The Discovery Laboratory – A Student-Centred Experiential Learning Practical: Part I – Overview

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Abstract

Chemical Engineering's Discovery Laboratory at Imperial College London is a practical teaching programme designed specifically to support student-centred learning at an advanced level, bridging the gap between instructions driven lab experiments and fully open ended research. In the first part of this article we present an overview of this programme with particular attention given to the design of the pedagogical framework and the execution of teaching. The teaching goal is delivered by in-depth experiential learning, where students are assigned a specific subject area to conduct their own research within a set timeframe and boundary conditions that guarantee a successful learning outcome. Academic supervisors and teaching assistants play an important role in this process, where they provide students with continuing guidance throughout. The use of research or industrial grade equipment ensures the students' preparation for their final year research project as well as their post-graduation careers. In addition to summative assessments, students also receive formative feedback periodically from academic supervisors and teaching assistants. The Discovery Laboratory has received positive feedback from both teachers and students since its inauguration in 2011 and here we share some useful insights for the execution of such a practical teaching programme.

Keywords

Chemical engineering laboratory; Practical education; Problem-based learning; Student-centred learning; Experiential learning cycle; Educator role profile.

1. Introduction

Two decades ago, the shift from the traditional Instruction Paradigm to the Learning Paradigm was advocated in the higher education community (Barr and Tagg, 1995). Six dimensions of these paradigms were outlined clearly:

1) mission and purpose;

2) criteria for success;

3) teaching/learning structures;

4) learning theory;

5) productivity/funding;

6) nature of roles.

Since then, educators across the globe have answered the call for this paradigm shift through the adoption of various learner-centred approaches in higher education (Webber, 2012).

The importance of such a paradigm shift in teaching has also been recognised by various official bodies. For example, the European Association for Quality Assurance in Higher Education (ENQA) has published standards that emphasise the importance of student-centred learning, teaching and assessment in higher education by outlining specific standards on this issue (European Association for Quality Assurance in Higher Education (ENQA) et al., 2015). In essence, the Learning Paradigm aims to encourage students to be active learners by designing and executing their own educational activities accordingly.

In practical disciplines such as chemical engineering, this educational goal can be delivered by the problem-based learning (PBL) approach, which "empowers learners to conduct research, integrate theory and practice, and apply knowledge and skills to develop a viable solution to a defined problem" (Savery, 2015). There is solid evidence to show that the PBL approach is effective in enhancing the learning of students in the engineering and medical disciplines (Tiwari et al., 2006; Walker and Leary, 2009; Yadav, et al., 2011). In the context of chemical engineering education, several PBL modules have been designed and reported in the literature (Woods, 1996; Woods et al., 1997; Cline and Powers, 1997; Gossage et al., 2001). At McMaster University, the PBL module consisted of 120-hour workshops that helped students to develop 37 problem-solving skills and apply them to chemical engineering and daily life (Woods, 1996; Woods et al., 1997). At Carnegie Mellon University, the PBL module was laboratory-based and was designed around open-ended problems that were provided by local companies (Cline and Powers, 1997), whereas the PBL modules at Lamar University relied on computer-aided modelling and simulation (CAMS) (Gossage et al., 2001).

The chemical engineering department at Imperial College London invested £9 million in 2010-11 into the ChemEng Discovery Space, a set of facilities for undergraduates to explore different subjects in their curriculum. For instance, the new teaching laboratory has over 30 major pieces of industrial grade equipment to support various teaching activities, covering subjects ranging from particle engineering to membrane separation. Learning from the best practices of PBL modules in chemical engineering education (Woods, 1996; Woods et al., 1997; Cline and Powers, 1997; Gossage et al., 2001), the practical undergraduate curriculum in our department was designed by teaching staff with significant experience in industry, secondary and higher education with input from academic researchers. This ensures that the designed programme is academically and pedagogically stimulating as well as practically relevant. Receiving direct coaching from experts in a particular subject area, students can optimise their learning outcomes following their own individual interests.

2. Course Context – Module Design with the End in Mind

The hands-on learning opportunities offered in the department serve to prepare the students for their final year design and research projects, which challenge them with solving open-ended real-world problems (**Figure 1**). Students undertake these practical learning opportunities in the undergraduate teaching laboratories in three different stages as they progress in their undergraduate studies: Foundation Laboratory, Knowledge Laboratory and Discovery Laboratory.

In the Foundation Laboratory, first-year undergraduate students are introduced to the laboratory environment, where they learn to perform experiments by following specific procedures precisely and safely, and to record and report data in a professional fashion. All foundation experiments present students with a *fixed problem* for which they have to determine a *fixed solution*. Lab hand-outs provide step-by-step instructions on how to execute a safety assessed experimental plan, what variables to measure at what time interval, and how to analyse the data as well as estimate experimental error. A combination of lab briefings, detailed hand-outs, and in session support by the module leader and graduate teaching assistants (GTAs) facilitates the development of hands-on competency. In the second year, students move up to the Knowledge Laboratory. All experiments in the Knowledge Laboratory introduce students to experimental objectives when investigating a *fixed problem*, which they can choose to solve through different experimental routes. Here, students are given *intermediate freedom* by designing their own experiments to solve the *fixed problem* with the equipment and material at hand. Activity risk evaluations of the proposed experimental plan before and supervision during execution ensure safe operation. Finally, in the Discovery Laboratory, third-year undergraduate students are given a set of equipment (e.g. a filter dryer) and a suggested investigational area (e.g. the filter drying of paracetamol) at the beginning, but they have the freedom to redefine the problem in consultation with an academic supervisor and investigate areas of their own interest. Hence, they are given *intermediate freedom* to define the problem as well as the appropriate approach to find a solution. The same safeguards as in the Knowledge Lab apply.

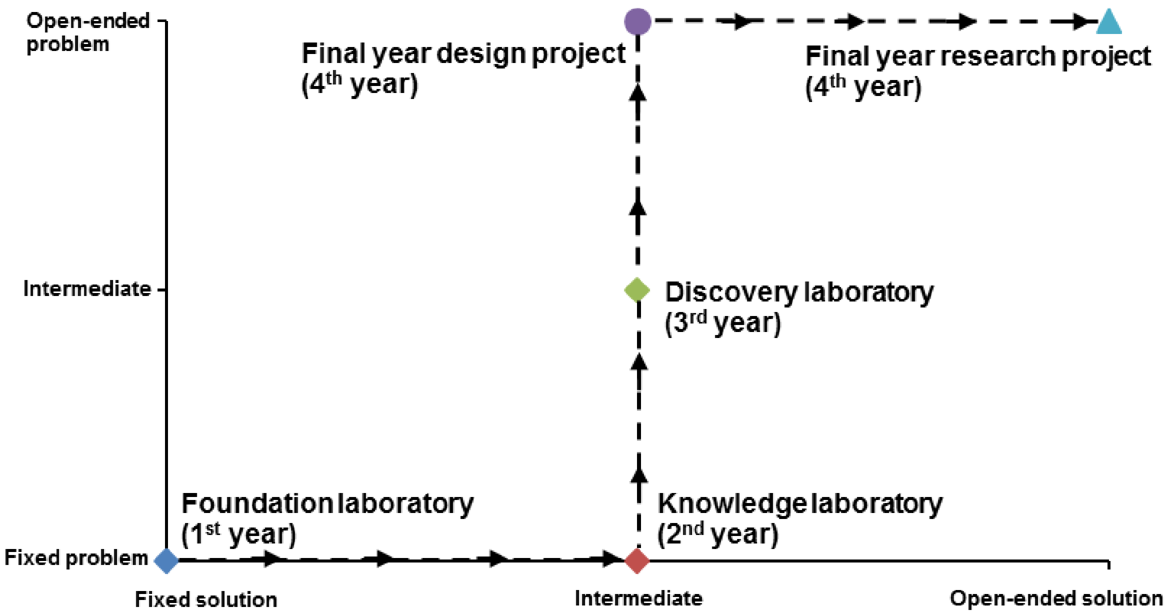

Figure 1 Problem-based learning opportunity for chemical engineering students

Although laboratory-based modules similar to the Foundation Laboratory and Knowledge Laboratory, as well as final year design and research projects are common features in chemical engineering degree programmes, students often need to overcome the intellectual gap between handling fixed and open-ended problems by themselves. The Discovery Laboratory was specifically designed to bridge this gap (**Figure 1**): as students have more freedom in defining and solving the problem than in the first and second year of undergraduate study, they have to plan and follow their own path that will decide the final outcome of their efforts. Through this process, they become more active and mature in learning and decision making, preparing them for the open-ended nature of real life issues.

The Discovery Laboratory covers a wide range of technologies in all unit operations (**Table 1**), giving each student the opportunity for an in-depth appreciation of one topic, the associated technology and the practical difficulties involved. This intentional diversity in experience is also extremely useful for the final year design and research projects, where students work in differently composed teams on different subjects. As all team members have first-hand experiences with numerous technologies, each team has a wide range of expertise available which mirrors real life team work.

Table 1 List of projects in the Discovery Laboratory course

	Project theme	Description
1	Multi-Phase Flow	Students investigate the effect of viscosity, pipe diameter and inclination on the drift velocity of large gas bubbles in a stagnant fluid.
2	Membranes	Students determine optimum operating conditions and energy requirements for concentrating a simulated fermentation broth solution at bench and pilot scale.
3	Batch Processing	Students develop a plant operating protocol, perform material compatibility checks and carry out test runs to produce a target amount of pharmaceutical product in a mini batch plant.
4	Heterogeneous Catalysis	Students determine the steady state and transient behaviour in a packed bed catalytic reactor and investigate the effect of pressure, flow rate, temperature and feed concentration on steady state conversion.
5	Tablet Dissolution	Students produce paracetamol tablets with a given composition, measure their physical characteristics and perform dissolution tests to identify optimum manufacturing conditions that give improved dissolution performance.
6	Fluidised Bed	Students determine pressure drop and bed expansion through fixed and fluidized beds of different media, observe and quantify the onset of fluidisation and compare experimental results with predictive equations.
7	Spray Drying	Students investigate the effect of spray drying operating conditions (atomisation pressure, inlet temperature and solution concentration) on particle morphology and physicochemical product characteristics of lactose.
8	Filter Drying	Students characterise a 2L pilot scale filter dryer to produce a data package for a sales department specifically investigating the drying characteristics of paracetamol and the filtration cake characteristics of calcium carbonate.
9	Preparative Chromatography	Students investigate the different parameters governing the efficiency of chromatographic separation of parabens, design an analytical chromatography protocol and scale it up to a preparative separation.
10	CO_2 Adsorption in Polymers	Students investigate the interaction of CO_2 with polymeric samples studied in-situ using FTIR to understand the possible applications of a green solvent to industrial processes.
11	Crystallisation	Students understand the experimental approach required for developing an industrially viable crystallisation process of a pharmaceutically relevant compound.

2.1 Course Structure

The Discovery Lab module is offered in the Autumn Term and operates from the 1st week of October until the 2nd Week of December each year. All students enrolled in the third year integrated masters' programme participate in the Discovery Lab, including exchange students. Typically, a cohort of more than 100 students takes this core module every year. Students are grouped in teams of four and were originally assigned a project at random from the list in Table 1. We have since refined this approach based on student feedback: From Autumn of 2015, learners can now express their preferences and are guaranteed one out of five choices. All experiments which receive at least four votes from students will be operational. Students are informed about their assignment before the end of the Summer Term, and the lab schedule (including when deliverables are due) is communicated to students well before the start of the Autumn Term, giving them the option to engage with the topic in advance of their third year of study. In term time, students have time tabled sessions for lab briefing, literature search, planning, equipment familiarisation, training, experimental work, and write up. Planning, literature search and write up can be carried out on locations on or off campus at the students' discretion. For all other scheduled sessions attendance on campus is mandatory. Typically, 9 out of 11 experiments on offer are in use simultaneously during term time, with a total of approximately 36 students present in the lab at a time. GTAs train the students on the equipment and are present for the first and last half hour of each lab session. The module leader or lab supervisor is in attendance throughout the lab session and guides students if they require assistance in the absence of GTAs. Equipment operation and experimental work is fairly complex, providing students with a first-hand impression of real world research which requires teamwork to achieve its objectives.

Each project has to be completed in seven weeks (**Figure 2**). The preparation stage spans over the first two weeks, followed by two weeks of experiments and finally three more weeks for report writing and interview. The whole process intends to replicate what a real life practical project would be like, albeit at a compressed timescale and with a guaranteed positive outcome. At the beginning of Week 1, students are briefed by the module leader and the individual academic supervisor about the expectations of this module and their specific topic. Teaching assistants show students the materials and equipment available for each group, so that they can realistically plan their experiments. Students then work on the pre-laboratory class deliverables, which include an experimental plan, a thorough risk assessment for the proposed experiments and a focused literature search on the relevant subject areas. In the experimental plan, the objectives, actions and personnel involved in each activity must be specified clearly. Students receive feedback about their pre-laboratory deliverables from the academic supervisor at the beginning of week 2, so that they can make changes before finalising these documents by the end of that week after having received training on experimental equipment. During weeks 3 and 4, students spend a total of 24 hours conducting the experiments under the direct supervision of teaching assistants. The academic supervisor meets the students three times to discuss their progress ("Design-Analysis-Evaluation Cycle" in **Table 2**), in order to ensure that the investigation proceeds in the right direction. In weeks 5 and 6, students write a report that summarises their findings based on the experimental data, and perform self and peer assessment in order to gauge the contribution of individuals towards this group project. In the last week of the course, students are interviewed by the academic supervisor about their report and complete the learning cycle by receiving constructive feedback on their performance.

Table 2 Module deliverables and corresponding marks weighting

	Deliverable	Weighting	Assessment Method
1	Literature search/ preparation work (group)	10 %	Assessed in terms of: • Breadth/depth of search • Appropriate search terms used • Selectivity • Clear and concise summary of key references (~5) • Used to inform planning
2	Work plan (group)	10 %	Final work plan assessed in terms of: • Good use of resources (people and equipment) • Suitably challenging/realistic • Clearly presented • Sufficiently detailed • Includes key tasks and interim deadlines • Responsive (tracked changes)
3	Lab book (individual)	0 %	Not formally assessed. Used to provide supporting evidence for other deliverables.
4	Design-Analysis-Evaluation Cycle (group)	20 %	Assessed in terms of the progress made by the groups with respect to the experimental plan.
5	Industrial report or journal article (group)	30 %	Assessed in terms of: • Overall presentation of the findings • Quality of the solutions/answers to the research problem • Innovativeness of the research problem and its solutions/answers
6	Short interview/ feedback (individual)	10 %	Individual marks awarded for: • Clarity of explanation • Background subject knowledge (depth and breadth) • Understanding of experimental procedure and data analysis • Understanding of implications of result
7	Transferrable skills (individual)	10 %	Peer and self-assessment.
8	Risk assessment (group)	0 %	Checked by academic supervisor. Must be signed off before practical work starts.
9	Safe working (individual)	10 %	Overall mark awarded by teaching fellow based on the behaviours noted by teaching assistants. Assessed in terms of: • Safety • Cleanliness and tidiness
10	Practical skills (individual)		

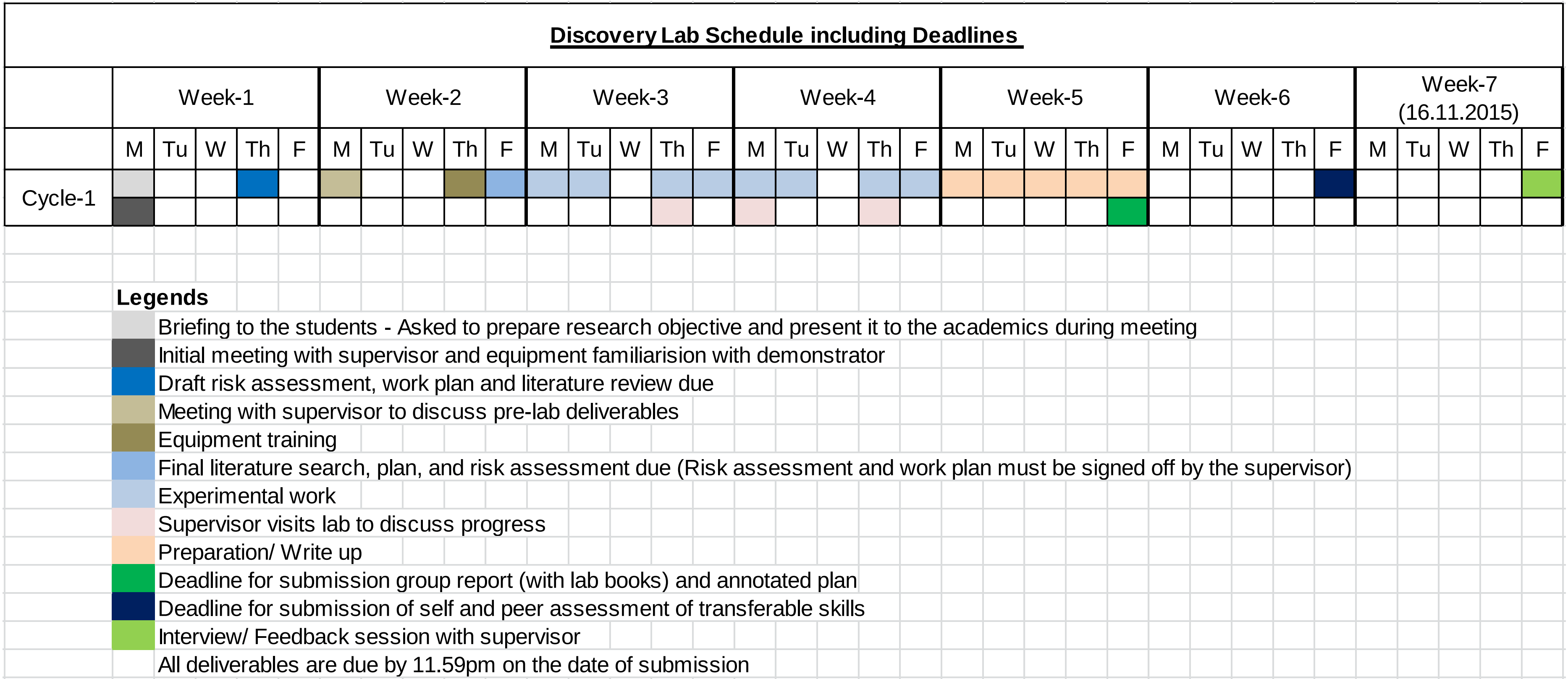

Figure 2 Timeline of the module

3. Theory

3.1 Pedagogical framework

The pedagogical design of this course is based on the Experiential Learning Theory (ELT) of David Kolb, which states that "learning is best conceived as a process, not in terms of outcomes" (Kolb and Kolb, 2005). This proposition of learning determines the assessment of students (**Table 2**), which has a distributed weightage over the entire learning process instead of just assessing the final report alone. For instance, the preparation for experiments (**Item 1 and 2 in Table 2**) accounts for 20% of the overall mark, whereas the execution of experiments (**Item 4, 7, 9 and 10 in Table 2**) accounts for 40% and the final report and interview (**Item 5 and 6 in Table 2**) account for the remaining 40%. This framework is explained to students up front, so that they know exactly what to expect.

With such a format, the assessment aims to evaluate the performance of students in Kolb's Experiential Learning Cycle (**Figure 3**), which consists of abstract conceptualisation, active experimentation, concrete experience and reflective observation. The preparation stage is where students engage with abstract conceptualisation: they are given information about the system they are assigned to and think about what to achieve and how to tackle foreseeable technical challenges. The execution of experiments allows students to go through the learning cycle several times. This means through active experimentation, students obtain concrete experience of the various aspects of the process (e.g. safety, operation and control of system, data collection and analysis etc.) from the perspective of a practising engineer. To further enhance their understanding, students also perform reflective observation of the process and summarise their learning in abstract conceptualisation.

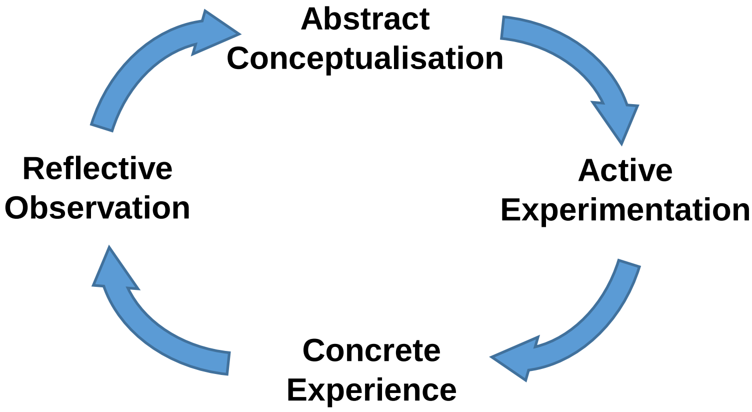

Figure 3 Kolb's Experiential Learning Cycle

The Design-Analysis-Evaluation Cycle (**Item 4 in Table 2**) captures this learning process effectively, as students have to write down:

1) experiments completed,

2) key findings from these experiments,

3) issues/risks identified, and

4) actions to be taken in response to 2) and 3).

The Design-Analysis-Evaluation Cycle is performed by the students every two days (i.e. three times in total during the two weeks of experiment) and assessed by the academic supervisor. Finally, the students' learning cycle is completed by returning to abstract conceptualisation when they compile the report and discuss their work in the interview and feedback session.

3.2 Laboratory Implementation

For each project in the Discovery Laboratory, the teaching is delivered by an academic supervisor and a teaching assistant. The academic supervisor oversees the entire project thus ensuring students are on the right track to achieve the learning outcomes. The teaching assistant is in charge of supervising students during the laboratory sessions, monitoring student safety and proper use of the equipment. To enhance student learning, the academic supervisor and teaching assistant act as the experiential educators (Kolb et al., 2014). By playing different roles in the Educator Role Profile (**Figure 4**) interchangeably, they match the teaching styles with the learning styles of students to facilitate the learning process. Being the expert in the relevant subject matter, the academic supervisor mainly serves as the subject expert and facilitator. The teaching assistant is a PhD candidate doing research in a relevant or related subject matter. As such, he/she mainly acts as the coach and standard-setter, giving students more action-oriented advice during the planning and execution of their experiments. For instance, when the teaching assistant demonstrates how to operate a certain piece of equipment, he/she can introduce standard working practices including practical tips and tricks based on personal experience. In addition, when students encounter issues during their experiments, the teaching assistant serves as the first point of contact and provides guidance on how to overcome them.

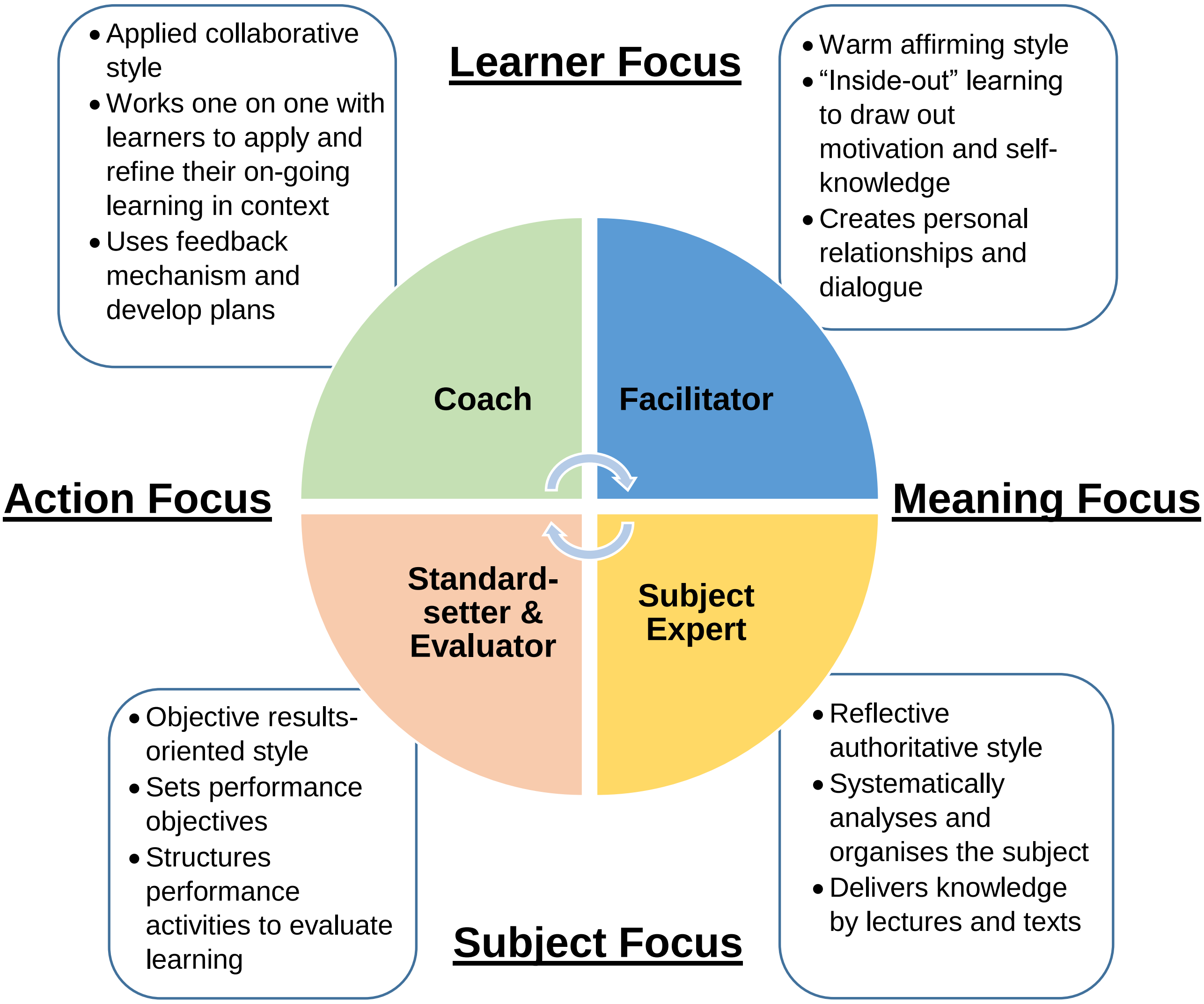

Figure 4 Kolb's Educator Role Profile (adapted from Kolb et al., 2014).

3.3 Assessment of Learning Outcome

This project incorporates both summative and formative assessments in order to enhance student learning. The summative assessment is designed to assess the level of subject mastery by the students at different stages of the project. As shown in **Table 2**, it consists of literature search, work plan, report and a short interview, attributing to 60% of the total marks. All summative assessments are conducted by the academic supervisor in a fair and transparent manner. Assessment methods and criteria are made available to students at the beginning of the project, as suggested in the Standards and Guidelines for Quality Assurance in the European Higher Education Area (European Association for Quality Assurance in Higher Education (ENQA) et al., 2015).

It is widely agreed by students that traditional summative assessments such as written examinations tend to encourage or even force students to learn for the sake of excelling in assessment only (Sambell et al., 1997). This is manifested in the typical learning pattern of students: “little learning effort for 2 or 3 months, followed by binge-learning for a couple of weeks prior to the tests” (Cilliers et al., 2012). In other words, the traditional end-point summative assessment is essentially a make-or-break opportunity for students to prove their ability and is hence responsible for such learning behaviour. The design of the summative assessment in this project took this practical consideration into account. The summative assessment is split into several components, each having specific marking guidelines geared towards assessing the quality of learning. This approach de-risks the assessment process significantly and attempts to reward deep learning, which leads to mastery of the subject. For instance, the assessment template for literature search (Supplementary material (SM-1)) lists five marking criteria in the form of questions. The first three questions assess the students’ methodology for literature search. A sound methodology should include the use of relevant keywords, appropriate databases and a clear search strategy. The next three questions assess the quality of the literature search, in order to see if students are able to focus their search, identify relevant materials to cover the topic of interest, and select key information from the literature that are useful for their projects. Each question can be answered with five alphabetical grades: ranging from A (best) to D (worst), and F (fail), which is in line with all other departmental coursework assessment schemes. Lastly, the academic supervisor can leave free text comments and constructive feedback for students to help them improve.

In order to assess the process of knowledge acquisition, formative assessments are in place and account for a significant proportion of the total mark (40%). The formative assessments are jointly conducted by the academic supervisor (**Item 4 in Table 2**) as well as the students themselves (**Item 7 in Table 2**). As shown in another study (Flores et al., 2014), assessments are perceived as a “fairer and more effective process” by the students if they are actively involved in the assessment process. Based on personal observations of the course designers, we can absolutely confirm that the three formative assessments in this project have significant and self-critical involvement of students. The Design-Analysis-Evaluation (D-A-E) Cycle is conducted at the early, middle and late stages of the experimental phase. Students have to summarise their experiments, the corresponding findings and their planned actions in a given form (Supplementary material (SM-2)) and discuss these items with the academic supervisor who supports students in their decision making. An innovative element in this assessment is the “overall project status”, where both students and academic supervisor have to put down their assessments of the progress. This allows any discrepancy between their assessments to be resolved in a timely manner and prevents escalation into a dispute. Since the teaching assistant monitors the students closely during their experiments, he/she is in the best position to assess the safe working and practical skills of students (Supplementary material (SM-3)). Discovery lab experiments run for a total of eight practical sessions. GTAs are required to observe students throughout and provide formative feedback to them for the duration of the project. They record this in the template detailed in SM-3, which allows close monitoring of progressive improvement or deterioration in the safe working and practical skills of a particular student. Lastly, self and peer assessments are conducted regularly by the students themselves, ensuring that individual contribution to the group work is properly recognised.

The Discovery Lab is a group module and students work in randomly selected groups of four individuals, where different working styles and preferences are inevitable. The experiments on offer pose unique intellectual challenges and the degree of success depends on creativity, planning, and execution skills of a team. In rare cases, this may lead to one group member being significantly less engaged than others. We try to address this up front by highlighting to students the benefits of building a universal skill set which can be applied to any post-graduation career path, not just research. Formative feedback sessions with the academic supervisors to discuss literature search, experimental plan and the D-A-E cycle as well as observations through GTAs provide regular opportunities to gauge team dynamics, identify potential passengers and take corrective action. As stated above, peer observation is also a part of the assessment scheme and provides a last resort for the assessor to balance individual marks according to individual contribution.

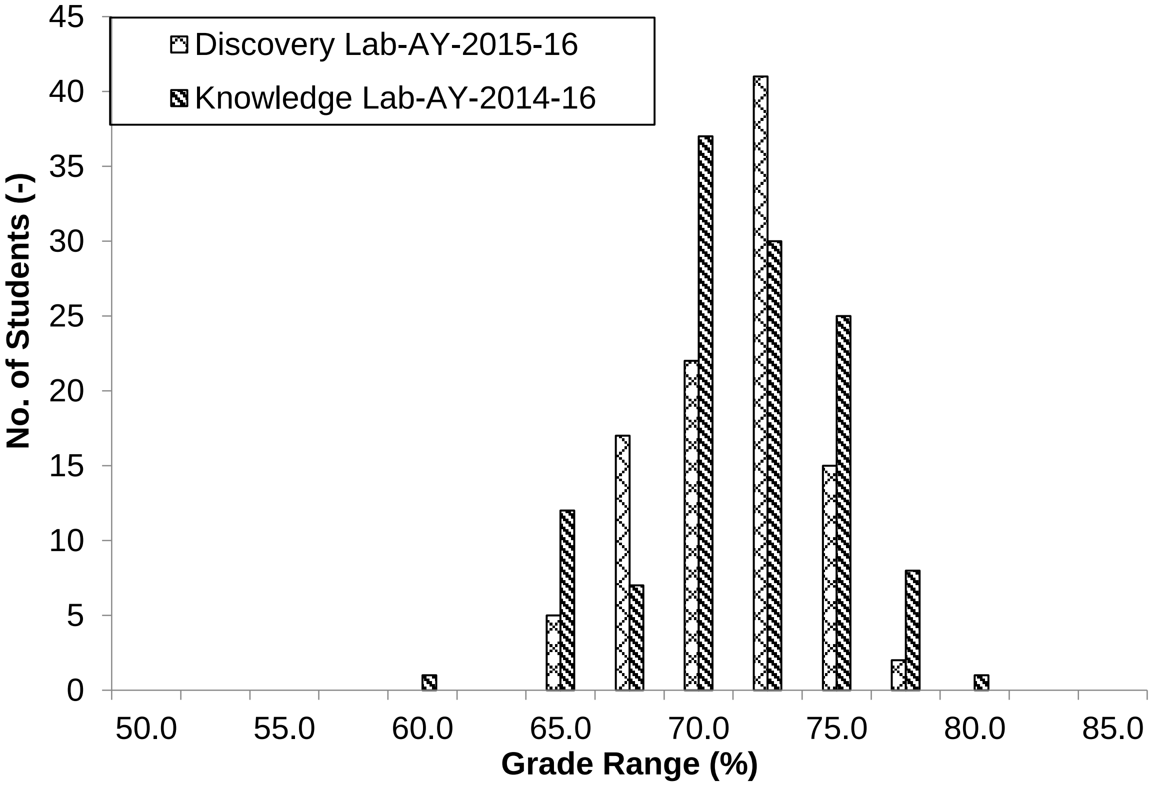

Figure 5 Comparison of marks distribution between Knowledge and Discovery Labs

The assessment scheme for the Discovery Lab has been designed to assess a broad range of skill sets required for developing students into early stage researchers. Consequently, it is highly discrete, which has the inherent risk of causing a too narrow marks distribution. However, as can be seen from

Figure 5, this is not the case here. In fact, the distribution of marks for Knowledge and Discovery Lab for the same cohort of students using different group sizes and assessment schemes is broadly similar.

4. Results and Discussion

4.1 Feedback from Students

For quality assurance, students' feedback is gathered after the course through Imperial College's central Student Online Evaluation (SOLE) tool. It is college wide practise to obtain constructive feedback from students on each course module as well as its lecturer(s). SOLE is an anonymous survey that gauges students' satisfaction about the various aspects of the course. Quantitative data and textural comments from SOLE are evaluated every year and results are discussed with student year representatives and departmental staff. Changes are then made according to this feedback in order to improve the quality of the module.

For evaluating the design and delivery quality of a module, SOLE offers four statements related to four different performance attributes as follows:

1) The module is well structured (Structure).
2) The content of the module is intellectually stimulating (Interest).
3) Where applicable; I have received helpful feedback on my work submitted so far (Feedback).
4) Overall, I am satisfied with the quality of module (Quality).

Each statement has six answering options, "definitely agree", "mostly agree", "neutral", "mostly disagree", "definitely disagree", and "not applicable". In addition to these multiple choice answers, students are allowed to provide free text comments, highlighting what has worked well for the course and where it can be improved.

SOLE results obtained over the span of successive years have been used as quantitative and qualitative measures to assess the effectiveness of the module. For the purpose of comparison, **Figure 6** shows the survey results for the Foundation, Knowledge and Discovery Laboratories taken by the same cohort of students in the academic year of 2013 to 2015. In general, the Discovery Laboratory has significantly better feedback than the other two modules, especially the percentage of students who were in the “definitely agree” category. For example, the percentage of students who “definitely agreed” that the module was intellectually stimulating increased significantly from 20% for both the Foundation and Knowledge Laboratories to 44% for the Discovery Laboratory. As students have more independence in the Discovery Laboratory rather than following instructions most of the time in the other two modules, this survey result shows that they indeed have to think deeply about the different aspects of the research process and then make sound decisions accordingly. Similarly, the percentage of students who “definitely agreed” that they received helpful feedback increased from 15% and 17% for the Foundation and Knowledge Laboratories to 60% for the Discovery Laboratory. This indicates that the feedback system in place (especially during the Design-Analysis-Evaluation Cycle) worked effectively.

Foundation, Knowledge, and Discovery Labs are all led by the same module leader. The module leader conducts lab briefings, details module outlines, prepares assessment templates, and communicates them to students. All experiments for Foundation, Knowledge, and Discovery Lab are demonstrated by GTAs. For each course, more than seven GTAs are involved in direct student instruction. For the Discovery Lab, nine academic staff act as project supervisors for the different experiments and these have remained more or less the same for consecutive years. Students’ opinion on individual lecturers / staff may influence their responses, which could cause a survey spike. However, such individual effects are normalised in the survey when inviting comments on the overall quality of the module. As students progress through a degree programme they may also engage better with advanced courses due to increased maturity, which can result in an increase in survey ratings for senior modules. Following this logic, the Knowledge Lab module should have better overall student satisfaction compared to the Foundation Lab. However, this does not seem to be the case if we consider the “definitely agree” category in **Figure 6.** Any of the four survey questions do not seem to result in statistically significant differences between Foundation and Knowledge Lab. Significant differences observed in the survey between Foundation, Knowledge and Discovery Lab are, therefore, not due to the students’ better overall engagement with the chemical engineering programme as they progress through their degree. The evidence strongly suggests that the positive trend from Foundation/

Knowledge Lab to Discovery Lab is a direct result of the innovative teaching approaches employed in this study, which is further borne out by contextual comments from the students themselves, such as:

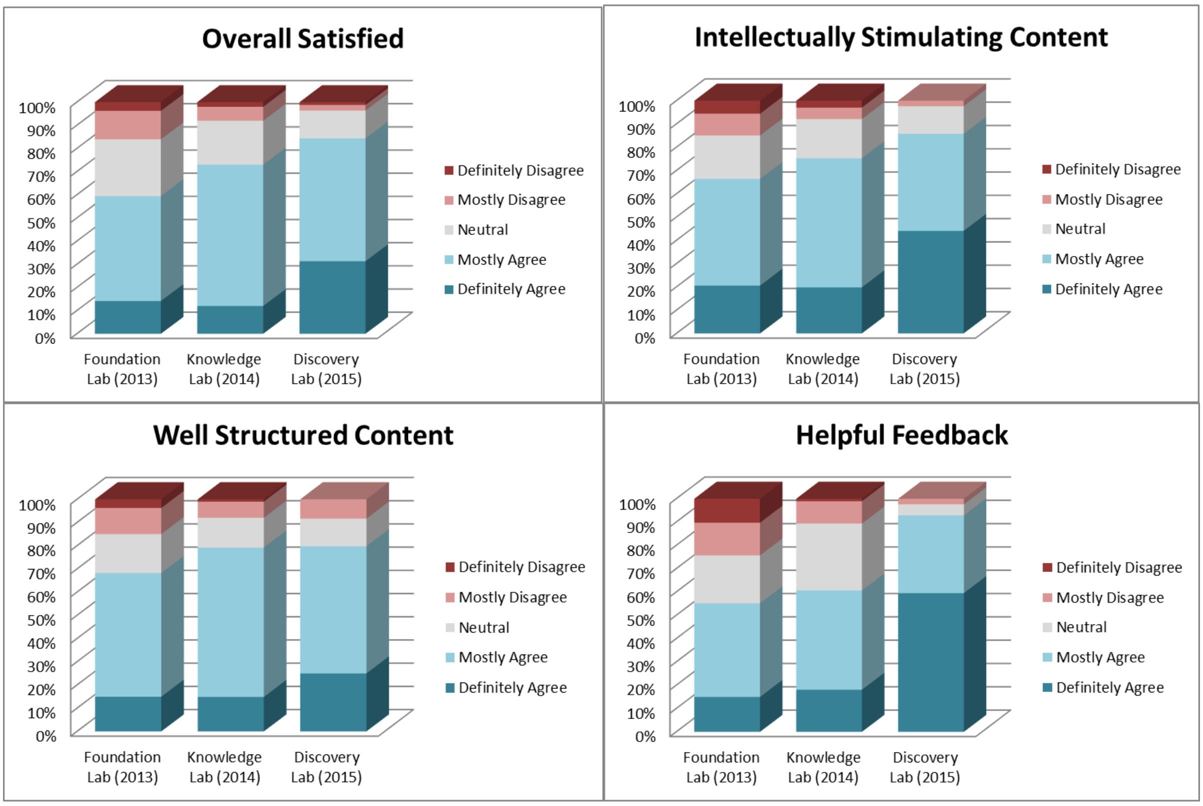

Figure 6 Survey results for the Foundation, Knowledge and Discovery Laboratories taken by the same cohort of students (academic year 2013 – 2015)

"*the carbon capture pilot plant option for discovery labs should become a permanent fixture. It was the best experiment/project I have done to date. I really enjoyed the whole experience, despite how much work it was.*"

Analysis of survey data across cohorts from 2013 to 2015 (**Figure 7**) shows that the overall satisfaction has increased from 61% in 2013 to 83% in 2014 and 2015, while most of the students (>80%) have consistently found the module intellectually stimulating. The data for well-structured content fluctuates slightly, because this depends on how well a group of students meets the expectations of their academic supervisor, given the open-ended nature of the module. The key to a positive outcome is to have these students reach agreement with their academic supervisor at the very beginning of the module, so that they can have a definite goal and a clearly structured experimental plan. Otherwise, the investigation would be heading in less fruitful directions with the need to change course regularly, which causes students to perceive the module as less well-structured. Changes in the module structure following suggestions from students and teachers have also been received differently by the separate cohorts. For example, it was found that changes made in the module structure for AY-2014-15 in response to students requests were well received resulting in approx. 25% more students agreeing that the module has a well-structured content. In the same review, students also asked for a greater degree of freedom for their explorations. In the following year, students were given this when defining their research questions, in the selection of characterisation techniques and different test compounds (subject to approval after risk assessment). Although these changes resulted in a higher number of students agreeing with the module being intellectually stimulating, it caused a 5% reduction in number of students agreeing with the module being well structured, which readily illustrates the general interdependence of structure and freedom: you can have the one only at the expense of the other. In terms of feedback, academic supervisors provide timely and clear feedback to students throughout the module. This is not easy to achieve and does put strain on the teaching staff due to the high frequency of feedback. Students, however, appreciate this obvious commitment to quality which is reflected in the percentage increase of students who agree that they "*have received helpful feedback*".

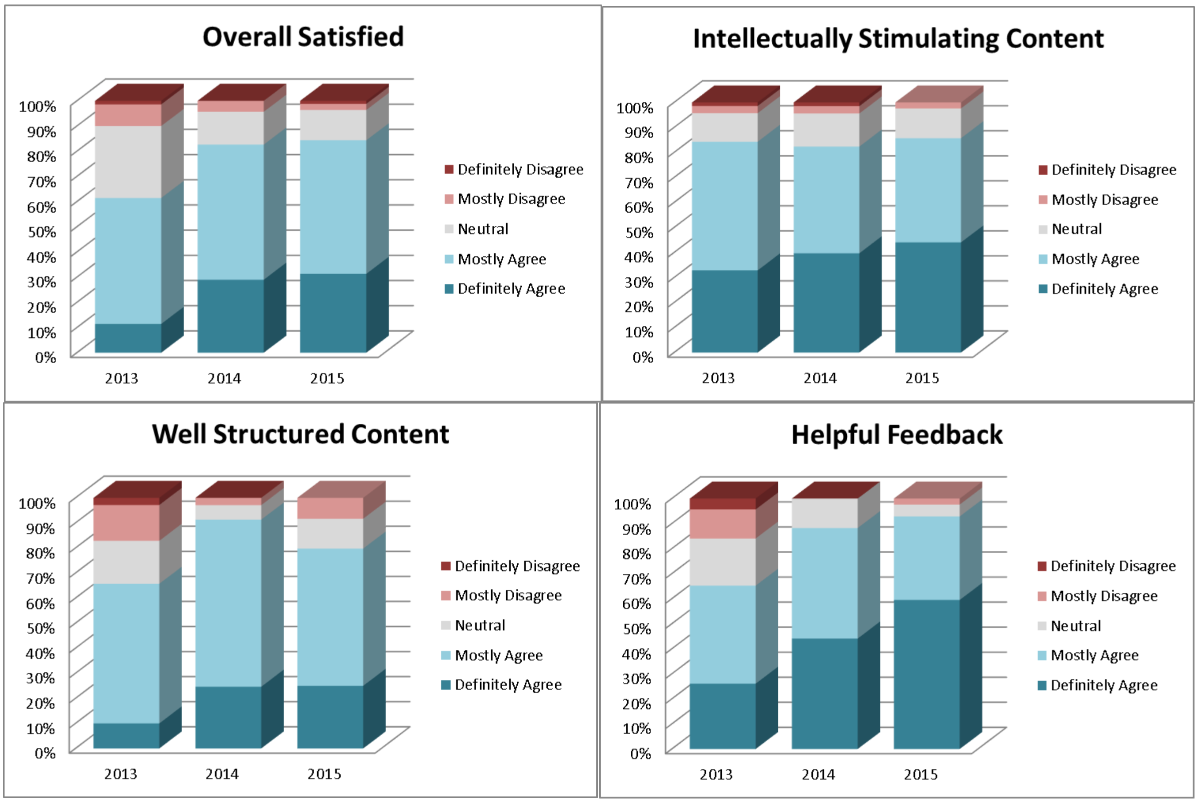

Figure 7 Survey results for the Discovery Laboratory (academic year 2013 – 2015)

According to the free text comments captured by the last section of the survey, students strongly welcome the idea of being given freedom to decide what to investigate, as well as dedicating time and resources to explore one subject matter in depth. Students also like the flavour of the research project style where the learner is in charge and allowed to make key decisions about their learning. A sample of contextual comments, which reflect positive student opinion, is given below:

1) "*We are able to experience what true research would be like*"; "*It has real industrial relevance*"
2) "*We were stretched and pushed*"; "*This project provided us opportunity to produce work of a standard worth publishing*"
3) "*This was something never done before*"; "*It was the best project I have done to the date*"
4) "*Continues to build on the softer skills students require for future careers*"; "*Extremely useful experience*"

In terms of the execution of teaching, many comments praise the quality of feedback provided by the teaching assistants and academic supervisors who, as mentioned earlier in this article, are experts in the relevant subjects:

1) "*The feedback of this course is good and very efficient*"
2) "*The level of feedback is excellent*"
3) "*Feedback on our work was efficient and concise*"

Equally importantly, the last part of the survey is also able to capture the comments of students who are dissatisfied with the course. None of the negative feedback contradicted the positive comments mentioned above. Instead, they were mostly about perceived differences in teaching styles and hence offered some useful insights on this aspect:

1) "*In order to avoid confusion, the teaching assistant should always maintain a good communication with the academic supervisor, so that they stay in line with each other when giving feedback to students.*"
2) "*The teaching assistant and academic supervisor should make a clear point that the students should be aware of the time limit when planning the experiments.*"
3) "*The academic supervisors should try to establish a consensus among themselves for the expected quality of students' works in order to make the marking fairer.*"

In addition to the university wide SOLE survey, the module leader also organises regular After Action Reviews (AAR) for the Discovery Lab, involving academic supervisors, teaching assistants and student representatives. All critical aspects of the SOLE textural comments are discussed as are any potential changes to be implemented in future years as a response. Minutes of the AAR are circulated to all relevant academics and student representatives, and changes to the module are communicated to the next cohort in a briefing at the beginning of term.

Constructive comments have been consistently incorporated into developing the structure of this module, which is reflected in the survey findings described above. For example, in 2014 students raised an issue about the fact that they were assigned to projects that they had little interest in. This was corrected in the following academic year, where a new project assignment programme was put in place to give priority to students who take other courses that are relevant to the experiment that they choose: a student who takes the membrane technology lecture course is more likely to get the membrane project in the Discovery Laboratory if he/she puts this project high in his/her preference list. With this valuable cycle of improvement in place, the Discovery Laboratory course will continue to evolve to support the students' experiential learning in the chemical engineering discipline at Imperial College.

5. Conclusions

The Discovery Laboratory module adopts the problem-based learning approach, where students are given a high level of freedom to explore the application of various technologies which are relevant to chemical engineering practice. With a specific set of research and industrial grade equipment assigned to them, students can define their own research goals and conduct experiments under the supervision of academic supervisors and teaching assistants who have in-depth knowledge of the subject matter. A total of eleven projects are available, covering a wide range of industrially relevant technologies. The course is designed based on the experiential learning theory of David Kolb and carefully executed by incorporating both summative and formative assessments. Feedback from students is collected through an anonymous survey after the course, helping the course designers to improve the quality of teaching based on the students' experience. Based on the survey results of the academic year 2014/2015, an overwhelming majority of students (81.2 % - 91.3 %) were satisfied with different aspects of the course. It was explicitly stated that they enjoyed the freedom to conduct their own research and the support given by academic supervisors and teaching assistants. This shows that the course framework is able to deliver the intended outcomes of the course, which is to support student-centred experiential learning.

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Supplementary Materials

SM1

Department of Chemical Engineering

UG Teaching Lab

Discovery Lab

Assessment Template for Literature Search – AY – 2015 – 16

Names:	Group:
Experiment title:	
Assessor's initials:	Date:

Criteria	**Alphabetical Grade**
Sources - Literature search covers a sufficiently wide range of sources (e.g. library, databases, journals)	
Relevance - Relevant material selected and irrelevant material is rejected	
Understanding - Selected literature demonstrates a clear understanding of the background knowledge relevant to the investigation	
Critical Evaluation - The selected literature critically evaluated regards usefulness for the chosen investigation	
Identify Scope - Knowledge gaps in the current literature / scope for the investigation correctly identified	

Comments and Constructive Feedback

Discovery Lab Literature Search Marking Criteria

70% and Above - Grade A

The student demonstrates excellent scientific understanding and enthusiasm for the subject area. The student shows real flair, well above average. There is evidence of substantial background search of the literature and thorough understanding of prior work. Summary of the searched literature present critical review and identify any knowledge gap in the current literature. From the literatures searched highlight of the ones which are most relevant or must read for the readers is provided.

For a mark in this category, the literature review must give evidence of ability to identify most relevant publications in the subject area, and a critical, insightful discussion leading to the identification of knowledge gap in the summary presented.

60-69% - Grade B

The literature search demonstrates a clear grasp of the relevant background knowledge of the experiment. Referred relevant publications in the subject area and reported critical review of the searched literature.

To confirm a mark in this category, the assessors will require the identification of relevant literature and critical review.

50-59% - Grade C

The student demonstrates knowledge of basic concepts involved with the experiment and this is reflected in literature searched. Identify literature and provide summary of literature searched. Literature searched is not limited to the text books or few journal articles which may have been pointed out by the contact academics or demonstrators; however, review generally lacks structure or provides no critical review.

Literature search is lacking in logical structure or of a poor quality. Merely reporting what is stated in the abstracts of the literature searched (and not critical review) will usually fall into this category.

40-49% - Grade D

Literature searched is not directly relevant to the experiment and demonstrates no or poor understanding of the aims and objectives of the experiment. Scope of literature search is limited and provide literature summary without organised structure or logical flow.

Literature search is barely of degree standard.

<40% - Grade F

The literature referred is inadequate and no summary presented. There may be many serious errors. Work is not up to degree standard.

SM2

Discovery Labs Progress Summary

Project name:____ Project team: Cycle ____ Group ____

Date: / /2015 Lab session: ____of 8 Supervisor: ______________________

1) Experiments/ analysis completed (since previous progress summary)

-
-
-

2) Key findings – What have you learned/ discovered? Is it supported by evidence in the lab book and analysed data?

-
-
-

3) Issues/ risks indentified

-
-
-

4) Action points – What have you decided to do in response to sections 2 and 3?

-
-
-

5) Points arising from discussion with academic

-
-
-

Overall project status

STUDENTS			SUPERVISOR
☐	Green -	Good progress	☐
☐	Amber -	Adequate progress	☐
☐	Red -	Limited progress	☐

Date discussed: / /2015 Signed (Supervisor):

UG Teaching Lab

Discovery Lab

Design-Analysis-Evaluation Cycle Marking Criteria – AY – 2015 – 16

70% and Above - Grade A

Original work carried out/ proposed, Develops own models/ correlations, Comments on implications of findings, Unusual/ unexpected results followed up, Uses ongoing evaluation to improve experiment design, Comments on the scientific significance of experimental evidence/s, Scientifically justifies choices and recommendations, Critically evaluate data to make predictions.

For a mark in this category, students must demonstrates critical thinking and creative problem solving skills in design of experiments, continuous evaluation of experimental results, and successfully manoeuvring the experimental design in sync with the analysed results to address research questions.

60-69% - Grade B

Design experiments to address research questions. Processes data as it is being collected. Repeats measurements/ makes additional measurements/ reduces measurements as informed by ongoing data processing, Implements changes in original experimental plan to address research questions, Put an effort to provide scientific explanation to any results obtained correlating trends with theories or published literature.

To confirm a mark in this category, students must demonstrate experimental design aiming to address research questions, continuous processing of data yielded, and logical alternation of experimental plan.

50-59% - Grade C

Uses manuals, equipment specs to write a detailed procedure, Notes all changes to the procedure, Selects a suitable range and frequency of data points, States conclusions based on a reasonable interpretation of the data, Compares results to those in the literature/ theoretical values, Explain results providing scientific rationale

To confirm marks in this category, students must demonstrate ability to design experiments, operate equipments following instructions from equipment manual, collect appropriate data, and calculate necessary derived quantities, and identify trends in the derived quantities to comment.

40-49% - Grade D

Follows prescribed procedure. Processes data after experimental work has been completed, Identifies major weaknesses and limitations, Recommends further work to be carried out.
Design of experiment, evaluation or results, analysis is barely of degree standard.

<40% - Grade F

The design of experiment is seriously flawed; have difficulty operating equipments or follow operating instruction from the equipment manual, identified inappropriate variables for data collection. There may be many serious errors. Work is not up to degree standard.

SM3

Discovery Lab Safe Working and Practical Skills Proforma

Student ____________________ Demo _____________________

/ /2015	/ /2015	/ /2015	/ /2015	
☐	☐	☐	☐	Followed the lab code of practice
☐	☐	☐	☐	Gloves not removed after handling chemicals
☐	☐	☐	☐	Reminder to wear PPE required
☐	☐	☐	☐	Unsure of experiment specific risks/precautions without refering to risk assessment
☐	☐	☐	☐	Required considerable support to carry out risk assessment
☐	☐	☐	☐	Took necessary precautions to minimise risks
☐	☐	☐	☐	Recorded safety checks
☐	☐	☐	☐	Identified a hazard in the lab and took appropriate action
☐	☐	☐	☐	Checked stocks and informed demonstrator in good time to order more
☐	☐	☐	☐	Gave proper notification of any equipment left running
☐	☐	☐	☐	Used minimum chemicals/ disposables
☐	☐	☐	☐	Separated and minimised waste
☐	☐	☐	☐	Returned equipment/chemicals at the end of the session
☐	☐	☐	☐	Left work area untidy/ contaminated at the end of the lab session
☐	☐	☐	☐	Reminder to clear up was required
☐	☐	☐	☐	Equipment thoroughly cleaned and made ready for the next group
☐	☐	☐	☐	Spilled chemicals
☐	☐	☐	☐	Caused flooding/ damaged equipment
☐	☐	☐	☐	Cleaned up any spills/ breakages immediately using appropriate method
☐	☐	☐	☐	Disposed of waste correctly
☐	☐	☐	☐	Disposed of waste incorrectly (eg solvent waste down the drain)
☐	☐	☐	☐	Kept their lab bench tidy
☐	☐	☐	☐	Labelled samples and dispensed chemicals
☐	☐	☐	☐	Samples/ dispensed chemicals not identified
☐	☐	☐	☐	Did not take necessary precautions/ worked in an unsafe manner
☐	☐	☐	☐	Relied on other students to carry out practical work
☐	☐	☐	☐	Required more demonstrator assistance than average
☐	☐	☐	☐	Asked for assistance when required
☐	☐	☐	☐	Relied on the demonstrator to tell them what to do
☐	☐	☐	☐	Interpreted and followed procedures accurately
☐	☐	☐	☐	Adapted to new circumstances
☐	☐	☐	☐	Used lab manuals effectively to troubleshoot
☐	☐	☐	☐	Could recall and apply relevant background theory/ methods from literature
☐	☐	☐	☐	Unprepared for the lab session
☐	☐	☐	☐	Familiar with the handout and operating manuals
☐	☐	☐	☐	Worked in a disorganised manner
☐	☐	☐	☐	Trained other students in how to use equipment
☐	☐	☐	☐	Good teamwork/efficient distribution of work
☐	☐	☐	☐	Used specialised equipment and carried out complex procedures independently
☐	☐	☐	☐	Modified/ built equipment/ tools (with permission)