Foundations of Chemistry
https://doi.org/10.1007/s10698-022-09419-w

Knowledge building in chemistry education

Margaret A. L. Blackie[1]

Accepted: 22 December 2021

Abstract

Teaching chemistry remains a profoundly challenging activity. This paper arises from reflection on the challenges of creating meaningful assessments. Herein a simple framework to assist in making more visible the different kinds of knowledge required for mastery of chemistry is described. Building from a realist foundation the purpose of this paper is to lay the intellectual scaffolding for the framework. By situating the framework theoretically, it is intended to highlight the value of engaging with philosophy for the project of knowledge building in chemistry. Use of this framework has laid bare some significant limitations to the ways in which organic chemistry has been assessed. Making the visible to students aids in their engagement with knowledge and for a small minority has developed their understanding of science more generally. The framework provides a simple, easily usable tool for the evaluation of chemistry assessments.

Keywords Realism · Teaching and learning · Assessment · Organic chemistry · Knowledge building

Introduction

This paper is a conceptual paper and arises out of two interrelated observations around summative assessments in undergraduate organic chemistry courses. The first observation is that we may not be assessing what we presume we are assessing in our tests and exams (Rootman-le Grange and Blackie 2018). The second observation is that students may use marked assessments as opportunities to learn far less than we assume (McArthur et al. 2021). The question which is explored in this paper then is this: Can we develop a simple stratification of the structure of knowledge in chemistry that could assist both academic staff and students to make better use of assessments?

It is important to recognise that any educational endeavour is never socially neutral. It is therefore necessary to state my own position with respect to various elements: the purpose of higher education; the nature of scientific knowledge; and the particular context in which the teaching is taking place. It is necessary to make this explicit because

---

✉ Margaret A. L. Blackie
mblackie@sun.ac.za

[1] Department of Chemistry and Polymer Science, Stellenbosch University, Stellenbosch, South Africa

the reliability and reproducibility of scientific data across varied contexts can result a blindness to the complexity and particularity to science education. Science education will always be socially bound even as students are given access to a kind of knowledge which is beyond the particularity of any one social environment.

It has been noted that, in general, chemists are not particularly interested in philosophy (Bernal and Daza 2010). This can lead to serious misconceptions when engaging in research on chemistry education (Scerri 2003). This paper is founded on a realist approach. In the scientific realism described by Harré (2013) there is a distinct shift which brings the human being more into the frame. According to Harré, scientific realism has four features:

1. Human perceptual organs are used to give access to regions of the world that exist independently of human observers;
2. People have learnt to distinguish reliable perceptions from illusions;
3. The methods of science have enabled people to gain reliable information about the world;
4. Humans have been able to develop concepts. These concepts transcend our perceptual power.

Harre's notion of scientific realism provides a sufficient foundation of the nature of chemical knowledge in that it provides a clear distinction between the physical world we are interrogating and the conceptual world. It also indicates that concepts are something beyond simple human perception and therefore potentially have a power of their own. Concepts are thus a human creation that emerge from the employment of the scientific method.

The desired goal of the paper is to provide a framework which is clearly founded on education theory, but which can be used and applied by both academics and students who do not have knowledge of the theory. The reason for this is to provide a robust tool with a relatively low activation energy to implementation. The paper draws on the literature, on prior research carried out in collaboration with others, and my own reflection on both my teaching practice and the value of a chemistry degree.

The paper draws on a number of elements from different intellectual environments. It may thus be helpful to outline the various components before diving into the detail. The paper begins with a description of the teaching context. This is followed by a declaration of my own educational philosophy which necessarily underpins what I perceive to be the goal of an undergraduate chemistry degree. This paper built on a key insight that making the structure of knowledge or the organizing principles thereof visible to students is important. Various attempts to evaluate assessments particularly using Bloom's taxonomy have been undertaken in chemistry, illustrative examples of these are included herein. Then I show how the epistemic framework derived from Legitimation Code Theory connects and can be used powerfully and simply to both enhance evaluation of assessments and give students access to the nature of knowledge in chemistry. The way in which this is enacted in my own teaching context is then described. This is then linked to current developments in chemistry education. The broader implications of this work—particularly the manner in which this system can be adapted for application in other knowledge fields and in the critique of the curriculum—are discussed. In the end the epistemic framework is a simple tool which can be used effectively even when the user is unaware of the theoretical underpinning described in this paper. However, the purpose of this paper is to robustly situate the framework in the context of established theory.

Teaching context

I teach organic chemistry at both undergraduate and Honours level at a research intensive university in South Africa. (In South Africa the Honours degree is a single year after a three-year undergraduate degree and is required for entry into any Master's level course). I have taught on various introductory chemistry courses for over a decade. I also teach specialist organic chemistry courses to both science students and chemical engineering students. Whilst our students do come from a diversity of backgrounds representative of the cultural diversity of South Africa, students from previously disadvantaged backgrounds remain underrepresented.

Students entering Bachelor of Science degrees in chemistry are required to have done physical science and mathematics at high school. Physical science combines both physics and chemistry. The nature of the high school science is that it is highly focused on exam training, and much of the content of the school syllabus can be learned by rote or by drilled practice. There is also a dearth of sufficiently trained high school science teachers in the system (Ogunniyi and Rollnick 2015). The net result can be that students who have achieved high marks at high school may have surprisingly little conceptual depth of knowledge in physical science (Potgieter et al. 2008; Potgieter and Davidowitz 2011). Whilst these studies are now somewhat dated, the system has not changed significantly in this respect over this time period.

The purpose of undergraduate education

The majority of students who major in chemistry at South African higher education institutions will not go on to pursue further study in chemistry. It is thus highly likely that they will never use the knowledge they have so diligently attempted to acquire in any meaningful way (Blackie 2019). When this fact is considered, the temptation can be to attempt to focus on generic skills. However Ashwin (2020) argues that skill building is never generic, it is always situational. The skill is always developed in a specific context, and the value of the skill must be evident within the knowledge building project of the discipline. Once the skill is mastered within the situation, it may indeed have some transferability, but the skill will likely need some adaptation (Ashwin 2020). For example, Wang and coworkers (2021) argue that a particular approach to a practical on iron corrosion develops 'critical thinking'. The evidence does seem to support their claim. Nonetheless, the kind of critical thinking employed to interrogate iron corrosion may provide a foundation for critical thinking in evolutionary biology but some adaptation will surely be required to meaningfully apply critical thinking in a new knowledge field.

It is my position that the purpose of an undergraduate degree in chemistry must equally serve two purposes. Firstly, it must provide a solid conceptual foundation for those who will continue on in the field of chemistry whether in postgraduate study or work. Secondly, it must provide a coherent introduction into the development of knowledge in the field of chemistry. On this second point, I believe we should be aiming for graduates who know the extent and limitations of their knowledge. If they have some idea of the way in which to judge their own ability within a given field, that is a powerful skill which is relevant to the learning of anything (Blackie 2019) even if it requires some translation or adaptation to be applied to different kinds of fields of study.

Holding these two purposes together mean that we can conceive of a strong conceptually bound chemistry curriculum in which the students are continually drawn into reflection on their knowledge. This should serve both purposes well. The content of the curriculum will be most strongly driven by the needs of those who will continue in chemistry. It is well established assessment drives learning (Shay 2008) and there is great flexibility around the nature of activities, tasks and assessments. So it is in this dimension that real consideration of making knowledge building explicitly visible is potentially possible. Stowe and coworkers (2021) have made a substantial critique of chemistry assessments. Noting that on some introductory chemistry courses the nature of molecular interaction is not assessed at all.

Teaching chemistry

There is no question that chemistry is a cognitively demanding subject (Zoller and Tsaparlis 1997). The conceptual complexity of chemistry has been written about for decades and this challenge is clearly elaborated upon in Taber's book 'The Nature of the Chemical Concept' (Taber 2019). Learning chemistry requires moving between the symbolic, the macroscopic world and an understanding of what is happening at an atomic level (Johnstone 1982). Occasionally the extraordinary failure of our educative efforts is laid bare. Perhaps the most stark example comes from the study done some decades ago (Gabel et al. 1987). Incoming graduate students were asked what is in the bubbles that form when water boils. To be clear; these are students who have successfully completed an undergraduate degree in chemistry. The correct answer is water molecules in the gas phase. Nearly 20% answered 'air' which is a physical impossibility, but the real concern is the 5% who answered 'a mixture of hydrogen and oxygen'. There are several problems with this answer, but what it reveals is a profound lack of understanding of chemical bonding. Given that an understanding of bonding underpins almost everything that one learns in chemistry this is deeply distressing. It shows that one can actually graduate with a chemistry degree and hold this level of misconception. The introduction of submicro diagrams may have gone a long way to solving this particular problem, but there are doubtless many more examples which could be used.

One of the problems in chemistry assessment appears to be that the seemingly complex questions that are set in tests and exams, may not in fact test the depth of understanding that we presume it does (Zoller 2002). Dávila and Talanquer (2010) carried out an analysis of end of chapter questions in several popular introductory chemistry textbooks using Bloom's taxonomy. They conclude:

> Beyond the inclusion of more questions that ask students to translate or interpret particulate representations of matter, which certainly are needed, we must recognize the serious lack of problems in the higher cognitive categories (output, or synthesis and evaluation levels) that require students to apply what they have learned in new contexts, and to use their knowledge and understanding to make hypothesis, create models, design experiments, generalize ideas, and make critical judgments. These types of questions and problems are practically inexistent in the analyzed textbooks, which likely limits students' opportunities to develop more meaningfully and lasting understandings. (Dávila and Talanquer 2010)

It is likely that these kinds of issues permeate STEM fields more generally. The work of Mazur and coworkers certainly points to very similar issues in physics education. They observed that pre-med students at Harvard could solve complex mathematical problems, but had very little understanding of the real world implications of the solution they had just found (Crouch and Mazur 2001; Fagen et al. 2002). Zoller and Pushkin use the notion of higher-order cognitive skills (HOCS) and lower-order cognitive skills (LOCS) to explain this observation.

> 'In many respects, algorithmic exercises are the classic illustration of lower-order thinking. This does not, however, imply that conceptual exercises illustrate higher-order thinking…. Conceptual thinking is actually more evolved than higher-order or algorithmic thinking, for it requires learners to understand on a broader level what computational exercises address' p156 (Zoller and Pushkin 2007)

These studies suggest two potential issues.

(1) STEM assessments may not be testing what we think they are testing.
(2) That students may be unaware that there is a difference between passing a course and understanding the subject.

In many circumstances when a deficit in the system of STEM teaching becomes clear, the first move is towards a more interactive learning structure. There is much evidence to suggest that the move to active learning is helpful (Arthurs and Kreager 2017; Dou et al. 2018). Indeed, active learning usually provides more avenues for informal feedback. For example, Mazur and co-workers moved to using a model of peer instruction and included the use of in-class clickers to facilitate feedback (Crouch and Mazur 2001; Fagen et al. 2002).

Similarly in chemistry, Partanen (2016) describes the move from a traditional teaching system to much more interactive 'student centered' approach. This is a good example of moving a chemistry course, in this case thermodynamics, to a much more dynamic format. Furthermore, she uses a variation of the revised Bloom's taxonomy to structure assessments and to scaffold learning. In the revised Bloom's system there is a separation between the knowledge dimension and the cognitive dimension. The knowledge dimension is divided into four: factual knowledge; conceptual knowledge; procedural knowledge and metacognitive knowledge. The cognitive dimension is divided into six categories: remember; understand; apply; analyse; evaluate and create (Krathwohl 2002). Partanen goes to some length to code every question on every formal assessment using this system (Partanen 2016). The implication is that the lecturers have a better idea of what they are assessing, but it is unclear whether this system is made visible to the students. Regardless, the combination of the four categories of knowledge and six cognitive categories gives rise to 24 possible combinations. Even if this is made explicit to the students, such a system may just provide more 'noise' to them than real gain. In other words, it is not at all evident that it fulfils the requirement of Hattie and Clarke (2018) that feedback should help the student on where to go next.

Nonetheless, this points to the very important reality discussed by Stowe and co-workers (2021) in a memorably entitled paper 'You are what you assess'. In this paper, having evaluated assessments of three general chemistry courses at three different institutions they comment: 'We observed that students enrolled in two of the three environments could succeed without ever connecting atomic/molecular behavior to how and why phenomena happen' (p2490). On this basis they argue that only one of the courses is legitimately a 'chemistry' course.

A simple model of knowledge stratification

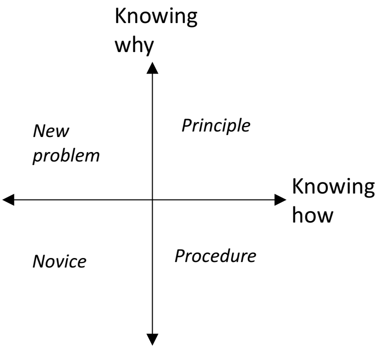
Making stratification of the levels of knowledge operational in chemistry education could have an impact on assessment and on teaching, as lecturers begin to think in these terms. Importantly, could also be useful in terms of providing meaningful feedback to the student. We can make a distinction between knowing how and knowing why. If we plot these on a cartesian plane we can see the possible variation of complexity in chemistry Fig. 1. This is derived from Wolff's (2017) work in engineering education and draws on the epistemic plane from Legitimation Code Theory (Maton 2014). It has been used in the context of engineering education to develop meaningful learning of unit conversions (Tadie et al., 2018).

Movement around the plane shows how knowledge gain may operate. The plane reveals that there are multiple kinds of insight at play in knowledge development in chemistry. The focus here is on the making visible the kinds of insight that are required for mastery of chemistry. Nonetheless, the insight is always personal. In Maton's terms there is always knowledge and a knower (Maton 2014). Hence what is used here is properly a derivation of the epistemic plane (Maton 2014).

The novice will be sitting in the novice quadrant. As they learn *how* to do various operations they move into the procedural quadrant. This is a move into the acquisition of procedural knowledge i.e. the development of insight into learning how to do something. However, understanding *why* that operation is necessary, or the principle underlying the operation, requires strengthening of conceptual understanding and hence a move into the principle quadrant. The specialist or expert is then able to employ the knowledge in new situations which may require unforeseen and novel operations to solve the problem, this requires strong conceptual understanding but procedures may be imported or created in service of the new problem. Ultimately, there may be an intuitive leap (a new insight) made by an individual which precipitates a move back into the novice quadrant which is where new fields emerge. This final move is beyond the reach of the vast majority of undergraduates and the creativity involved in such a leap could not reasonably be examined but we should find ways to award credit when such a leap is evident. It is also true that this final creative leap would likely be beyond the realm of any specific course. The goal of any educational effort in a knowledge code subject is to teach a fairly tightly bound set of principles and associated procedures.

Recall that I am operating from an understanding of undergraduate education as giving students access to a strong conceptual foundation of the subject matter and making visible

Fig. 1 Different kinds of knowing



the process of knowledge building to students such that they are well set for life-long learning. Thus making such a framework visible to students would mean that we can achieve both of these goals without diminishing conceptual depth.

Applying this to organic chemistry

The link to established work in chemistry education in depth after a concise description is given here. The context of application is a second-year organic chemistry course. Students will have already completed an introductory chemistry which includes some organic chemistry. In such a course a fairly standard exam or tutorial question would be Fig. 2:

Give the mechanism of the reaction below.

To answer this question requires several different kinds of knowledge insights.

(1) The student must be able to interpret EtMgBr, THF and H_3O^+
(2) The student must recognise the line drawings understand that they are representations of molecules
(3) The student must know that 'mechanism' is a particular form of drawing which shows how the reaction occurs through the movement of electrons.
(4) Finally, the student must be able to draw the mechanism.

Such a question is fairly standard on organic chemistry exams and would generally be regarded as demonstrating conceptual understanding. If we analyse the breakdown, we can see that what it requires. Firstly, some 'vocabulary'—things which just need to be learnt: for example, THF is an acronym to denote the solvent tetrahydrofuran—(1) Secondly, some low-level conceptual understanding—the interpretation of the line structures—(2) Provided the low-level conceptual understanding is in place the student can learn the mechanism by practice—(4) But what this question fails to achieve is to assess whether the student actually understands the underlying principle behind the drawing of the mechanism. In other words, we presume that the capacity to draw this mechanism implies a sound grasp of point—(3), but this question does not actually test this. For clarity this plotted on the cartesian plane Fig. 3. (The bracketed 3 indicates that it is not actually evident that we have assessed this).

It is important to recognise that the level of the course is significant in terms of what can be taken as 'novice', 'procedure', 'principle' and 'new problem'. What is illustrated here is taken from an intermediate level organic chemistry course. The capacity to interpret a line structure is built on the knowledge that carbon can only have four bonds and that what is not shown can be presumed to be hydrogen. Thus 'novice' is particular to the environment—here intermediate organic chemistry. It should not be taken as an absolute. Rather the full use of plane should be relative to needs of the particular context. This is to say that if one is interrogating an intermediate organic chemistry course the range of knowledge should only span legitimate entry requirements and reasonable expectations on exit from this course. Hence here the interpretation of (1) and (2) is regarded as residing in the novice quadrant because at this is appropriate to an intermediate organic chemistry course.

This process also highlights the challenge in using a framework such as Bloom's revised taxonomy as was done by Partanen (2016). In the revised Bloom's framework the knowledge dimension is given by fours levels: factual knowledge; conceptual knowledge;

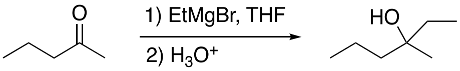


Fig. 2 An example of a typical question in an organic chemistry exam

procedural knowledge and metacognitive knowledge (Krathwohl 2002). Whilst it is absolutely correct that some conceptual knowledge must be in place before procedural knowledge can be implemented (here shown by the positioning of 2 further up the y axis than point 1). It is not at all evident that the underlying principle (3) has indeed been tested, and therefore we have no way of knowing whether the student has actually understood that principle or not Fig. 3.

In practice the idea of plotting every element of every question on a plane would be an onerous task. Such a system would be confusing to students and irritating to academics. Thus, a simpler derivation of this system is given below. The distinction between positions 1 and 2 in Fig. 3 is not of great consequence, and so the infinite variation afforded by the cartesian plane can be collapsed into a typology. This collapse to typology would be actively discouraged by Maton (2014), so once again this is to be understood as a derivation from the epistemic plane rather than an enactment thereof.

Table 1 shows classes of questions which have been developed through use of the cartesian plane. An example of the kind of question which we would ask in organic chemistry is given and that is then given a quadrant on the epistemic plane. Remembering that the plane affords infinite variation rather than a four-part typology, variation in complexity can be represented if that level of detail is required. Finally, in the last column the kind of knowledge is given which can be connected to the philosophy of knowledge but is beyond the scope of this paper.

To date this has been used in organic chemistry assessments in four different undergraduate chemistry courses. It has been found to be applicable across all years for study. This framework is used to categorise all tutorials, tests and exams. This is made visible to the students by clearly categorising the question on the paper. The most challenging part of implementing such a system is ascertaining what kinds of questions are appropriate at what

Table 1 Epistemic framework for feedback and assessment which can be derived from the epistemic plane

Category	Example of the nature of the question	Cartesian plane location	Kind of knowledge
Vocabulary/Symbols	Information which must be learned	Novice	Knowing the fact
Simple procedure	Single step calculation	Procedural	Knowing how
	Give reagent/product/starting material		
	Recognising a reaction type		
Complex procedure	Multistep calculation		
	Known mechanism		
	Multistep synthesis		
	Explanation of known scenario		
Principle	Explanation applied to new scenario fill in the gaps on a new mechanism	Principle	Knowing why
New Problem	Application of knowledge to a new scenario	Problem	Powerful knowledge

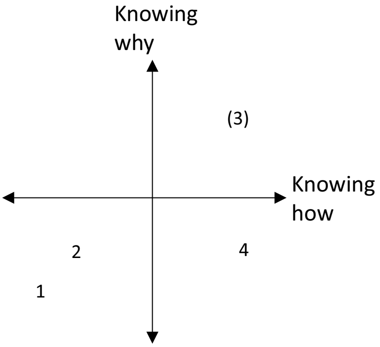


Fig. 3 Plotting of the different knowledge elements required to answer the question. 3 is not actually tested

level. What is given in Table 1 is the current classification in our environment. The connection to the chemistry education literature should help clarify the intent.

Connection to chemistry education literature

It should be clear that applying this system to assessments will make visible what is actually being assessed. We therefore should be able to avoid the pitfalls of assessment pointed out by Stowe and coworkers (Stowe and Cooper 2017; Stowe et al. 2020, 2021).

This stratification links to the notion of higher and lower order conceptual skills (HOCS and LOCS) (Zoller and Tsaparlis 1997; Zoller 2000). Zoller and Tsarparlis (Zoller and Tsaparlis 1997) distinguish between problems which requires a simple application of known theory categorised as LOCS and ‘original’ problems i.e. problems not previously encountered by the student as HOCS. These would equate to the ‘procedure’ and ‘new problem’ in the epistemic assessment framework.

However, this framework has distinct advantages. It makes visible the necessity of learning the ‘vocabulary’. This is an important part of scaffolding on knowledge building in chemistry. It makes this requirement visible. The notion of vocabulary ties in with elements of the ‘patterns of mechanism’ curriculum for organic chemistry described by Flynn and Ogilvie (2015). For the most part this idea of vocabulary is not emphasized at all within papers discussing the chemistry assessments. This may be due to two factors. Firstly, the general allergy to the notion of ‘rote learning’. However, if the vocabulary is learned in this manner, it could potentially reduce the cognitive load in a meaningful way, giving the student a greater ability to deal with more complex problems. Secondly, vocabulary cannot be assessed well using multiple choice testing. The student could get by with simple pattern recognition.

In addition, requiring the student to write a meaningful description of what is going on in the ‘principle’ category proves to be a significant challenge for many students. This ties in with the work of Lieber and Graulich (2022) who investigated the importance of capacity to provide a written rational for the choice of one plausible mechanism over another. They argue for the importance of being able to construct an argument to support the position taken. Watts et al (2020) also point to the importance of written description in developing reasoning skills in their investigation of acid-catalysed amide hydrolysis. It is important to recognise though, that the principle will only be tested if it requires application to a new scenario. Otherwise the student can simply learn an acceptable answer to a known scenario. It is for this reason that the written description of a known scenario is categorised as ‘complex procedure’. In some environments creation of a separate category for such questions may be desirable.

Thus the epistemic assessment framework is consistent with various important streams of investigation currently underway. The important addition here is a coherent system which can be easily operationalised in any chemistry environment. Without doubt the enactment of the framework is likely to be enhanced by drawing on the work of the authors named in this section. Stowe, Flynn and Graulich all focus on organic chemistry. And the work of Stowe and Cooper (2017) on developing critical thinking in organic chemistry may easily be broadened to include other areas of chemistry.

It is important to note though that this framework has a specific purpose – making knowledge building explicit. In its current form it does not directly address concerns of developing the connection between the representation of molecules and understanding of the physical and chemical properties. Issues are more directly addressed in many of the references discussed in this section. Nonetheless, it does provide a robust and simple tool which could be used to good effect in any chemistry course.

Implications

In the past we had no way of distinguishing between two students who both attained a mark of 60%. (In the South African system 50% is a pass and 75% is a distinction). The presumption had been that both had similar levels of understanding. However, the application of the framework makes visible a possible differentiation. Presuming both students have scored equally well on simple and complex procedures, Student A may have scored all the possible core knowledge marks. To improve their mark, Student A’s only option is to deeply engage with the material to try to discover the underlying principle. For Student B who got several principle questions correct, but missed most of vocabulary marks, improvement is a much easier task. Simply learning the vocabulary component takes time, but is more likely to boost their marks. In terms of Hattie and Clarke idea of feedback as being showing the student where to go next (Hattie and Clarke 2018). This system is certainly a substantial improvement on what existed before.

However, Carless and Boud’s (2018) caution of the need to complete the feedback loop and determine whether the feedback is indeed having an impact is vital. In terms of student engagement, it has been clear that several things are required to facilitate constructive use of the feedback. Firstly, the framework must be clearly explained to students at the start of the course and then again after the first formal assessment when they first experience an assessment that has been categorized. Secondly, the data from a longitudinal study of undergraduate chemistry students (McArthur et al. 2021) suggested that students often do not look at marked assignments indicate that we have a systemic problem where students are not making use of even the minimal feedback of marked assignments.

However, interviews with students who have been on courses which have used this framework have shown that most students use the framework pragmatically to manage their time in tests and exams. They begin with vocabulary and simple problems and then return to the more ‘difficult’ problems. However, a significant minority of the students noted that this system has helped them to use their formal assessments to study more effectively. Knowing where they lack depth of understanding they know where to focus their efforts.

Even more significantly, in the South African system where students have been taught to succeed in science via rote learning or drilled practice, a few students noted that this system has changed the way in which they think about science in general. This preliminary finding is corroborated by research showing that that teaching metacognition to undergraduate chemistry students has an impact on their study methods (Muteti et al., 2020).

It is also significant that the use of the epistemic framework is proving helpful and insightful for the academics who are using it. There are two clear points of impact. The first has been in understanding the variation in performance of different kinds of questions. Over the last few years, prior to the development of the framework, under guidance of one of my colleagues we had begun to move from exams which essentially comprised only simple problems and complex problems, to exams where the full suite of levels described in the epistemic framework was used. However, it was found that students consistently did very poorly on one particular kind of question requiring a description of setting up an experiment. At the time there was no way of explaining why this was happening. With the development of this epistemic framework, it became clear that students were asked to solve a new problem, on the basis of exposure to several examples of complex procedures but the teaching had not actually scaffolded the underlying principle. The problem of this particular exam question was thereafter ameliorated by downgrading the first introduction of this question to the level of principle at second year level and only testing the new problem level at third year.

The use of the framework was also very useful when the Covd-19 pandemic necessitated a change from a closed- to an open-book exam. A deliberate and explicit reduction in vocabulary questions with a concurrent increase in principle and new problem questions afforded the development of an exam which was better suited to the conditions. Both of these kinds of questions require understanding of the underlying principle i.e. knowing why. The existence and application of the framework meant that this move was much less contentious and could be done with relative ease.

Finally, I have noticed that in my own teaching I far more deliberately tie individual examples to the underlying principles. This is in line with the motivation behind the development of Legitimation Code Theory as making knowledge structures more visible (Maton 2014). Maton argues for the importance of ‘semantic waving’. This is the move between everyday language and specialist language and/or the move between particular example and the abstracted concept. Maton suggests most people prefer a move in one direction or the other, but for semantic waving both ‘unpacking’ and ‘repacking’ are required (Maton 2009). In a similar fashion, I have begun to think of my teaching practice as ‘epistemic waving’. By this I mean moving explicitly between the principle I am trying to teach and the ways in which the procedure is underpinned by the principle. For example, in teaching a specific reaction mechanism making a deliberate link to the idea of a nucleophile and an electrophile. Explicitly reminding students that one can conceptually view the reaction through that lens. Then returning to the particular nucleophile and particular electrophile involved in the reaction under discussion.

Teaching in a South African context in particular, high school science tends to be taught in a rudimentary fashion. Students coming into university are often unaware of the conceptual foundation of the procedures they have learnt (Potgieter et al. 2008; Potgieter and Davidowitz 2011). This means that some students may in fact be oblivious to the fact that there are underlying principles which need to be understood. The epistemic framework makes this knowledge structure visible.

Discussion

Returning to one of the original aims of this exploration – the development of a tool which is easily accessible to academics and students. Use of the epistemic framework does not require any familiarity with education theory. Several academics in my own environment are now using it effectively without any awareness of the theoretical foundations. Students are also able to use it without being given any detail of the theory.

The epistemic framework can also be modified for use across any scientific education area. It will simply require a bit of trial and error to determine what kinds of questions fall in each category on existing assessments. To apply the framework to other environments, two considerations must be made. Firstly, it is important to ascertain whether all the levels are appropriate to use in the specific context. For example, the idea of a split between simple and complex procedures is useful in chemistry, but may have no value in biology. Secondly, the 'translation device' which is given in the second column is vitally important (Table 2). The translation device shows how the different categories are actually applied within a given environment. What is given in Table 2 is applicable to organic chemistry. Some small variations may be required for application to inorganic chemistry and some larger variations may be required with a move to physical or analytical chemistry. Those using this framework in other STEM fields would have to erase the content of the second column and insert examples applicable to the field.

Thus, each environment would choose which categories apply to their knowledge structure and would agree on what constitutes each category. This discussion may well prove both lively and useful, as it lays bare the ways in which academics functionally stratify knowledge. Once the framework has been agreed upon, it can be disseminated to the students as well (Table 2).

It is probably worth noting, that up until around five years ago all organic chemistry assessments we created fell largely into the simple procedure and complex procedure. Thus in any particular environment, the attempt to adopt this framework may reveal weaknesses in current assessment practices. All forms of assessment should be included for consideration including practical reports and writing assignments.

Table 2 Simplified epistemic framework

Category (choose those categories which are necessary to the environment)	Example of the nature of the question (needs adaptation for each environment)	Kind of knowledge (this column can be retained or omitted)
Vocabulary	Information which must be learned	Knowing the fact
Simple procedure	Single step calculation Gve reagent/product/starting material Recognising a reaction type	Knowing how
Complex procedure	Multistep calculation Known mechanism Multistep synthesis Explanation of known scenario	
Principle	Explanation applied to new scenario fill in the gaps on a new mechanism	Knowing why
New Problem	Application of knowledge to a new scenario	Powerful knowledge

Chemistry remains a tough subject for many undergraduates. The deep interconnection of the material, the seeming disconnection from life experience and the complexity of the knowledge itself all contribute to the challenge. Whilst there are various ways to ameliorate that challenge, one of the ways is to make the knowledge building process more visible to students. Herein I have demonstrated the way in which we have implemented such an approach. This is based on the distinction between knowing the fact, knowing how and knowing why. Making these elements visible mean that we can ensure that we are in fact testing the conceptual complexity required for the mastery of organic chemistry. It is clear that using this system also has an impact on the manner in which most students approach their assessments. For a minority of students, revealing the architecture of the knowledge has clearly impacted the way in which they approach learning, and thus begins to shape their experience of chemistry. The system fosters reflection from both students and academic staff.

This approach has already demonstrably influenced the way in which some students engage with knowledge and with assessments. Likewise it has influenced the way in which organic chemistry is assessed in our department. We are currently rolling it out across the department. An adaptation of the framework is also being used in the mathematics department. The framework has been incorporated into the assessment policy of the Faculty of Science which will be instigated in 2023.

The focus of this paper has been assessment. There are three reasons for this. Firstly, the framework was developed to answer a question on poor student performance on a particular question on an exam. Secondly, this is the way in which it has been operationalized in our department. Thirdly, it is known that assessment will shape learning (Shay 2008). However, it should be evident that this framework is more broadly applicable across the entire curriculum and the potential to influence the way in which material is taught. Furthermore, it can be used to evaluate courses. This work is currently underway.

Conclusion

The design of a simple model to stratify the knowledge required to master the field of chemistry has been achieved. The knowledge structure comprises four levels: knowing the fact, knowing how, knowing why and powerful knowledge. The goal to create a model which is sufficiently simple that the barrier to implementation is relatively low has been achieved. Both academics and students find the framework easy to understand. The impact on the practice of academics has already been observed in terms of evaluation of assessments. In addition, from my own experience, it is likely that use of this framework in assessments will also have an influence on teaching over time. Whilst students understand the framework, it is clear that more could be done to help students to actually use this framework to foster learning.

Declarations

Conflict of interests The author declares that there is no conflict of interest.

References

Arthurs, L.A., Kreager, B.Z.: An integrative review of in-class activities that enable active learning in college science classroom settings. Int. J. Sci. Educ. **39**(15), 2073–2091 (2017)

Ashwin, P.: Transforming University Education: A Manifesto. Bloomsbury Publishing (2020)

Bernal, A., Daza, E.E.: On the epistemological and ontological status of chemical relations. Hyle **16**(2), 80–103 (2010)

Blackie, M.: Educating scientists in South Africa in the 21st century. S. Afr. J. Sci. **115**, 11–12 (2019)

Carless, D., Boud, D.: The development of student feedback literacy: enabling uptake of feedback. Assess. Eval. High. Educ. **43**(8), 1315–1325 (2018)

Crouch, C.H., Mazur, E.: Peer instruction: ten years of experience and results. Am. J. Phys. **69**(9), 970–977 (2001)

Dávila, K., Talanquer, V.: Classifying end-of-chapter questions and problems for selected general chemistry textbooks used in the United States. J. Chem. Educ. **87**(1), 97–101 (2010)

Dou, R., Brewe, E., Potvin, G., Zwolak, J.P., Hazari, Z.: Understanding the development of interest and self-efficacy in active-learning undergraduate physics courses. Int. J. Sci. Educ. **40**(13), 1587–1605 (2018)

Fagen, A.P., Crouch, C.H., Mazur, E.: Peer instruction: results from a range of classrooms. Phys. Teach. **40**(4), 206–209 (2002)

Flynn, A.B., Ogilvie, W.W.: Mechanisms before reactions: a mechanistic approach to the organic chemistry curriculum based on patterns of electron flow. J. Chem. Educ. **92**(5), 803–810 (2015)

Gabel, D.L., Samuel, K., Hunn, D.: Understanding the particulate nature of matter. J. Chem. Educ. **64**(8), 695 (1987)

Harré, R.: Approaches to realism. Studia Philosophica Estonica **5**(2) 23–35 (2013)

Hattie, J., Clarke, S.: Visible Learning: Feedback. Routledge (2018)

Johnstone, A.: Macro-and micro-chemistry. Sch. Sci. Rev. **64**, 377–379 (1982)

Krathwohl, D.R.: A revision of Bloom's taxonomy: an overview. Theory Pract. **41**(4), 212–218 (2002)

Lieber, L. and Graulich, N.: Investigating students' argumentation when judging the plausibility of alternative reaction pathways in organic chemistry Chem. Educ. Res. Pract. (2022) in press

Maton, K.: Cumulative and segmented learning: exploring the role of curriculum structures in knowledge-building. Br. J. Sociol. Educ. **30**(1), 43–57 (2009)

Maton, K.: Knowledge and Knowers: Towards a Realist Sociology of Education. Routledge (2014)

McArthur, J., Blackie, M., Pitterson, N. and Rosewell, K.: Student perspectives on assessment: connections between self and society Assess. Eval. Higher Educ. 1–14 (2021) in press

Muteti, C. Z., Zarraga, C., Jacob, B. I., Mwarumba, T., D. B. Nkhata, D. B., Mwavita, M., Mohanty, S., and Mutambuki, J. M.: I realized what I was doing was not working: the influence of explicit teaching of metacognition on students' study strategies in a general chemistry I course Chem. Educ. Res. Pract. **22**(1), 122–135 (2021)

Ogunniyi, M.B., Rollnick, M.: Pre-service science teacher education in Africa: prospects and challenges. J. Sci. Teacher Educ. **26**(1), 65–79 (2015)

Partanen, L.: Student oriented approaches in the teaching of thermodynamics at universities–developing an effective course structure. Chem. Educ. Res. Pract. **17**(4), 766–787 (2016)

Potgieter, M., Davidowitz, B.: Preparedness for tertiary chemistry: multiple applications of the chemistry competence test for diagnostic and prediction purposes. Chem. Educ. Res. Pract. **12**(2), 193–204 (2011)

Potgieter, M., Davidowitz, B., Venter, E.: Assessment of preparedness of first-year chemistry students: development and application of an instrument for diagnostic and placement purposes. Afr. J. Res. Math. Sci. Technol. Educ. **12**(sup1), 1–17 (2008)

Rootman-le Grange, I., Blackie, M.: Assessing assessment: in pursuit of meaningful learning. Chem. Educ. Res. Pract. **19**(2), 484–490 (2018)

Scerri, E.R.: Philosophical confusion in chemical education research. J. Chem. Educ. **80**(5), 468 (2003)

Shay, S.: Beyond social constructivist perspectives on assessment: the centring of knowledge. Teach. High. Educ. **13**(5), 595–605 (2008)

Stowe, R.L., Cooper, M.M.: Practicing what we preach: assessing "critical thinking" in organic chemistry. J. Chem. Educ. **94**(12), 1852–1859 (2017)

Stowe, R.L., Esselman, B.J., Ralph, V.R., Ellison, A.J., Martell, J.D., DeGlopper, K.S., Schwarz, C.E.: Impact of maintaining assessment emphasis on three-dimensional learning as organic chemistry moved online. J. Chem. Educ. **97**(9), 2408–2420 (2020)

Stowe, R.L., Scharlott, L.J., Ralph, V.R., Becker, N.M., Cooper, M.M.: You are what you assess: the case for emphasizing chemistry on chemistry assessments. J. Chem. Educ. **98**(8), 2490–2495 (2021)

Taber, K.S.: The Nature of the Chemical Concept: Re-constructing Chemical Knowledge in Teaching and Learning. Royal Society of Chemistry (2019)

Tadie, M., Pott, R., Goosen, N., P. Wyk, P. V., and Wolff, K. E.: Expanding 1st year problem-solving skills through unit conversions and estimations. 2018 IEEE Global Engineering Education Conference (EDUCON) (2018)

Wang, C., Chen, P., Wang, J., Ling, Y.: Rigorous evidence and reasoning or not? a demonstration of iron corrosion to induce students' critical thinking. J. Chem. Educ. **98**(5), 1718–1725 (2021)

Watts, F.M., Schmidt-McCormack, J.A., Wilhelm, C.A., Karlin, A., Sattar, A., Thompson, B.C., Gere, A.R., Shultz, G.V.: What students write about when students write about mechanisms: analysis of features present in students' written descriptions of an organic reaction mechanism. Chem. Educ. Res. Pract. **21**(4), 1148–1172 (2020)

Wolff, K.: Engineering problem-solving knowledge: the impact of context. J. Educ. Work. **30**(8), 840–853 (2017)

Zoller, U.: Teaching tomorrow's college science courses–are we getting it right? J. Coll. Sci. Teach. **29**(6), 409 (2000)

Zoller, U.: Algorithmic, LOCS and HOCS (chemistry) exam questions: performance and attitudes of college students. Int. J. Sci. Educ. **24**(2), 185–203 (2002)

Zoller, U., Pushkin, D.: Matching Higher-Order Cognitive Skills (HOCS) promotion goals with problem-based laboratory practice in a freshman organic chemistry course. Chem. Educ. Res. Pract. **8**(2), 153–171 (2007)

Zoller, U., Tsaparlis, G.: Higher and lower-order cognitive skills: the case of chemistry. Res. Sci. Educ. **27**(1), 117–130 (1997)