A STRATEGY TO ENHANCE CONCEPTUAL UNDERSTANDING USING ACTIVE LEARNING
Project Report

Nimesh Mistry
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Executive summary

Overview

A study by Freeman (2014) showed that active learning in STEM subjects leads to higher grades and lower failure rates. However, active learning is only successful when challenging students’ misconceptions about scientific phenomena (Ortiz and Heron 2005; Hunter and Heron 2013).

This project aims to develop a strategy for using active learning that translates across disciplines and can be applied in different teaching environments. The key feature of this strategy is that it first identifies student misconceptions of a given topic, then uses an active learning activity that specifically challenges those misconceptions (below). The context for this study was organic chemistry (the chemistry of carbon-based molecules).

Active learning template to improve conceptual understanding

Key findings

- Students rely on simpler concepts they learn in secondary education to solve problems in chemistry.
- Active learning approaches to teach more complicated concepts in tertiary education should first expose the limitations of simpler models from secondary education.
- Students employ algorithmic approaches when using spatial reasoning to translate between 2D and 3D representations of molecules.
- Active learning approaches to teach spatial reasoning contain explicit instructions of how to use 3D models to translate between representations.
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1. Introduction

Active learning is an instructional method that engages students in their learning during class time. It is considered to be a student-centred teaching method where students are required to perform meaningful learning activities in the presence of a teacher. This is in contrast to traditional forms of teaching where the teacher will deliver material in a didactic format whilst the students are passive recipients of this information.

A study by Freeman (2014) comparing traditional to active learning approaches in STEM education found that active learning improved performance amongst all students. The improvement was particularly effective with the lower quartile with these students 1.5 times less likely to fail as a result of active learning. Active learning also reduces the achievement gap between students from disadvantaged and non-disadvantaged students (Haak and Freeman, 2011). Whilst research active learning for this project, authors have found that much of the existing research could be grouped into one of four domains (Figure 1).

![ACTIVE LEARNING DOMAINS]

*Figure 1: Domains of active learning.*

The first domain considers the learning spaces that have been developed to facilitate active learning. These include interactive lecture theatres such as Roger Stevens lecture theatre 18 and Mechanical Engineering lecture theatre B at the University of Leeds. The second domain considers generic models for employing active learning such as the flipped model and peer instruction. These are models that consider general principles of student learning such as constructivism which applies to all students, no matter the subject they are studying. The third domain is technological approaches such as clickers and lecture capture that allow students to engage more in an active learning classroom. The fourth
and final domain considers the discipline that active learning is being used within. This is important, yet often underrepresented domain within the active learning literature.

1.1 How important is the discipline-specific pedagogy domain?

Heron showed that active learning which did not address student misconceptions showed no improvement, however those did were particularly effective (Oritz and Heron, 2005; Close and Heron, 2013). By applying discipline-specific considerations Heron was able to successfully use active learning to improve student understanding.

Figure 2: Students misconceptions about the balancing objects remained after certain types of active learning. Only by understanding the origins of the misconceptions could successful active learning tasks be developed (Oritz and Heron, 2005).

We reason that those who wish to use active learning in their teaching need to consider discipline-specific pedagogy alongside the other domains for it to be successful. If, like in the author’s own field (organic chemistry), there is little existing literature of student misconceptions, threshold concepts and other difficulties within the discipline, designing active learning task would be challenging.
2. Project aims

2.1 Active learning template

An active learning template has been designed that practitioners could use to develop active learning tasks which will improve students’ conceptual understanding. The template is also designed so that it could be applied in any subject (Figure 3).

![Active learning template](image)

**Figure 3:** Active learning template to improve conceptual understanding

**Diagnose** – The first stage of the process is to diagnose student learning within the discipline and identify student difficulties. This provides the foundation upon which the practitioner can design active learning tasks. To meet this goal a novel method for diagnosing student learning is needed that is both reliable but also be easy to implement and analyse.

**Design** – The second stage is the design of active learning methods that will target specific learning difficulties. Here the practitioner may want to consider an appropriate theoretical framework in the design. For example, the conceptual change model (Duit and Treagust, 2003) stipulates that for students to learn a concept they must be dissatisfied with old ways of thinking; the new way of thinking must be intelligible; and the new way of thinking must be fruitful to learn. The active learning task should be designed to follow the theoretical framework for it to be effective.

**Deliver** – The third stage is to incorporate the designed activities into teaching. By considering student difficulties and designing active learning around them, the use of active learning will be more effective. Evaluation of the active learning task can be achieved by repeating the diagnostic test with the groups
that have completed the active learning task against the earlier cohorts who are used as the control group.

### 2.2 Aims

**Project Aim 1** – *Design a template for using active learning that could be applied across disciplines.*

The first aim was to develop and refine the template, and showcase its effectiveness (proof of concept). This would be achieved through its application towards a specific discipline.

**Project Aim 2** – *Apply the template towards two topics in chemistry education.*

There is little research in the area of conceptual understanding in tertiary chemistry education, particularly in a UK higher education. This provides an appropriate subject to apply the template whilst also gaining a better understanding as to why students find topics within this discipline difficult.

The first chemistry topic is fundamental reactivity in organic chemistry. This is a topic where students apply fundamental concepts of how carbon-based molecules reacts. In many chemistry degree programmes, these concepts are taught in the first year. For the remainder of this report this topic with be referred to as *Reactivity*.

![Figure 4: Example of organic molecules reacting which forms part of the Reactivity topic](image)

The second topic is stereochemistry in organic chemistry. This is a topic where students learn properties of molecules that arise from their 3D shapes. For the remainder of this report this topic will be referred to *Molecular Shape*. 
Figure 5: Example of an organic molecule in three dimensions which students learn for the Molecular Shape topic.

The remainder of the report will discuss the work carried out to achieve these two aims. The next section will discuss the methodology that was developed to diagnose student understanding. The following sections will discuss the active learning templates applied to the two topics in separate chapters.
3. Methodology

3.1 Methods to measure conceptual understanding

For this template to be practitioner-friendly, a method of diagnosing student understanding of a topic was needed which would provide an overview of student understanding from a cohort and could also be easily implemented. A variety of existing methods have been used in chemistry education research. The strengths and limitations of each method is summarised in Table 1. None of the existing methods satisfied all the requirements that was needed for this project so a bespoke methodology for diagnosing conceptual understanding was developed (Bretz, 2014).

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interviews</td>
<td>Provides depth of conceptual understanding.</td>
<td>Small sample size and time-consuming to perform.</td>
</tr>
<tr>
<td>(e.g. Bhattacharyya, 2014)</td>
<td>Shows linking of multiple concepts.</td>
<td></td>
</tr>
<tr>
<td>Concept Inventories</td>
<td>Validated instruments for measuring conceptual understanding.</td>
<td>Unavailable for many topics. Can take years to develop and validate a concept inventory. Students must complete all items for validity (time-consuming). May only measure single concepts.</td>
</tr>
<tr>
<td>(e.g. Mulford 2002)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Analysis of examination questions (e.g. Bodé and Flynn, 2015)</td>
<td>Large sample size.</td>
<td>Unable to distinguish conceptual understanding and algorithmic learning due to high stakes assessment. Issues with obtaining ethical approval.</td>
</tr>
<tr>
<td>Concept mapping</td>
<td>Provides depth of conceptual understanding.</td>
<td>Impractical due to amount of time required for completion.</td>
</tr>
<tr>
<td>(e.g. Anovino and Bretz, 2016)</td>
<td>Shows linking of multiple concepts.</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Summary of methods used to diagnose student learning in chemistry education.

The methodology we developed for use in this template has some of the advantages which are gained from using quantitative methods (e.g. large scale sampling) blended with some of the advantages gained from of qualitative methods (e.g. rich depth of data).

Diagnostic tests were used to gain large scale data which could be analysed using quantitative methods. The answers of the test were free form so that students could provide explanations alongside structures and reaction mechanisms. This would allow students to give rich data in their
answers, showing how they understand multiple concepts in unison which allowing qualitative methods of analysis could be employed.

3.2 Design and delivery of diagnostic tests

A diagnostic test was developed for each topic with each test containing 6 items. For the Reactivity test students questions were structured so they had to apply multiple concepts when explaining how organic molecules react (summarised in Appendix A). For the Molecular shape topic, each question was structured so students had to transfer between 2 dimensional and 3 dimensional representations of organic molecules, (summarised in Appendix A).

Each test was delivered to cohorts of students who had been taught the material previously, and would be required to apply this material in a course they were currently studying. This allowed to us to also use the tests a teaching tool and encourage participation. Feedback was given to the entire cohort and to individuals who chose to give their personal details.

Figure 6: Summary of how the diagnostics tests were delivered.

Tests were also delivered during periods of the academic year when students would not be preparing for upcoming examinations. This was to reduce the possibility of responses driven by algorithmic learning rather than conceptual understanding. Each student was randomly assigned one of the diagnostic test questions to complete and given 10 minutes to complete.
Table 2: Number of responses for both Reactivity and Molecular Shape diagnostic tests.

Overall were satisfied that this approach satisfied our requirements to develop a method of measuring conceptual understanding in a way that was ‘light touch’ in its approach and also provided the scale and depth of information required.

3.3 Method for analysing diagnostic tests

The method for analysing the responses were developed using thematic analysis as a framework (Braun and Clarke, 2006). A blend quantitative and qualitative approaches was taken to analyse the data to reflect the balance of outcomes we wanted to achieve. Qualitative methods revealed the complex nature of conceptual understanding whilst quantitative methods allows us to interpret the scale and significance of conceptual understanding across a cohort, degree programme or even across institutions (see Appendix B for an example). Our analysis can be divided into a number of stages.

3.3.1. Interpretation

To ensure validity in our interpretation of student results, each response was transcribed independently by two of the researchers. Each transcription was compared with one another. Agreement between the two transcriptions signifies a valid interpretation of the student answer and those without agreement prompted further discussion.

Before discussion the agreement across all answers was 84%. This rose to 95% after discussion revealed the majority of differences were simply differing wordings of the same interpretation. For the remaining 5% there was no agreement so these interpretations were not taken forward.
3.3.2. Coding and scoring

Codes were generated for each diagnostic test question which corresponded to a particular concept or aspect of answering the question. These were generated in an implicit manner using student responses. Each concept was given a score of +/-1.

3.3.3. Ranking and clustering

Student responses were ranked by score. As expected students with higher scores correctly applied more concepts than those with lower scores. The value of this quantitative approach was that it revealed clusters of students who were correctly or incorrectly applying certain concepts.

3.3.4. Cluster analysis

The responses in each cluster were analysed again but now interpreted in a qualitative manner. Within each cluster themes were identified by the researchers, i.e. students in each cluster were revealing the same conceptual understanding.

3.3.5. Cross-sectional analysis

Finally clusters and themes were compared across questions. Comparing clusters across different questions revealed similar responses in each question. As with the previous step this helped to develop overarching themes in our analysis.

3.4 Validation of the methodology

We recently conducted student interviews of the diagnostic questions to validate our interpretations. Pleasingly, when students discussed their thought processes they matched our interpretations of the test results. Overall method that we developed validated its purpose for identifying conceptual understanding across a large number of students. When considering that clusters of students were giving the same responses across different year groups then it is likely that similar levels of conceptual understanding or misconceptions are being applied. The findings from each topic and its application towards the rest of the strategy will be discussed in the following sections.
4. Reactivity topic | results and discussion

4.1 Organic chemistry

Organic chemistry is a topic that is traditionally seen to be hard to learn (Graulich, 2015). Amongst the difficulties encountered, one is the requirement to use multiple concepts when solving mechanistic problems (Cartrette and Bodner, 2010). To the novice it can also appear that the mastery is achieved by learning lots of information, however the reality is that a few underlying concepts underpin the majority of chemical reactions. Novices tend to use surface features to make connections between structure and reactivity whilst experts use these concepts to make deep underlying connections (Galloway and Flynn, 2018). It is important for students to understand and apply the material in the same way as experts as it this will lead to improved performance in the subject (Frey, 2017).

4.2 Results from the Reactivity diagnostic tests

Clustering of results during the quantitative analysis allowed responses to be classified into 3 general groups (Appendix C for a detailed breakdown).

1. **Correct answers**: A answer where all or most of the concepts were correctly used.
2. **Partially correct answers**: These followed the pattern where some concepts were correctly used but others were incorrect or not used at all.
3. **Incorrect answers**: The initial concepts needed were used incorrectly and the following concepts were not used.

Student from Leeds who completed the tests in autumn 2016 and 2017 showed similar results for questions 1-4 of the diagnostic test, whether their answers were correct, partially correct or incorrect. This suggests that students have specific levels of understanding that is independent to the teaching they have received in year.

Initial analysis of question 5 and 6 from the 2016 cohort concluded that the structure and wording of the questions were too ambiguous for students, hence their results were not analysed further. These questions were modified for the 2017 cohort.

Question 1 and question 3 of the Reactivity test asked students to apply their understanding to the same type of chemical reaction and so they produced the same type of correct, partially correct and
A strategy to enhance conceptual understanding using active learning

incorrect answers. In all types of answer students would apply electronegativity, a concept introduced in secondary education, to answer the question. This concept provides a partially correct answer if correctly used, however but some students used the concept incorrectly. FMO theory is a concept introduced in tertiary education that could have also been applied instead of electronegativity (secondary concept) to get the first part of the answer correct but this was not used by any group of students. Partially correct students only applied electronegativity (secondary concept) whereas students who achieved the fully correct answer also applied either acid-base theory (tertiary concept) or resonance (tertiary concept).

Question 2 was generally well answered. Here students could use just one concept to get the correct answer instead of having to apply a number of different concepts, hence the question could be deemed to be easier. Some students gave partially correct answers by providing the correct mechanisms but for the wrong compounds. It was thought that these were answers due memorisation of the answers but no conceptual understanding to apply to the correct chemical reaction.

Question 4 gave a very similar pattern of results to questions 1 and 3. Almost all students applied electronegativity (secondary concept) correctly to answer the first part of the chemical reaction. However, to achieve the fully correct answer tertiary concepts were needed in the second part of the chemical reaction. Here most students failed to apply the tertiary concepts leaving their responses as partially correct. In fact, the partially correct chemical reactions are exactly what is taught in secondary education and would be fully correct at that level.

Across the answers to these four questions a general theme began to emerge whereby students were consistently applying the concepts taught to them in secondary education. A lack of application of tertiary concepts led to our conclusion that students had a poor understanding of these concepts. We also reasoned that this was linked to their reliance on concepts taught at the secondary level.

4.3 Designing active learning workshops for tertiary level concepts

In the majority of answers students were reliant on secondary concepts to understand fundamental organic reactions whether they are correct, incorrect or partially correct responses. The reason more complicated concepts are introduced in higher education is that these simpler concepts break down and so higher levels of understanding are needed. The strategy of breaking down simpler models to introduce more complicated models is common practice in developing concepts science education and one that students will have encountered throughout their studies.
To help students understand the tertiary level concepts we decided to apply the conceptual change framework (Duit and Treagust, 2003) applies the model or breaking down old concepts to learn new ones. The framework states that for students to change or adapt their conceptual thinking, new concepts must be introduced through the following steps:

1. Become dissatisfied with the old ways of thinking
2. Present new concepts in an intelligible way
3. Appear fruitful to learn new concepts

Active learning tasks were developed in the form of problem-based learning workshops where students would given information and structured questions relating to various concepts. Because the understanding of tertiary concepts was linked to secondary concepts, the first part of the workshop would focus on exposing the limitations of the secondary concepts (conceptual change framework step 1) with specific questions. Tertiary concepts would then be introduced (step 2) and students would work through questions that could only be answered using the tertiary concepts (step 3).

### 4.4 Delivering active learning workshops for tertiary level concepts

Many of these concepts are first introduced in CHEM1000 ‘An introduction to modern chemistry’ which runs as a 20 credit module in semester 1. For the duration of this module, 1 hour workshops are delivered on a weekly basis to complement the lectures. The organic chemistry lectures are taught by Professor Paul Taylor who after discussion of diagnostic test results agreed to use two of these workshops for our active learning tasks.

The first workshop was themed around the structure of the carbonyl functional group. In this workshop students would use electronegativity (secondary concept), FMO theory (tertiary concept) and resonance (tertiary concept) to solve problems with the emphasis on why FMO theory and resonance is needed to have a full understanding of structure.

The second workshop was themed around a type of reactivity exhibited by the carbonyl functional group. The importance of resonance (tertiary concept) was reinforced whilst acid-base theory (tertiary concept) was also introduced. Again, the workshop highlighted why electronegativity (secondary concept) only gives partial understanding of its reactivity.
4.5 Determining the success of the active learning workshops

These students completed their CHEM1000 examination in January. Their results relating to these concepts will be analysed. The students will also complete the same diagnostic tests are the 2016 and 2017 cohorts in autumn 2018. Their results will be compared to the 2016/17 cohorts who will act as a control group.

4.6 Summary of the active learning strategy applied to Reactivity

To summarise, we have applied the strategy to the topic of Reactivity in organic chemistry. Our key findings from the diagnostic tests were that students relied on concepts learnt in their secondary education to understand the reactivity of organic molecules to mixed success. To help them understand concepts taught in tertiary chemistry education, which would ensure improved understanding of the reactivity of organic molecules, we applied the conceptual change framework to design workshops that expose the limitations of using these simpler models. These were delivered in the module CHEM1000 which introduces these students to these concepts.

We are interesting in investigating if this theme of using secondary-level concepts is also applied in other UK higher education chemistry departments, and if this links to poor understanding of tertiary concepts as shown with students from the University of Leeds. We have partnered with the University of Warwick and University of York to analyse their students’ responses. To date we have data from a cohort of Warwick students with more data from both institutions to be received in the coming months. If there is a similar pattern emerging then it sheds new light of how we teach chemistry concepts across secondary and tertiary level with implications of how we design the curriculum at both levels.
5. Molecular shape topic | results and discussion

5.1 Molecular Shape (stereochemistry)

Molecular shape (or stereochemistry as it’s technically known) requires students to understand the properties of molecules using 3D-spatial reasoning. One of the most difficult tasks for students to do is translate between these representations (Vlacholia M, 2017). When students are given instruction of using 3D models of molecules, either in a physical or computational form, their performance on Molecular Shape improves (Stull 2016). Other attempts to improve performance encourages algorithmic approaches that bypass 3D spatial thinking (Hutchinson, 2017).

![2D representation of molecule](image1)

**Figure 7:** Students must be able to translate between 2D and 3D representations of molecules to understand their properties.

5.2 Results from Molecular Shape diagnostic tests

Tests for molecular shape were completed by two cohorts of Leeds students in different year groups but who both received instruction from the author on this topic. Warwick students also completed the diagnostic tests.

All groups of students gave a similar pattern of results. Very few students gave answers that were completely incorrect. Rather the main differences in answers lay in subtleties which determined whether the answers were fully correct or partially correct. Nevertheless, these partially correct results revealed a common pattern which we could determine as we had taught the Leeds students this topic. Students were given a particular style of instruction of how to translate between representations using exemplar molecules. It was expected that students would learn how to translate between representations using these examples whilst also thinking about 3D shape of the molecule so that the instructions could be adapted when asked to view molecules from different perspectives. However, because these students were learning the translations by rote and without 3D thinking, their answers contained consistent mistakes.
Many of the errors fell into a few categories:

1. Viewing the molecule along the wrong direction of the bond.
2. Drawing functional groups on the wrong side of the central carbon atom.
3. Not drawing bonds facing forwards or backwards when needed.

Whilst the details of instruction was not as well-known with Warwick students, these same errors persisted, implying that they too were translating between representations without 3D spatial thinking.

5.3 Developing active learning resources for 3D spatial reasoning

As with the Reactivity topic, our strategy for active learning is to help students see the limitations of using their existing approaches to learn the correct approach way of thinking. In this case the strategy was to improve students’ ability to translate between representations by teaching them how to use 3D models and by extension how to think in 3D. Molecular models can be either be in the form of physical model kits, or computer-based models. Whilst physical models are sometimes given to students, it is rare that they bring these to lectures so using physical models would be an unreliable method. Online resources such as ChemTube3D (www.chemtube3D.com) are available to allow students to view molecules in 3D but they contain little to no instruction of how students should use them to translate between two representations.

5.4 Creating a free online tool to translate between 2D and 3D representations

To be able to use active learning to improve 3-dimensional spatial thinking it became apparent that we needed to create a resource that would guide students between representations with a 3D model. We decided to use computational models as a free online resource as this would give maximum access to students. We are currently working with the Technology Enhanced Learning team in MAPS to achieve this. Once the resource has been created active learning workshops will be created for students to engage with the resource.
5.5 Creating a textbook to teach Molecular Shape

A tutorial textbook has been commissioned by the Royal Society of Chemistry on the topic of molecular shape, written by the author with the Professor Paul Taylor at the University Leeds, and Professor Andrew Clarke and Dr Russell Kitson at the University of Warwick.

The textbook will focus on the problems students face with 3D representation of molecules. The results from the diagnostic tests have been very useful in highlighting the issues students face and will guide the structure of the book and the problems for students to work through. The online resources being created will be used as a resource to supplement the book as well.
6. Conclusions

Overall we have achieved the main aim of this project to pilot the active learning template and prove that it can be used to identify misconceptions which can be used to develop active learning methods. The template has been refined based upon our experience of applying it in practice. The template uses a novel method for determining misconceptions and threshold concepts from the analysis of diagnostic tests. Overarching themes of how students understand concepts of molecular shape and reactivity were discovered from our analysis from students at Leeds, and we are beginning to investigate if these findings are replicated at other universities to gain a national picture. Preliminary analysis of students at the University of Warwick reveal that there are similarities with Leeds students when interpreting molecular shape.

For the reactivity topic we discovered was that students rely almost exclusively on concepts learnt in secondary education whether that is to achieve the correct, partially correct or incorrect answer. We hypothesised that the reliance on these simpler models to students having a poor understanding of the concepts taught in tertiary education. Active learning workshops were designed for the module CHEM1000 which used the conceptual change framework. The strategy was to help students see the limitations of these secondary concepts to then value of the new concept introduced.

For the molecular shape topic we discovered that students learnt to translate between 2D and 3D representations of molecules by algorithmic methods which meant incorrect representations were produced when looking from different perspectives. Resources are being created that will help students use 3-dimensional structures of molecules as a way of translating between representations in the form of an online resource and a textbook published with the Royal Society of Chemistry.

6.1 Future work

- We are continuing to investigate the ways students learn in these two topics to see if students these are general issues which affects all chemistry students irrespective of the institution they are studying.
- The impact of our active learning workshops will be measured in the coming years when the student reach the same point in their studies as previous students who have completed the diagnostic tests.
- Both the online 3D molecular resource and textbook will become available in the coming years to help students visualise molecules in 3D.
• We will look to apply the active learning strategy in other subject areas.

A detailed timeline of the current and future objectives of the project is available in Appendix D. Past and future outputs are available in Appendix E.
References


Appendices

Appendix A | Summary of concepts used for both Reactivity and Molecular Shape diagnostic tests

<table>
<thead>
<tr>
<th>Diagnostic Test</th>
<th>Concept</th>
<th>Question</th>
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<td>Reactivity</td>
<td>Electronegativity</td>
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</tr>
<tr>
<td></td>
<td>Structure (stability)</td>
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<td>Sterics</td>
<td>X</td>
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<tr>
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<td>Resonance</td>
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<td>FMO theory</td>
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<td></td>
<td>Stereochemistry</td>
<td>X</td>
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</tbody>
</table>

Table 3: Summary of concepts used in Reactivity diagnostic test.

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<th>Concept</th>
<th>Question</th>
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<td></td>
<td>1 2 3 4 5 6</td>
</tr>
<tr>
<td>Molecular shape</td>
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<tr>
<td></td>
<td>Diastereomers</td>
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</tr>
<tr>
<td></td>
<td>Sterics</td>
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<tr>
<td></td>
<td>2D to 3D representation</td>
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</tr>
<tr>
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<td>3D to 2D representation</td>
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<td></td>
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<td>X X X X X</td>
</tr>
</tbody>
</table>

Table 4: Summary of concepts used in Molecular Shape diagnostic test.
Appendix B | Example of the analysis methodology

Figure 8: An example of the analysis methodology applied to question 1 of the Reactivity concept quiz. The left-hand portion shows the quantitative analysis that was used to cluster student responses. The green (correct) and red (incorrect) segments indicate the correct or incorrect use of each concept respectively. Qualitative analysis showed responses in each cluster were the same, implying students had the same level of understanding within each cluster.
Appendix C | Results from Reactivity diagnostic tests

Results from Reactivity diagnostic tests from Leeds 2016 students shows how students consistently apply concepts learnt in secondary education, whilst those taught in tertiary education were rarely used.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Introduced in secondary or tertiary education</th>
<th>Question</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Electronegativity</td>
<td>Secondary</td>
<td>X</td>
</tr>
<tr>
<td>Structure (stability)</td>
<td>Secondary</td>
<td>X</td>
</tr>
<tr>
<td>Sterics</td>
<td>Secondary</td>
<td>X</td>
</tr>
<tr>
<td>Resonance</td>
<td>Tertiary</td>
<td>X</td>
</tr>
<tr>
<td>Acid-Base theory</td>
<td>Tertiary</td>
<td>X</td>
</tr>
<tr>
<td>FMO theory</td>
<td>Tertiary</td>
<td>X</td>
</tr>
<tr>
<td>Stereochemistry</td>
<td>Tertiary</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 5: Breakdown of concepts in each question and whether they are taught in secondary or tertiary education.

**Question 1 (N = 42)**

<table>
<thead>
<tr>
<th>Responses</th>
<th>Correct</th>
<th>Partially correct</th>
<th>Incorrect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronegativity (secondary)</td>
<td>13</td>
<td>7</td>
<td>22</td>
</tr>
<tr>
<td>Acid-base theory (tertiary)</td>
<td>31%</td>
<td>17%</td>
<td>52%</td>
</tr>
<tr>
<td>Resonance (tertiary)</td>
<td>1</td>
<td>14</td>
<td>9</td>
</tr>
<tr>
<td>FMO theory</td>
<td>11</td>
<td>14</td>
<td>9</td>
</tr>
</tbody>
</table>

**Question 3 (N = 34)**

<table>
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<tr>
<th>Responses</th>
<th>Correct</th>
<th>Partially correct</th>
<th>Incorrect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronegativity (secondary)</td>
<td>11</td>
<td>14</td>
<td>9</td>
</tr>
<tr>
<td>Acid-base theory (tertiary)</td>
<td>33%</td>
<td>41%</td>
<td>27%</td>
</tr>
<tr>
<td>Resonance (tertiary)</td>
<td>1</td>
<td>14</td>
<td>9</td>
</tr>
<tr>
<td>FMO theory</td>
<td>1</td>
<td>14</td>
<td>9</td>
</tr>
</tbody>
</table>

**Question 1 and 3 combined (N = 76)**

<table>
<thead>
<tr>
<th>Responses</th>
<th>Correct</th>
<th>Partially correct</th>
<th>Incorrect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronegativity (secondary)</td>
<td>24</td>
<td>21</td>
<td>31</td>
</tr>
<tr>
<td>Acid-base theory (tertiary)</td>
<td>31%</td>
<td>28%</td>
<td>41%</td>
</tr>
<tr>
<td>Resonance (tertiary)</td>
<td>1</td>
<td>21</td>
<td>9</td>
</tr>
<tr>
<td>FMO theory</td>
<td>24</td>
<td>21</td>
<td>31</td>
</tr>
</tbody>
</table>

29
<table>
<thead>
<tr>
<th>Topic 1: Resonance in organic chemistry</th>
<th>Pre-TEPL</th>
<th>LITE-TEPL</th>
<th>Post-TEPL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conceptual</strong></td>
<td><strong>Design</strong></td>
<td><strong>Data/active learning</strong></td>
<td><strong>Feedback to Students</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Collaboration with York and Warwick established</strong></td>
<td><strong>Analysis of conceptual understanding</strong></td>
<td><strong>Gather data from Leeds, Warwick and York</strong></td>
</tr>
<tr>
<td><strong>Active Learning</strong></td>
<td><strong>Collaboration with Active Invites</strong></td>
<td><strong>Gather data from Leeds, Warwick and York</strong></td>
<td><strong>Local impact is in blue</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>External impact is in red</strong></td>
</tr>
<tr>
<td>Topic 2: Stereochemistry (3D shapes)</td>
<td>Pre-TEPL</td>
<td>LITE-TEPL</td>
<td>Post-TEPL</td>
</tr>
<tr>
<td><strong>Conceptual</strong></td>
<td><strong>Design</strong></td>
<td><strong>Data/active learning</strong></td>
<td><strong>Feedback to Students</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Collaboration with York and Warwick established</strong></td>
<td><strong>Analysis of conceptual understanding</strong></td>
<td><strong>Gather data from Leeds, Warwick and York</strong></td>
</tr>
<tr>
<td><strong>Active Learning</strong></td>
<td></td>
<td></td>
<td><strong>Local impact is in blue</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>External impact is in red</strong></td>
</tr>
</tbody>
</table>

**Timeline of project objectives and impact**

- **Sep 18 - Oct 18**: Pre-TEPL
- **Nov 18 - Dec 18**: Pre-TEPL
- **Jan 19 - Feb 19**: Pre-TEPL
- **Mar 19**: Pre-TEPL
- **Apr 19**: Pre-TEPL
- **May 19**: Pre-TEPL
- **Jul 19**: Pre-TEPL
- **Aug 19**: Pre-TEPL
- **Sep 19**: Pre-TEPL
- **Oct 19**: Pre-TEPL
- **Nov 19**: Pre-TEPL
- **Dec 19**: Pre-TEPL
Appendix E | Summary of project dissemination

Conference talks/posters

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
<th>Organiser</th>
<th>Location</th>
<th>Poster/Talk</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 17</td>
<td>Methods in Chemistry Education Research (MICER 17)</td>
<td>Royal Society of Chemistry</td>
<td>Burlington house, London</td>
<td>Poster</td>
<td>Delivered</td>
</tr>
<tr>
<td>Aug 17</td>
<td>Variety in Chemistry Education (VICEPHEC 17)</td>
<td>Royal Society of Chemistry, Institute of Physics</td>
<td>University of York</td>
<td>Poster</td>
<td>Delivered</td>
</tr>
<tr>
<td>Jan 18</td>
<td>Student Education Conference</td>
<td>LITE</td>
<td>University of Leeds</td>
<td>Talk</td>
<td>Delivered</td>
</tr>
<tr>
<td>Mar 18</td>
<td>Work in Progress seminar</td>
<td>LITE</td>
<td>University of Leeds</td>
<td>Talk</td>
<td>Abstract accepted</td>
</tr>
<tr>
<td>Mar 18</td>
<td>Chemical Education Research Group Webinar</td>
<td>Royal Society of Chemistry</td>
<td>Online</td>
<td>Talk</td>
<td>Invited talk</td>
</tr>
<tr>
<td>May 18</td>
<td>SEDA Annual Conference</td>
<td>SEDA</td>
<td>Hilton, Leeds</td>
<td>Talk</td>
<td>Abstract accepted</td>
</tr>
<tr>
<td>Jul 18</td>
<td>HEA Annual Conference</td>
<td>Higher Education Academy</td>
<td>Birmingham</td>
<td>Talk</td>
<td>Abstract accepted</td>
</tr>
</tbody>
</table>

Publications

<table>
<thead>
<tr>
<th>Date</th>
<th>Topic</th>
<th>Type</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep 18</td>
<td>Conceptual understanding of Reactivity topic of Leeds students</td>
<td>Journal Article</td>
<td>Target journals include J Chem Ed and CERP</td>
</tr>
<tr>
<td>Dec 18</td>
<td>Royal Society of Chemistry stereochemistry textbook</td>
<td>Book</td>
<td>Textbook commissioned by RSC</td>
</tr>
<tr>
<td>Jan 19</td>
<td>Molecular Shape understanding of Leeds students</td>
<td>Book Chapter</td>
<td>Invited chapter contribution for Festschrift</td>
</tr>
<tr>
<td>Aug 19</td>
<td>Conceptual understanding of Reactivity topic at national scale</td>
<td>Journal Article</td>
<td>Target journals include J Chem Ed and CERP</td>
</tr>
<tr>
<td>Aug 19</td>
<td>Molecular Shape understanding at national scale</td>
<td>Journal Article</td>
<td>Target journals include J Chem Ed and CERP</td>
</tr>
</tbody>
</table>
About the author and acknowledgements

About the author

Nimesh is a Senior Teaching Fellow in the School of Chemistry. He is currently holder of a University Student Education Fellowship.

He obtained an MChem in Medicinal Chemistry at the University of Leeds in 2006, which also included a year in industry with GlaxoSmithKline. After his undergraduate degree, Nimesh undertook his doctorate in the Clarke group at the University of York working towards the synthesis of (+)-phorboxazole B, a marine natural product with potent anti-cancer properties. He remained in York for a short postdoctoral fellowship in the Clarke and Thomas group before being appointed as a Teaching Fellow in the Department of Chemistry in 2011. In 2013, he moved back to the University of Leeds to take up his current position.

His research interests are in the development of innovative approaches to enhance student education using the scholarship and pedagogic research. Most of his work so far has been within the context of chemistry education but can be applied into many other disciplines.

Acknowledgements

I would like everybody at the LITE team for supporting this project and providing help and guidance throughout. I would also like to thank Steve Marsden and Paul Taylor for their support within the School of Chemistry. I am grateful to Russ Kitson at the University of Warwick and Glenn Hurst at the University of York for kindly agreeing to use the diagnostic tests at their respective institutions. I would like to thank Samantha Pugh for supporting the ethical approval for project through PRISM. Finally, I would like to thank Michael Lloyd and Steven Nicholson for their excellent contributions towards this work.

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