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Inquiry and its assessment: lessons learnt from research and practice

La indagació i la seva avaluació: lliçons apreses des de la investigació i la pràctica

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abstract

Inquiry-based science education has been the focus of many national and international programs in Europe in recent years as a way to develop students' knowledge and skills, extend their science learning and develop employability skills. This paper explores the interrelation between learning aims, teaching strategies and assessment practices within the context of an inquiry framework. While learning aims and teaching strategies are often considered in tandem, the strategies for on-going evaluation of the student learning are often only considered at the end of the process.

keywords

Assessment, inquiry-based science education, employability skills.

resum

L'educació científica basada en la indagació ha estat el centre d'atenció de molts programes nacionals i internacionals a Europa en els últims anys com a forma de desenvolupar els coneixements i les habilitats dels estudiants, ampliar-ne els coneixements científics i desenvolupar habilitats d'ocupabilitat. Aquest article explora la interrelació entre objectius d'aprenentatge, estratègies d'ensenyament i pràctiques d'avaluació en el context d'un marc d'indagació. Tot i que els objectius d'aprenentatge i les estratègies d'ensenyament sovint es consideren un tàndem, les estratègies per a l'avaluació continuada de l'aprenentatge de l'estudiant només es consideren al final del procés.

paraules clau

Avaluació, educació científica basada en la indagació, habilitats d'ocupabilitat.

Introduction

From the variety of papers presented at the ECRICE 2016 conference, there are many different aspects of research that we (collectively) are conducting on chemistry education. Many themes are evident, *e.g.* addressing many aspects of laboratory teaching, active learning, learning objects, blended learning, teacher education, to highlight just a few. In most justifications for this research, we note that we need to encourage students to study chemistry (at all educational levels) for them to derive satisfaction and understanding from their endeavours. But we can ask why do we want students to take up chemistry, particularly why do we encourage them to study chemistry at second level, even if they do not wish to pursue it in further studies? Many reasons may be given, but I will focus on relevance in future careers through development of employability skills.

So what exactly are *employability skills*? The recommendations from a coalition group of business leaders, education leaders and policymakers, known as P21, are of note as they build «collaborative partnerships among education, business, community and government leaders so that all learners acquire the knowledge and skills they need to thrive in a world where change is constant and learning never stops» (*http://www.p21.org/about-us/our-mission*). Their *Framework for 21st century learning* defines the skills and knowledge required by students to succeed in work, life and citizenship, as well as the support systems to these outcomes. In addition to the key subject areas, including *e.g.* language, mathematics and science, the *Framework* identified three main skills areas:

— Learning and innovation skills (of creativity and innovation, critical thinking and problem solving, communication and collaboration).

— Information, media and technology skills (such as information literacy, media literacy and ICT literacy).

— Life and career skills (flexibility and adaptability, initiative and self-direction, social and cross-cultural skills, productivity and accountability, and leadership and responsibility) (*http://www.p21.org/about-us/p21-framework*).

These skills are supported by the creation of suitable learning environments, professional development of teachers, suitable curriculum and instruction, as well as appropriate standards and assessment. Focusing on the learning and innovation skills, these are also evident and emphasised by other organisations at third level through for example the RSC undergraduate skills and achievements portfolio (*http://www.rsc.org/cpd/undergraduates*) or graduate attributes (*e.g. https://www.adelaide.edu.au/learning/strategy/gradattributes/* or *http://www.dcu.ie/generation21*). So if we accept that development of employability skills is important and that it is an outcome for our students from studying chemistry, then our challenge as chemistry educators and researchers is to identify and develop these employability skills within the context of teaching chemistry. A review of the literature will quickly point to inquiry teaching methodologies as suitable for providing opportunities for students to develop these skills, in addition to accumulation and development of content knowledge and understanding. Indeed, international reports, such as Rocard (2007) and Osborne & Dillon (2008), have pushed much of the focus in teacher education to inquiry and active learning pedagogies (many supported through EU funding schemes), and many countries have now adopted at least some element of inquiry in their national science curricula.

How can we recognise and assess learning through inquiry? This paper will focus on inquiry and its assessment, drawing on examples of my own practice and experiences at third level and second level, highlighting three initiatives of how inquiry activities have been incorporated into our chemistry programmes and also how they have been assessed. Specifically, these are through changes in laboratory practice and a multidisciplinary module at third level and through EU inquiry projects (ESTABLISH and SAILS) at second level.

Inquiry: how do we recognise it?

Many of the EU funded projects (such as PARSEL, PATHWAY or ESTABLISH) have been very successful in raising the discussions about inquiry, increasing and sharing our understanding of inquiry and generating inquiry activities that could be used in the classroom. Rather than analysing the interpretation of *inquiry*, it is much more useful to look at how Harlen & Allende (2006) have detailed how you would recognise a classroom in which inquiry was taking place (table 1).

If students are involved in these practices most of the time, then they are involved in inquiry learning. Also then teachers are creating learning situations that support inquiry. Obviously, in any one class, all of these practices/events cannot take place; however, there is a reasonable expectation that over time students are

Table 1. Inquiry leaning in the classroom (Harlen & Allende, 2006)

Inquiry learning is taking place if students are…
— *Engaged in observation* and, where possible, handling and manipulating real objects.
— *Pursuing questions* which they have identified as their own even if introduced by the teacher.
— Taking part in *planning investigations* with appropriate controls to answer specific questions.
— Using and developing *skills of gathering data* directly by observation or measurement and by using secondary sources.
— Using and developing *skills of organising and interpreting data, reasoning, proposing explanations, making predictions* based on what they think or find out.
— *Working collaboratively with others*, communicating their own ideas and considering others' ideas.
— *Expressing themselves* using appropriate scientific terms and representations in writing and talk.
— *Engaging in lively public discussions* in defence of their work and explanations.
— Applying their learning in *real-life contexts*.
— *Reflecting self-critically* about the processes and outcomes of their inquiries.

given opportunities to engage in these activities.

Inquiry: how and what to assess?

If students are involved in inquiry activities and developing inquiry skills, then how can these be assessed? The term *assessment* can have many meanings; however, within the SAILS project (*http://www.sails-project.eu*), it was used in its broadest sense as any activity that gives information on student learning and which informs the next steps in learning. Assessment has many purposes, such as informing the teacher what they should do next in guiding the students in the learning process; reporting on how well the student has done or reporting on student performance; informing the students, allowing them to report on and guide their learning. Assessment involves feedback to the learner, giving guidance for the learning, provided the feedback is timely and informative. Interestingly, feedback given in the form of a grade may be less informative than feedback with appropriate comments (Black & Wiliam, 1998). Grades only or grades with comments have been shown to be less effective in guiding learning than comments only feedback. Provision of appropriate comments can guide the learner as to appropriate action to deepen their understanding/knowledge. Students who score all correct answers in an assignment may have a limit set to their learning by being given a grade of 100 % or can be assigned a more challenging problem to extend/deepen their learning.

Students can be subjected to graded assessments from an early age; *e.g.* in primary school, students are often given say 10 *sums/spellings* to complete. Assume two students score the same grade of 8/10; however, one

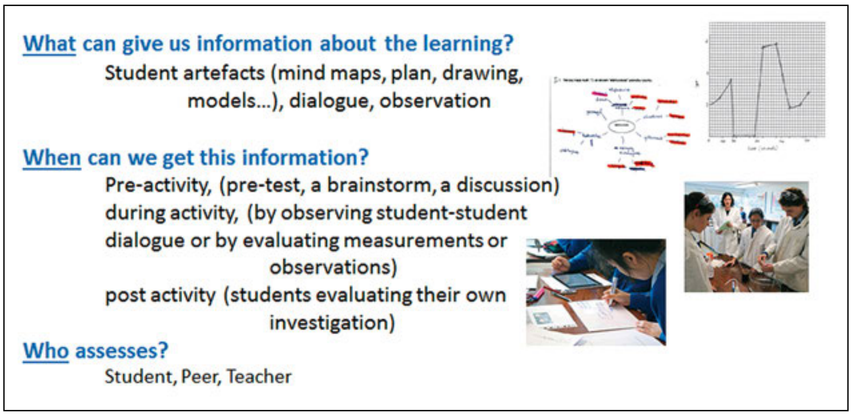


Figure 1. Assessment opportunities as identified through SAILS project (http://www.sails-project.eu).

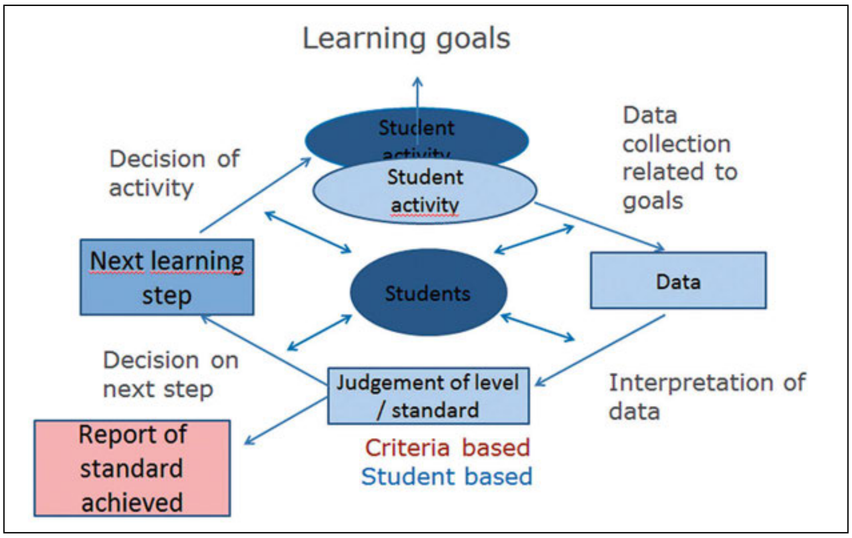


Figure 2. Assessment to inform learning (adapted from Harlen, 2013).

student gets the two most difficult questions correct making *slips* in the easier questions, which the other makes errors in the more difficult questions. The next steps in learning are quite different for each of these students; however, the grades are the same. Hence different assessment feedback is required to each of these students to guide their next steps of learning.

Within the SAILS project, we investigated where evidence of student learning could be obtained within the inquiry activities, specifically what could be obtained, when could it be obtained and who could provide the assessment. Fig. 1 summarises the key ideas. As teachers look at student generated mind maps, investigative plans, process drawings or listen to student dialogue, they are making judgement calls on student performance, therefore they are assessing. Also all assessment need not be teacher focused (self and peer-assessment is also very informative).

The assessment cycle shown in fig. 2 (adapted from Harlen, 2013) is an useful one to consider in terms of informing learning. As a teacher, you have developed or decided on some student activities in order to achieve the learning goals. You collect some data related to these goals (the teacher must then interpret the data and make some judgement based on that data). The judgement then leads to the next steps in learning, which results in the next student activity. This cycle can be repeated several times and even many times within the same class. Occasionally, the judgement must be made to exit the cycle where a student is measured by some criteria which ultimately lead to a report on the standard achieved.

This type of assessment monitors the learning process and the development of student' understanding; it provides feedback to the teachers for deciding on next steps for them in planning the teaching process, and it provides feedback to the students on the learning objectives, where their current work is at in relation to the learning objectives and also, most importantly, what their next steps should be towards attaining their learning objectives.

The assessments carried out may be informal and spontaneous (so called *on-the-fly*), or may be planned to occur at particular points pre-, during or after the activity. Bell & Cowie (2001) state that this type of assessment can be both formal (maybe using specific tools) or informal, and can be planned or spontaneous. In the next section, two initiatives of how inquiry activities have been incorporated into our third level chemistry programmes are presented.

Third level initiatives in inquiry

Example 1. Chemistry laboratory

The first year cohort of science students in our universities are now generally a very diverse group with regards to, for example, interests, backgrounds, age, culture, as well as their previous knowledge of chemistry and their motivation. Previous studies have examined factors that can be used to predict student success (*e.g.* Potgieter, Ackermann & Fletcher, 2010); however, if we know the profile of the «student-on-entry» to first year university including motivation, approaches to learning, expectations and perceptions of university, then we, as academics, may be able to build on their strengths and address any weaknesses. To this end a profile of the science «student-on-entry» to university has been determined (Lovatt & Finlayson, 2013). In summary, the findings showed that the majority of the students were intrinsically motivated and interested in their chosen subject area; they wished to develop knowledge and skills; they wanted to take interesting and stimulating courses, to become more independent and to make a difference in the world. The students have a preference for deep and strategic approaches to learning (where «use of evidence, monitoring effectiveness, achieving, relating ideas and seeking meanings» are rated highly). However, they are less confident in terms of their abilities «to initiate and organise their own study, to meet deadlines and to work without direction from a teacher». This emphasises that the students are willing to engage in autonomous learning but need assistance in becoming autonomous learners.

The first year chemistry laboratory is an ideal learning space to address some of these issues through an inquiry approach. When planning this laboratory, having identified the particular skills required in first year, we then set out to create a positive learning environment and appropriate assessment to help students increase their chemical knowledge and develop the links between theory and practice. We felt it was important: *a*) to assign tasks (post pre-lab and post-lab) with specific weekly deadlines which would lay the pattern for lab preparation (and self-organisation), and *b*) to provide at least some lab tasks where students could work without direction, *i.e.* open tasks where they had to decide on next steps or on how to tackle the problems. Additionally, rather than writing up weekly laboratory reports, the students had to focus on maintaining a laboratory notebook (giving clear, informative and accurate recording of data, analysis of data and implications of the data in relation to the aims of the experiment).

In terms of the assessment, it was closely aligned to the learning intentions of the session (examples of particular activity aims are shown in table 2 and matched to the appropriate assessment).

Table 2. First year laboratory assessment strategy matched to activity aims

Activity aim	*Assessment focus*
To develop manipulative skills for titration.	On the experimental answer obtained.
To design an experiment to generate data to show a particular principle.	Plan drawn up and the analysis of the data generated.
To develop an answer to the open environmental analytical problem.	On the use of planning and interpretation of the data.

In this way, the assessment strategy was closely aligned to the laboratory aims. More particularly, we altered the assessment to suit the activity each week, *e.g.* if the key learning aim in a particular activity as based on the development of a manipulative skill, the assessment focused on determining their competence in that skill; if the activity is focused on an oral presentation, then the assessment is on how well the student has made the presentation; if the activity say builds on a particular concept, the assessment focused on the determining the understanding of that concept.

Immediate and informative feedback was given to students each week on recording in their lab notebooks and through oral discussion between lab tutor and student. All of this was possible to do with the support of the lab tutors in a ratio of 1:10 in the lab where the lab tutor was more actively engaged in the assessment and teaching within the lab.

Example 2. Group work in problem-solving multidisciplinary module

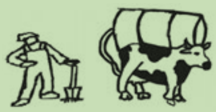
As stated above, the development of employability skills can be achieved through inquiry learning. Through a «multidisciplinary module», we do this with first year students (highlighting group work, using relevant «real life» science problems and providing scope for students to expand their knowledge beyond the bounds of the curriculum). Each week, students in groups of four tackle a particular problem in science, loosely based on material relevant to their first year courses. Table 3 highlights two of the problems assigned within the module.

The «Home brewing» problem gives an outline of the brewing process and details of the containers used in each process (size and materials), temperatures required, volumes of liquid, etc. Students must model the process and determine the cost of generating a certain volume of beer using the containers specified. As an extension, they can optimise the model and determine the minimum price that they can charge the beer to make a reasonable profit. This problem is assessed as a «closed» problem initially (with «correct answers» possible for the information given); however, there is also scope for students to extend their knowledge through the optimisation process, this giving the groups more autonomy for their solution.

The «Cow problem» focuses on developing and justifying assumptions using so called *back of the envelope* type calculations. The question simply asks if a cow can produce sufficient methane gas to supply the average energy needs of a normal family home. This is all the information given. Students need to figure out where the methane is coming from, the amount produced, how it can be collected in a backpack, the amount of power required by the family home, etc. The emphasis of the problem is on how the results can be justified in relation to the assumptions made. Students must estimate, predict, make assumptions and draw conclusions. A key aspect of the problem was to develop collaborative problem solving. From analysis of student reports and focus group interviews (Kelly, McLoughlin & Finlayson, 2016), the students are really good at exploring and understanding the problem, and formulating answers. However, the groups are not so good at monitoring how they are going about solving the problem and how they are reflecting on their answers. Their ability to perform calculations is low and this low level of mathematical ability has been mentioned in other presentations at this conference. This is particularly worrying when you see student comments such as:

> With the calculations, I wouldn't be very comfortable with them, because I know that I wouldn't be able to get a good answer and I would [sort of] be afraid that if I did it [and] I'd do it wrong. I just prefer to let someone else do it and do it properly.

Table 3. Two group problems in the multidisciplinary module

Skill/key objective	*Title of problem*	*Brief overview of instruction*
Modelling, teamwork	«Home brewing» Starch → sugars → alcohol + CO_2	Given an outline of the brewing process and specific details on vessels used, conduct energy and thermodynamic calculations to decide on an appropriate selling price per litre of beer. Prepare a business plan of the model used.
Collaborative problem-solving processes	«Cow problem» 	Determine whether a cow herd could be used to produce all the power required in the average family home.

This student is focused on project outcome, not on learning. Likewise this view is echoed by another group where «everyone just picked the part that they were good at and they did it. Whoever is good at that part does that part and so on, so we didn't really help each other out; we stuck to our own stuff». These two groups interestingly received good marks for their outputs, completing the project well. In contrast, another group stated that «no one in my group was actually good at calculations and so we always try to do those bits together» (here a good learning experience where the focus is on collaborative effort and group learning). If there was no competence in the group, then students had to work together to solve the problem; however, if expertise existed within the group, then students use it.

This is an area that requires more research in terms of inquiry work. While individual contributions to the group can be monitored and assessed, is the overall assessment focused on the group's output or on the individual learning that has occurred? The balance between these need to be optimised in favour of student learning.

Second level initiatives

At second level, experience of two particular inquiry activities developed through the ESTABLISH and SAILS projects are discussed to highlight assessment practices.

Inquiry activity with super absorbing polymers (SAPs)

Within the ESTABLISH project, there was a series of inquiry activities around the theme of holes: macroscopic holes that allowed materials to pass through (such as in separations and filtering), to invisible holes (*e.g.* in polymer films), to «designed» holes (*e.g.* in superabsorbing polymers, cyclodextrins, making polymer films) (*http://www.establish-fp7.eu/resources/units/exploring-holes.html*).

Many of these inquiry activities start with students designing experiments to determine answers to questions that they have asked themselves or which have been given by a teacher. One such example is with superabsorbing polymers (SAPs), where, after a general discussion and observation of SAPs in use (*e.g.* in nappies or flower gels), the question arises as to how much water SAP can absorb. When students and pre-service teachers are presented with this question, they initially design an experiment such as (fig. 3): *a*) a titration type experiment where water is added to a known mass of SAP until no more is absorbed, hoping for a clear «end point»; *b*) a filtration type experiment where water is added to a funnel containing known mass of SAP and the volume measured until «breakthrough» indicating that the SAP is saturated, or *c*) clarity of solution (where the «solution» of SAP and water is «cloudy» but, when saturated, the pattern of light reflected would change).

After initial designing of the experiment, they are asked to implement their method, but they quickly realise that there are additional factors that they have not considered, such as time of contact and criteria for saturation. So, criteria need to be set (these can be individually set or set by the group to allow for comparison, and then, depending on the criteria set, a range of answers can be determined), all of which are correct according to the criteria set.

So in terms of an inquiry activity of this type, the students need to be given play time/exploration time so that they can determine what they should measure/monitor/control; it also gives them a «feel» for the data to be measured, including *e.g.* the size of beakers required, quantity of material to use, etc. Following this exploration time, they then need some time to finalise their design of the experiment, which they can then implement with a certain degree of confidence that they can obtain reasonable results.

It is important, in my opinion, when the students complete their experiment, that there is a value placed on their efforts, *i.e.* that

Figure 3. Approaches taken to determine the amount of water absorbed by SAP.

the question initially set was a valid question to ask and hence, the result is meaningful and relevant. If they have designed an experiment to achieve good results, then we should appreciate their efforts by recognising also the value of their results.

This particular activity can be easily extended into further investigations (*e.g.* examining the effect of solutes in the water —monovalent vs. divalent cations and anions, sugars, etc.— mimicking urine). This type of activity can be used with lower second level students focused on planning an investigation, while upper second level students can explore the structure of the polymer and the effect of different ions on the absorption.

Inquiry activity: rate of reaction

A core concept in chemistry teaching is the determination of the rate of reaction and the factors that can affect the rate. Many introductory texts use the reaction of HCl with marble chips to investigate these factors. However, both of these reagents may be unknown to some students. Hence the use of another reaction in an everyday context as suggested in the SAILS project (*http://www.SAILS-project.eu*) which examines the rate of reaction of effervescent vitamin C tablets with water. The focus of particular activities based on this reaction is shown in table 4.

Teachers from five different countries have used these materials with their class groups, adapting them as appropriate, noting the skills assessed, how they assessed, the criteria they used to make judgements and the next steps they took in driving the learning forward. These are available on the SAILS website as case studies. Here I will focus on two aspects: *a*) planning the experiment, and *b*) the assessment strategy.

When asked to design/plan an experiment to determine the rate of the reaction and the factors that affect the rate, students (following «exploration time» as discussed above) generally examined the rate at which CO_2 is released by *e.g.* measuring the change in circumference of a balloon, using a pressure sensor or simply measuring the amount of «froth» generated when the tablet is added to water that contains a drop of detergent (fig. 4). Relative rates were obtained when variables are changed such as amount of tablet, particle size and water temperature. This activity gives ample opportunity for critique of the different methods used, discussion of the varied results obtained, and the validity and reproducibility of the results. An interesting extension to this activity is to determine what reactions are happening when the vitamin C tablet (which contains citric acid, ascorbic acid and sodium bicarbonate) is added to the water, including formation of the CO_2, the relative concentrations of citric and ascorbic acids, and the reactivity of the two acids with the carbonate.

Within this activity, what opportunities for assessment are presented? Students should be able to observe that bubbles were released and then identify what is causing the bubbles and what is

Table 4. Main focus of reaction rate activities

Focus of activities	*Activity A: designing an investigation*	*Activity B: determining reaction rate*	*Activity C: altering reaction rates*
Concept focus	Production and properties of CO_2 Acid-carbonate reaction Handling of gases	Acid-carbonate reaction Distinguish between reacting and dissolving	Effect of variables
Inquiry skill focus	Planning investigations Working collaboratively	Planning investigations	Forming coherent arguments Working collaboratively
Scientific reasoning and literacy	Scientific reasoning (argumentation) Scientific literacy (critiquing experimental design)	Scientific reasoning (proportional reasoning	Scientific literacy (presenting scientific conclusions)
Assessment methods	Classroom dialogue Worksheets Student devised materials	Student devised materials (experimental plan)	Student devised materials Presentations (poster)

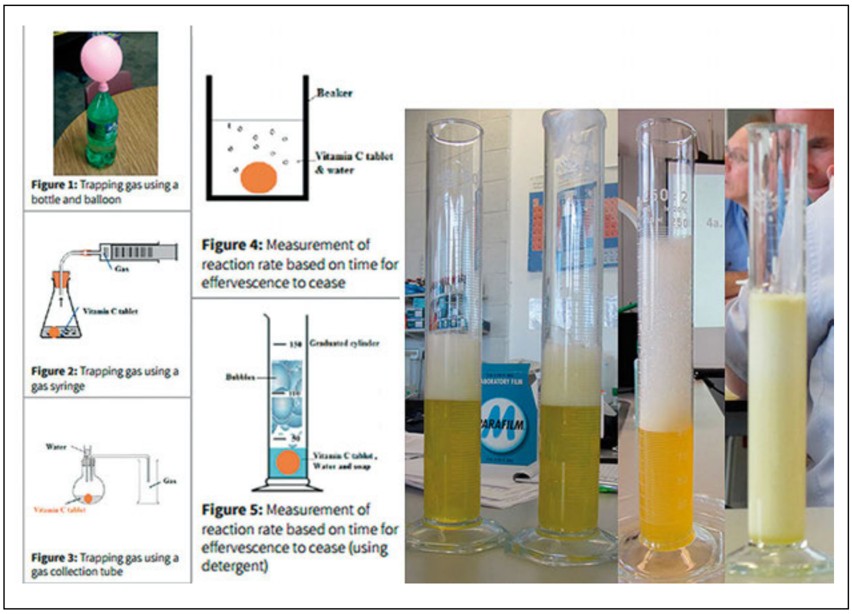
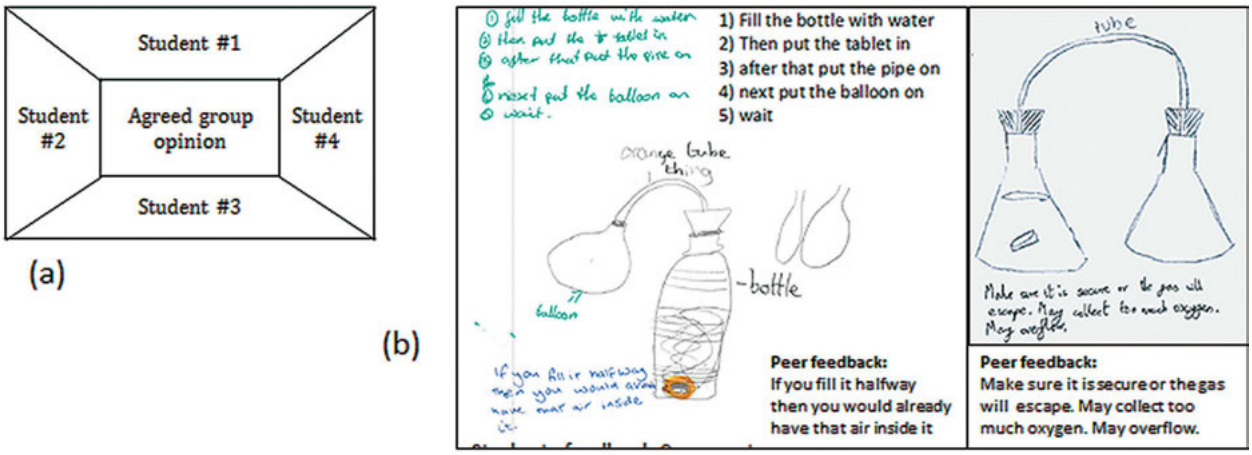
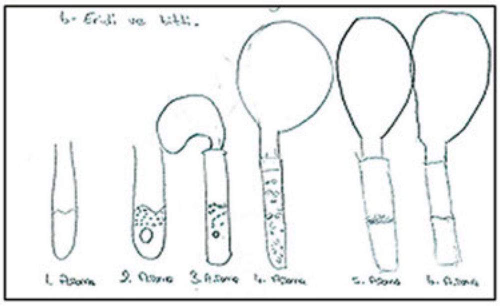


Figure 4. Student methods for trapping gas produced after addition of effervescent vitamin C tablet to water.





(c)

(d)

Levels	Beginner	Intermediate	Advanced
Planning and implementation of experiment	The group needs the teacher's guidance to complete the task, their questions are not pertinent to the task, they record their results inconsistently. They do not know what the different pieces of equipment are used for.	The groups needs occasional help. Their questions are not always pertinent. They record their results consistently but with omissions. They lack confidence in using equipment.	The group works without help. Their questions are pertinent to the problem. They record their results accurately. They can choose the appropriate equipment.

Figure 5. Assessment strategies used: a) *capturing individual input;* b) *plan followed by peer review;* c) *drawn plan;* d) *extract from assessment rubric.*

inside the bubbles. They could design a way to trap the gas and identify it. Following this, they could share/discuss and compare their experimental design and results with their peers, and then justify their conclusions based on the evidence they had accumulated. Teachers have used the following aspects in assessment:

— A focus on collaboratively working to brainstorm ideas on how to identify the gas: using the placemat strategy, individual student input could be captured before finding out the group response (fig. 5*a*).

— Written plan, then maybe followed by peer review: an initial experimental set up is peer reviewed before implementation; both the initial plan and the peer review can be assessed (fig. 5*b*).

— Student drawings can be informative on their experimental plans (fig. 5*c*).

— Generation of an assessment rubric to monitor progression in particular skills (fig. 5*d*).

Finally, dialogue can be help in diagnoses of misconceptions. Two extracts from different teachers given below:

Teacher 1: Moreover, I realised my student's misconception about gases during the discussion, whereby for instance they said that the bubbles would be acid. When I realised this problem, I asked extra questions to extend their reasoning for this observation:

Me: What are the characteristics of the bubbles?
Students: It is an acid.
Me: What is your evidence to support your claim?
Students: When we drink fizzy drinks, we observe bubbles due to acid. In the similar way, we can say that source of bubbles would be acid.

Teacher 2: One group thought the gas produced was hydrogen. The group deciding on hydrogen reasoned that the bubbles rose to the surface, which suggests a gas of low density. The packaging of the tablets was on the teacher's desk, accessible to the students. Since they saw the word *hydrogen* in sodium hydrogen carbonate on the packaging, this seemed to confirm their hypothesis and they chose this as their answer.

Final comments

We can encourage students to take up chemistry as in studying chemistry, they can develop skills and competencies that are valued within the workplace, so called *employability skills*. However, we need to incorporate the development of these skills within our teaching and learning of chemistry. One of the ways to achieve that is to incorporate inquiry pedagogies within the chemistry lessons.

Many good inquiry activities relating to chemistry have been developed, *e.g.* through EU funded projects. However, any activity can be implemented in both an inquiry manner and in a non-inquiry manner. Therefore, we should be clear of our learning goals and implement activities and assessment accordingly. The assessment strategy should align with these learning goals. Being aware of the many opportunities for assessment within any activity can provide us with a very rich information set on which to make decisions on the next steps that we need to take to guide the student learning. There are lots of opportunities for assessment within any activity that we are doing with students; we need to recognise these opportunities and use them to gather appropriate evidence for us to be innovative in our approach to assessment, based on the learning goals we have set out.

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