain risk of missing out on important information. In my experience, the most productive method is somewhere between the two: analysis of the first selection of episodes leads to the recognition of the need for an additional selection.

Domain specific research of this nature is often small-scale because of the time consuming methods of analysis. However, records of laboratory/ classroom discussions can be a rich source of information. It can be very useful for teachers to produce their own records for analysing their teaching activities as well as the conceptual difficulties of their students. This is illustrated by the following two examples. Both are concerned with the teaching of electrochemistry to upper secondary school students.

4. Examples

In the first example, the teacher introduces and discusses a specific electrochemical cell: the zinc-copper galvanic cell (Daniell cell). The teacher explains this cell and uses expressions like 'the zinc is negative' and 'the copper is positive'. The teacher goes on to explain that the copper bar becomes heavier because copper has been deposited on it by the following half-reaction:

$$Cu^{2+} + 2e^{-} \rightarrow Cu$$

It is important to note that the teacher does not use the expressions 'the zinc electrode is negative' and 'the copper electrode is positive', although these phrases are given in the students' textbook. (As a matter of fact, the terms 'negative' and ‘positive’ do not refer to the sign of charge of the electrodes but to the whole half cell under consideration. The signs are relative and depend on the particular combination of half cells. The sign of charges can be determined by electrical measuring methods including the use of a voltmeter or an ammeter).

The following discussion between two students was recorded.

Student 1:

According to this half-reaction, the copper ions get electrons by moving to that bar. But that electrode is positive. How comes that positive ions move to that positive electrode? We have learnt that entities with the same sign of charge will repulse each other, isn’t it?

Student 2:

Yes! I do not understand it either. But this is chemistry, you know …

Note that Student 1 uses the term ‘bar’ as well as ‘electrode’. The first term refers to an object, the second one to an (electrochemical) function of the object. However, the student does not consider the whole electrochemical context but only interprets the situation as a local one. He wants to use Coulombs’ Law of electrical attraction and repulsion. But its use cannot explain the moving of copper ions towards the copper bar (copper electrode). In conclusion, the teacher’s choice of words in providing explanations appears to have caused a big cognitive conflict amongst the students. The teacher has reasoned from a measurement point of view, in the sense that his expression ‘copper is positive’ implicitly refers to the sign of charge on the ‘copper’ half cell in relation to the ‘zinc’ half cell. However, the students are reasoning from another context, viz that of an electrical particle. If the teacher analyses this record of the students’ discussion, he should become aware of students’ conceptual difficulties and this should help him to develop other ways of explaining the zinc-copper galvanic cell.

In the second example, the teacher has demonstrated the electrolysis of a KBr solution between carbon electrodes. After the students have observed what happens they are asked to describe the electrode reactions.

It is important to know that the students had already been taught to predict electrode reactions by consulting a table of half reactions and the accompanying standard electrode potentials. That table shows that the standard electrode potential for the H_2O/H_2 couple (- 0.83V) is higher than for the K^+/K couple (- 2.92V). Students are supposed to conclude that H_2O is a better oxidising agent than K^+, and for that reason is involved exclusively in the electrode half reaction. However, this way of reasoning is not clear to every student as the following record of a classroom discussion shows.

Teacher: *In this case, what is the best oxidizing agent?*

Student *K^+ … uh, uh,... 2 H_2O …*

Teacher: *Water is the best oxidizing agent (…) The minus electrode, water produces... H_2...so, the gas you saw was hydrogen …*

Student: *But that potassium plus is attracted and water is not …*

Teacher: *(…) It is sufficient to take water, quite common according to the rules*

In the recorded episode, the student does not feel the necessity to accept a new chemistry rule from the teacher who said “it is sufficient to take water, quite according to the rules”. However, the student prefers to use an existing physics rule which is more plausible to him, saying “but that potassium plus is attracted and water is not”. In other words, the teacher reasons from a chemistry context, while the student reasons from a physics context.

Both examples show that one of the barriers to student understanding of (electrochemical) concepts and rules was the fact that teacher and student were reasoning in different contexts. The examples illustrate how records can bring to light, not only student misconceptions, but also communication difficulties between teacher (lecturer) and student which arise (for example) when both assume different contexts. Other records of laboratory or classroom discussions can also be used to investigate teachers’ conceptions and actions.

5. Establishing closer links between research and teaching

Teachers, whether at school or university level are one of the most important ‘actors’ in the process of improving chemistry education. In that process, they can play different roles. They can be consumers of results of research and development projects (providing that the gap between ‘theory’ and ‘practice’ is not too big); they can be producers of new teaching materials and strategies. They can also act as researchers in their own classroom.

The motivation for this research is likely to be the recognition that students (or the teacher) are experiencing difficulties, and that there is room for improvement in the teaching. Having identified some specific learning difficulties, it is necessary to postulate reasons to explain the observed difficulties and then to devise teaching activities which will remedy the problem. These two steps are best based on research data which may be collected (as described above) by collecting audio records in the classroom and transcribing and analysing them. On the basis of the analysis the teacher can start to reconstruct his or her teaching practice based on a firm understanding of the problems experienced by the students. This individual approach means that the teachers address the problems which are personal to themselves. The lessons they learn can be made more widely available by sharing them with colleagues from the same institute or school and by inviting colleagues to discuss the results, and to use the same approach. Well analysed data which leads to useful conclusions can form the basis of a professional publication in an educational journal, thus emphasising the role of teacher as researcher and helping to establish closer links between research and teaching.

In doing this kind of research it is useful to remember that it is only a first step to introducing a change in teaching based on the analysis of a record. It is usually necessary to repeat the cycle which Lijnse[7] has referred to as the *‘developmental* *research'* approach. In this approach, a small-scale curriculum development is linked to in-depth research on social, content and context specific teaching and learning processes. The structure of the research activities involves repeated cycles (a spiral) of activities, in which each cycle includes the following stages

- an evaluation of a current educational situations;
- formulation of research questions in conjunction with reflection on chemistry and chemistry education;
- development and implementation of new teaching strategies and materials;
- investigation of teaching and learning processes during classroom and laboratory sessions (important research instruments are audio/video-tapes for producing records of laboratory /classroom discussions);
- repetition of the cycle.

The cyclical approach is crucial to the individual teacher and can be used by professional research teams. It allows practitioners to link small-scale curriculum development to more in-depth research. Furthermore, if developmental research is carried out and published by practitioners at secondary level as well as at university level, the results can also help to bridge the gap between chemical education at this interface.

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Chemical Education Research: Where from Here?

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Introduction

I should like to begin by recording a number of depressing facts about Chemical Education over the past forty years. When we have cleared that ground the remainder of the paper will be a positive attempt to address some of the unpleasant observations.

- Students are not flocking into chemistry thirsting for knowledge. Almost everywhere students are opting out of chemistry.
- Since the early 1960's we have been inundated with chemistry schemes and courses full of promise, most of which have come and gone, leaving the promise unfulfilled. Examples are: Chem. Study and ChemBond from U.S.A., Nuffield and Salters from England, Science for the 70's and Alternative Chemistry from Scotland, ReCoDiC from France and many others.
- As researchers we have solved almost none of the reported problems in chemistry teaching: the mole, bonding misconceptions, misunderstandings about the nature of matter, equilibrium, free energy and many more.
- Research literature has been dominated by work on misconceptions, but little has as yet appeared about how to reverse these or to avoid them altogether.
- Most countries are struggling to find well qualified and competent teachers.
- We are deluding ourselves if we imagine that the general public are taking an increasing interest in chemistry. For normal daily living most people believe that they need no knowledge of chemistry, and maybe they are right.
- A sure way to kill conversation at a party is to confess that you are a chemist. You might as well be a tax-collector or a priest! Your fellow guests say things like:

"I was never any good at chemistry"
"I never understood atoms and molecules"
"I enjoyed splashing about in the laboratory, but I did not understand what I was doing".

All of this is a very pessimistic, but realistic view of the current situation in Chemical Education. Things have gone badly wrong over the past 40 years at some fundamental level.

This period has been characterised by much development activity in the field of Chemical Education. Much has been done to design demonstrations, microchemistry, computer assisted learning, CD ROMs, units on societal issues and a