An Evaluation and Redevelopment of Current Laboratory Practices: An In-depth Study into the Differences Between Learning and Teaching Styles

by

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A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy at the University of Tasmania

University of Tasmania

March 2016
Declaration and Statements

Declaration of Originality
This thesis contains no material which has been accepted for a degree or diploma by the University or any other institution, except by way of background information and duly acknowledged in the thesis, and to the best of my knowledge and belief no material previously published or written by another person except where due acknowledgement is made in the text of the thesis, nor does the thesis contain any material that infringes copyright.

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Statement of Ethical Conduct
The research associated with this thesis abides by the international and Australian codes on human and animal experimentation, the guidelines by the Australian Government's Office of the Gene Technology Regulator and the rulings of the Safety, Ethics and Institutional Biosafety Committees of the University.

_____________________
Reyne Pullen (2016)
Acknowledgements

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Abstract

The study described within this thesis encompassed a series of cross-sectional case studies that were completed over a number of chemistry units offered at the University of Tasmania, Australia. This investigation aimed to compare three teaching approaches applied within the chemistry-teaching laboratory; the teaching approaches chosen being Expository, Guided Inquiry, and Problem Solving. Prior to this investigation, the prevalent laboratory teaching approach at the University of Tasmania most closely resembled the Expository approach. Through comparison of these teaching approaches it was intended to explore the advantages and/or disadvantages with respect to the level of chemistry and the type of experiments considered. A broad variety of experiments were selected from units offered within foundation, first, second, and third year level chemistry units. Through modification of these pre-existing experiments, a representative version of the selected experiments for each teaching approach was produced.

To analyse these different teaching methods, three perspectives were considered. Firstly, a student and demonstrator completed survey. Secondly, a post-experimental quiz targeting the students’ understanding of the concepts and techniques within the laboratory. Finally, a demonstrator assigned grade to the students’ performance and understanding throughout the laboratory was supplied. All data collected was de-identified and voluntary, as per the ethics approval (H0012564) procedure, upon completion of each experiment. Statistical analysis of quantitative data was completed using a one-way between groups ANOVA with post-hocs tests using SPSS. Qualitative data was analysed through common themes analysis.
The intended aims of this project can be separated into local and global aims. At the local level it was intended to improve the student experience of the chemistry laboratories for both those students undertaking chemistry as their focus of study and those undertaking chemistry as an elective or prerequisite. The measures of this improvement would be an increase in the engagement and enjoyment of students, greater development of chemistry specific knowledge, and the development of a broader skill set including problem-solving skills and critical thinking.

For the global implications of this study, two outcomes are intended. Firstly, the methodologies and outcomes observed from this practical could be utilised by other institutes. Secondly, the comparison of these teaching approaches provides insight into the interactions between alternative teaching approaches and the experiments commonly used within chemistry teaching laboratories.

Analysis of the data collected throughout these study indicated that statistically significant differences were mostly limited to the perceptions of students provided through the student-completed surveys. Of interest was the finding that at the foundation chemistry level, those students who have not undertaken chemistry before university, a gradual increase of the student ownership over the course of the semester was of most benefit. The results for the first year chemistry comparison indicated however, that the teaching approaches were independently suited to different experiments with no pattern observed. The second and third year units did not result in any definitive outcomes. Of most value from this project are the methodologies used, in addition to the benefits observed for the local development of the laboratories at the University of Tasmania.
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The study presented within this dissertation was in response to an increasingly louder call, both locally and globally. This call is to more closely inspect the current teaching practices used within universities when teaching chemistry, and to redevelop these practices where appropriate. (Gabel, 1999; Anderson & Mitchener, 1993; O'Toole & Rice, 2010). One area often raised for redevelopment is the teaching laboratories, where both teaching staff and students feel the experience needs improvement (Garnett & Garnett, 1995; Johnstone & Al-Shuaili, 2001; Bopegedera, 2011).

This PhD study aimed to comparatively investigate the advantages and disadvantages of applying alternative teaching approaches over a broad variety of pre-existing experiments within the chemistry program offered at the University of Tasmania. This study used a mixed methods approach, employing quantitative and qualitative data collection and analysis, to ensure a robust statistical foundation. The overall intended outcomes of this study can be described as to:

i. broaden the understanding of the interaction between alternative teaching approaches with a variety of experiment types; and
ii. develop an optimised laboratory course incorporating the first intended outcome.

The structure of this study is detailed in Chapters 3 and 4. The foundations, both historical and current, upon which this study was based will be detailed through Chapters 1 and 2.
1.1 Historical Approaches to Education

Throughout history there have been numerous models prescribed for explaining the process of learning and developing knowledge. As time has passed, our understanding of how people learn has accelerated. This acceleration has resulted in a number of rapid changes on how we develop our understanding of the world around us. Perkinson (1984) provides a summary of how the perception of the student learning environment has shifted over the years. Three phases are proposed by Perkinson:

1. The initiation metaphor. First appearing in ancient Greece, this model was perpetuated until the nineteenth century. The initiation metaphor relies upon a content-centric education where the content offered to learners is of the most importance.

2. The transmission metaphor. Transforming the former phase, the transmission metaphor ushered in the popularity of a teacher-centric environment. Teachers were considered the holders of knowledge and would transmit or transfer the required knowledge or skills to students.

3. The growth metaphor. The third and final metaphor proposed, shifts the perception once more to a student-centric learning environment, a model that is currently in favour. The growth metaphor proposes that students construct their own knowledge based on their past knowledge and experiences.

(Adapted from Perkinson, 1984, pp. 163 - 167)

Encapsulated within each of these metaphors are a number of identified learning approaches. Contention over the appropriate learning model in a practical teaching environment is ongoing (Tobin, Tippins, & Gallard, 1994). A learning approach identified from within the transmission metaphor is Behaviourism, first coined by J. B. Watson (McInerney, & McInerney, 2010, pp. 104-108).
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Kolesnik states that the Behaviourism classroom “...is based on the assumption that teachers and school administrators are able to identify ‘minimum essentials’ of knowledge and intellectual skills which all students should acquire...” (1975, pp. 110). Kolesnik (1975) admits that while some few gifted students may learn these skills without instruction, the majority of a student cohort would struggle or not acquire these skills on their own. A major change for this model is the recognition of students’ ‘prior learning’, understanding that students do not all enter a classroom at the same level and that their education may need to be tailored for that background knowledge. The more widely accepted model in current times is Constructivism, which is encapsulated within Perkinsons (1984) growth metaphor. In this model knowledge is constructed by students, based on what learners already know and understand. An elegant discussion of Constructivism has been given by Savery and Duffy (2001). Rather than the teacher fostering learning in passive students, the students actively engage with the learning environment. This engagement takes into account not only their prior learning but also their cultural or personal views and experiences to date. In this fashion, the classroom dynamic shifts such that the student becomes the centre of the learning process and the teachers’ role is to facilitate that environment. Slunt and Giancarlo (2004) present an example of this student-centric teaching environment in addition to a number of studies into this realm.

In recognition of the strengths of Constructivism discussed above and the known diversity of students undertaking chemistry units at the tertiary level, this learning framework was chosen to underpin this study. This allowed the focus to be placed upon developing a rich environment for students to engage within. This follows the tenets of Constructivism (construction of knowledge, process, not product, multiple perspectives, situated cognition, reflexive cognition, cognitive apprenticeship, and process-based...
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Evaluation). Through these, students are enabled in constructing new knowledge from the learning experience offered in conjunction with their past experiences and stored knowledge. When looking at experiences students undertake through a bachelor’s degree in chemistry, Read (1941) suggested it possible to divide the experiences into three broad areas: the time spent having interaction with a lecturer learning content, the time spent studying and/or researching outside of university contact hours, and learning within a laboratory environment. Reviews of websites from universities at the current time reflect that this classification, at a meta-level, is still relevant (Imperial College London, 2015; University of Sydney, 2015). To simply improve all of these aspects within chemistry education would be to consider a project scope too large by far for a single research project, and involves consideration of curriculum, pedagogy and leadership (Bedgood et al. 2010). To consider one aspect however is an achievable goal to enable growth in the chemistry education field.

1.2 Education Research

In approaching research of any kind, it is important to understand and clearly identify how you intend to conduct a study. Education research itself is a term that must be defined prior to engaging with research of that nature. The American Education Research Association (AERA) define education research as:

“Education research is the scientific field of study that examines education and learning processes and the human attributes, interactions, organizations, and institutions that shape educational outcomes. Scholarship in the field seeks to describe, understand, and explain how learning takes place throughout a person’s life and how formal and informal contexts of education affect all forms of learning.”
Education research embraces the full spectrum of rigorous methods appropriate to the questions being asked and also drives the development of new tools and methods. (American Education Research Association, 2016)

In this book, “Fundamentals of Educational Research”, Anderson (2004) discusses the dominant paradigms that influence educational research. The most prevalent paradigm being the scientific method, formally known as the positivist paradigm. Anderson presents criticisms of this methodology, as the nature of this approach relies upon assigning value to observations made. This criticism arises because the observations taken, particularly those observations made about people or their intentions and interactions, can be influenced by our own perceptions or may not be observable at all. Cohen, Manion, and Morrison (2011) describe the limitations of positivism in education research as:

“Where positivism is less successful, however, is in its application to the study of human behaviour where the immense complexity of human nature and the elusive and intangible quality of social phenomena contrast strikingly with the order and regularity of the known world.” (Cohen et al., 2011, pp. 7)

Further to this, Firth-Cousins and McKimm (2012) state:

“Educational research draws largely from the social sciences in its approach, research methods and interpretation of results, and may involve a shift in perspective from the seeking of irrefutable ‘facts’ and universal ‘truths’, to offering new insights, acknowledging the subjectivity of researchers, the impact of the research process itself on subjects and outcomes, and the agency of the subjects of the research.” (Firth-Cousins & McKimm, 2012, pp. 3)

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In this book "Introduction to Educational Research", Charles (1988) discussed the various types of educational research conducted. These included historical, descriptive, correlational, causal-comparative, experimental, and research and development. When placing this within the context of this study, a mixed approach combining two of the described types has been applied. Specifically these are experimental and 'research and development'. Experimental research is defined as being focused upon cause-effect relationships in situations where manipulation of one or more variables is possible (Charles, 1988, pp.11-12). This is achieved in this research through manipulation of the teaching approach used for each laboratory exercise. The effects of these changes have been examined in a number of areas of interest, including student perceptions, student understanding, and student performance. In this manner, the overall comparative study would fall within an experimental research type. Considering each teaching approach implementation individually, it is possible to see alignment with the research and development type. Charles (1988) describes the nature of the research and development type as being one where the outcome of a study leads to the generation of a new or improved product. In this PhD project, each laboratory exercise underwent a development phase to modify or build a new experiment to study. Following this, an evaluation of this change was undertaken using instruments to measure the value of each teaching approach and its transferability to outside environments.

1.3 Laboratory Education

Laboratory education is one of the founding pillars of chemistry teaching at universities (Garnett and Garnett, 1995). However, it has been continually evolving over the years (Pickering, 1993). One of the earliest examples of education taking place, specifically in a laboratory, is Liebig's laboratory dating back to 1820 (Pickering, 1993). In the years since...
Chapter 1 – Introduction

Liebig's laboratory, however, there has been an increasing amount of attention on the teaching laboratory and its relevance, or lack thereof, to the overall education of a student (Wellington, 1989). A review by Garnett and Garnett (1995) extensively details the concerns of a number of studies on the chemistry teaching laboratory.

Research into the teaching laboratory has been an ongoing topic of interest for a considerable part of the 20th century. For example, Hunt (1935) discusses the use of demonstrations to a class as opposed to laboratory exercises. The outcome of this study indicated that the greatest benefit for this change lies in economical savings for both cost and time, with no observable changes for the quality of learning. A review by Reid and Shah (2006) details some contrasting studies arguing the benefits of including laboratory courses within chemistry programs. Reid and Shah concluded from this review that the benefits of including an efficient and effective laboratory course outweighed the costs. Hofstein (2004) published findings from 30 years of research into the chemistry teaching laboratory. Within these findings it becomes apparent as to why there is so much discourse on this topic. The research uncovers a diverse range of variables involved in teaching within a laboratory. Furthermore, both commonly known and less well-known teaching practices that can be implemented are identified. Depending on the approach taken to develop the laboratory, considerable shifts in the economical factors involved can occur. In an ideal world, time, cost and resources would not be an issue with which to deal. Realistically however, whether due to institutional pressures or simply the limitations of the environment being worked in, laboratory courses can be compromised for their teaching quality to accommodate this (Lagowski 2002).

Given the broad nature of laboratory education, there are many avenues through which research could be directed to improve or alter the experience. Some of these include, but are certainly not limited to:
Chapter 1 – Introduction

- Changing the experiment itself;
- Changing the focus of the experiment;
- Shifting the laboratory to be more accessible to distance or disadvantaged students through use of remote laboratories;
- Altering the teaching approach framework within which the experiment is placed; and
- Mimicry of an authentic or real world research environment.

A review published by Domin (1999) looked at the most commonly observed teaching approaches documented in chemistry education research to that date. Of the research considered within this review, four overarching teaching approaches were identified: Expository, Inquiry, Discovery, and Problem Based. Domin notes one of the reasons behind this review was to counteract the rising volume of critiques leveled towards the Expository teaching approach. To clarify, Expository is more colloquially referred to as ‘recipe-style teaching’ (Hunter, Wardell, & Wilkins 2000; Seery, McDonnell, & O’Connor, 2007) or ‘spoon-feeding’ (Ellis & Allan 2010) laboratories, both of which have associated negative connotations.

Lagowski (1990, pp. 541) discusses the evolution of this particular teaching approach as a means to “consume minimal resources whether these be time, space, equipment, or personnel”. Throughout Domin’s review one of the key themes was the importance of recognizing that all teaching approaches have advantages and disadvantages. For example, as Lagowski (1990) discussed, Expository as a teaching approach is beneficial in terms of working within limited resources, as opposed to an open-ended experience that may require considerable economical and logistical support. In contrast, Hutchings (2006) gives weight to the strength of exploratory teaching approaches such as inquiry or problem-based learning.
when developing creative and critical thinking skills. Table 1 below outlines the descriptors separating the four teaching approaches Domin (1999) classified.

<table>
<thead>
<tr>
<th>Style</th>
<th>Descriptor</th>
<th>Procedure</th>
<th>Outcome</th>
<th>Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expository</td>
<td>Predetermined</td>
<td>Deductive</td>
<td>Given</td>
<td></td>
</tr>
<tr>
<td>Inquiry</td>
<td>Undetermined</td>
<td>Inductive</td>
<td>Student generated</td>
<td></td>
</tr>
<tr>
<td>Discovery</td>
<td>Predetermined</td>
<td>Inductive</td>
<td>Given</td>
<td></td>
</tr>
<tr>
<td>Problem-based</td>
<td>Predetermined</td>
<td>Deductive</td>
<td>Student generated</td>
<td></td>
</tr>
</tbody>
</table>

*Domin (1999, pp. 543)

Considering the descriptors Domin provides, it can be seen that Expository, where in all three areas the teacher generates the structure, could be most closely linked with earlier models of learning theory such as behaviourism. This focus on the teacher being the sole constructor simplifies the volume of work required of students, and as previously mentioned, minimises the resources required. As we progress through Table 1 we can see a gradual shift however, from the teacher generating the framework to a joint effort between teacher and student to solve both predetermined and undetermined outcomes. A more in-depth discussion of these advantages and disadvantages can be found in Chapter 2.

1.4 Systematic Review

Using the review published by Domin (1999) as a foundation, a systematic review was undertaken as part of this doctorate. Firth-Cousins and McKimm (2012) provide a concise description of the purpose of a systematic review:

"Systemic [Systematic] literature reviews are another educational research activity. These may be carried out as part of ongoing research to inform the research process..."
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...continued from previous page...

A total of 40 papers were selected from the body of research published between 1999 (post Domin 1999) and 2014. The conditions that each paper must abide by describe a study where research had been conducted upon a chemistry teaching laboratory. The selection of papers encompassed a number of journals including but not limited to: Journal of Chemical Education; Chemistry Education Research and Practice; International Journal of Science Education; and Studies in Higher Education; and regional areas of the United States of America; Ireland; France; Australia; Taiwan; Germany; Sweden; and Canada. The selection of papers to include in this systematic review was undertaken by selecting a broad range of journals (both prolific and otherwise) before searching for key words. These key words included: teaching methods, laboratory, problem solving, guided inquiry, expository, recipe, and experiments. Papers were then selected if the conditions above were met.

The distribution of publication dates for the selected papers is displayed within Figure 1. Excepting the year 2001, there were representations from all 15 years with a comparable number of publications. The year 2007 was an exception to this with a large number, 11 in...
Chapter 1 – Introduction

Total of publications in comparison to other years, responsible for over 25% of the sample group. No clear explanation for this increase in publications was found and was attributed to coincidence.

Figure 1. Number of publications in each year from within the sample of papers selected for this systematic review.

A focus for the review of the selected papers was on the quality of the methodology, findings, and conclusions. This required the adoption or development of a method of evaluation that had the highest degree of objectivity and repeatability. As such, it was decided to adapt the grading instrument used within Kennelley (2010) given the alignment between the instruments intended outcomes and the desired outcomes there. This instrument was developed to measure the quality and evidence of qualitative/quantitative/mixed-methods studies in a similar systematic review. As part of this study, several of Kennelley's questions were modified to shift the focus to give insight into the quality of the methodology, regardless of whether the data collected was quantitative, qualitative, or a mixed-methods approach. Kennelley's instrument was designed to provide an evaluation of quality and evidence...
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Qualitative studies specifically. For the purpose of the review in this thesis, the questions were modified to incorporate studies that were quantitative or mixed methods, as well as qualitative. Table 2 details the specific questions that were modified from the original grading instrument.

Table 2. Comparison of original and modified questions from Kennelley's grading instrument

<table>
<thead>
<tr>
<th>Original Question</th>
<th>Modified Version</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qualitative methods of inquiry are appropriate for the study aims. (The research sought to understand, illuminate, or explain the subjective experience or views of those being researched in a defined context or setting.)</td>
<td>Methods of inquiry are appropriate for the study aims. (The research sought to understand, illuminate, or explain the subjective experience or views of those being researched in a defined context or setting.)</td>
</tr>
<tr>
<td>The authors discussed why they decided to use qualitative methods.</td>
<td>The authors discussed why they decided to use the chosen methods.</td>
</tr>
<tr>
<td>Triangulation produced convergent conclusions.</td>
<td>The study included triangulation (namely, comparison of different sources of data re: the same issue).</td>
</tr>
<tr>
<td>• If &quot;no,&quot; was this adequately explained?</td>
<td>• If &quot;yes,&quot; triangulation produced convergent conclusions (or if divergent, they were discussed and justified).</td>
</tr>
<tr>
<td>• If &quot;no,&quot; was this adequately explained?</td>
<td>• If &quot;yes,&quot; triangulation produced convergent conclusions.</td>
</tr>
<tr>
<td>Study findings were generated by more than one analyst.</td>
<td>Study findings were generated by more than one analyst and/or were analysed with...</td>
</tr>
</tbody>
</table>
Chapter 1 – Introduction

Potential researcher biases are taken into account. For example, participation of author in study.

The authors identified new research areas or directions to be investigated.

The modifications made above fell into two categories of change. The first was the replacement of all specific references to qualitative methods with a broader term such as methods of inquiry. Or alternatively, listing qualitative, quantitative, and mixed methods. The second category of changes were minor tweaks to provide a narrower focus in some questions.

The final grading instrument used for this systematic review may be found in Appendix I. The instrument gives flexibility for each study to meet, approach or not meet a number of aspects deemed important to the quality of a research paper in this area. These included:

- Research Design
- Sampling
- Data Collection
- Data Analysis
- Findings/Results
- Research Value

To minimise bias, each study was scored against the adapted instrument by the primary author of this thesis and one of the supervisory team before an average was taken. In the event that a...
large disparity existed between the author and supervisor, a discussion took place to justify each scoring until a compromised score was accepted. Upon completion of the grading for each of the 40 publications, Figure 2 below was constructed to convey the distribution of publications into five levels, with the maximum score possible at 50.

![Bar Chart]

**Figure 2.** The distribution of the 40 papers included within the systematic review of the past 15 years of Chemistry Laboratory Education research

To first consider some of those papers that scored within the lowest bracket, 0 - 10 (Long, 2012; Mohrig, Hammond, & Colby, 2007; Wilczek-Vera & Salin, 2011; Yang, 2007), a common theme in the limitations of these published studies was observed. Each of these succeeded in describing an experiment or experience that could be installed within a laboratory course and sufficient information is provided to allow reproducibility of these conditions. In addition to this, the research aims were outlined to improve the quality of the learning experience within the chemistry teaching laboratory. When considering the methodologies employed to investigate the pedagogical value of these experiences, little to no discussion was provided.
Specifically, whilst the chemistry experimental procedures are clearly detailed, the education research methods including sample selections, data collection and analysis, pedagogical findings, and the corresponding contributions to the science education field were not present.

Those papers at the other end of the spectrum with scores between 41 and 50 (Berg, Bergendahl, Lundberg, & Tibell, 2003; Domin, 2007; Kable & Read, 2007; Kampourakis & Tsaparlis, 2003; Kelly & Finlayson, 2009; Newton, Tracy, & Prudenté, 2006; Seery, McDonnell, & O’Connor, 2007; Sandi-Urena, Cooper, Gatlin, & Bhattacharyya, 2011; Tomasik, Cottone, Heethius, & Mueller, 2013) exemplify those qualities the adapted instrument assesses. All of these publications were transparent and rigorous in their explanation and discussion of the research aims, methodologies, data collection and analysis, and how their findings contribute to the wider community.

There are of course, a large number of studies that achieve mixed success with respect to the qualities sought after in this systematic review. Two papers, both scoring 17 against the adapted instrument (Byrd & O’Donnell, 2003; Walker, Sampson, & Zimmerman, 2011), are examples where some discussion was dedicated to the findings of their respective studies and the implications for the wider community. The methodologies employed for these studies, including the sample selection and size, data collection, and analysis, were not been detailed. Therefore, while the chemistry experiments detailed in these publications are easily replicable with the provided information, to replicate the pedagogical investigation and results would not be feasible.

A study conducted by Hopkins and Samide (2013), scoring 24.5 against the adapted instrument, provides a well-rounded example where all areas covered in this systematic review were
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Partially addressed. Hopkins and Said (2013) investigated the use of a thematic laboratory-centred curriculum for general chemistry units, and is perhaps most limited by a lack of clarity when detailing their research methodologies and findings. Blonder, Mamlok-Naaman, and Hofstein (2008) provide an example of similar quality (scoring 30) where despite the strength of their research framework, discussion of the findings and where they have originated from is limited in detail.

It is clear from this review that there is a range of quality, as defined by the adapted instrument used there, within studies undertaken in the chemistry teaching laboratory space. Moving forward, the quality of studies in this field must evolve to reach those high standards to validate the results obtained. As such, those qualities that have been highlighted from the publications scored above 40 were considered a focus for this study. Specifically, a rigorous methodology that aligns with the research aims was developed where triangulation of several data collection and analysis approaches was used to strengthen any findings observed.

1.5 Research Aims

Taking into consideration the insight gained from the systematic review discussed within Section 1.4, this study sought to meet a number of research aims. The four aims of this doctorate study are:

1. The development of an 'optimised' laboratory course at the University of Tasmania;
2. The development of a rigorous methodology for the investigation and validation of laboratory teaching practices;
3. To explore the advantages and disadvantages of alternative teaching approaches in comparison to one another; and
4. To...

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=O:0;6:9=1 ( =68:9D&H9M3919= ( =9Lo ( 13:98O99 9%1999 9 " 9 " %D33996; -315 9 1M3390 (9 1G2 1D3390)

HM D3999999%O999 9%19D469&1D9;9 8L=9G6"0;6;0:8=0 ( 1%68:9B83:981511D46196886)

FM D3999999%O999 9%19D469&1D9;9 8L=9G6"0;6;0:8=0 ( 1%68:9B83:981511D46196886)

FM D3999999%O999 9%19D469&1D9;9 8L=9G6"0;6;0:8=0 ( 1%68:9B83:981511D46196886)

i M D09190;9 3396=C66&6998686=9L=9G6=C66&6998686;9 69%19D469: %86:5C9996; -315 9 1M3390 (9 1G2 1D3390)

=O:0;6:9=1 ( =68:9D&H9M3919= ( =9Lo ( 13:98O99 9%1999 9 " 9 " %D33996; -315 9 1M3390 (9 1G2 1D3390)
4. To investigate the relationship between teaching approaches and the types of experiments undertaken.

These aims can be divided into two broad categories: the first aim, "The development of an 'optimised' laboratory course at the University of Tasmania," can be considered as being primarily focused at the local level. An 'optimised' laboratory course, or parts of, may have applicability in other institutions. However, the core intention for this aim is the improvement of teaching practices locally. These improvements would be seen in a number of ways: an improvement in the engagement and enjoyment of students, greater development of chemistry specific knowledge and skills, and the development of a broader skill set including problem-solving skills and critical thinking.

The second, third, and fourth research aims are all considered as global aims with implications for both pedagogical quality at the University of Tasmania, but more importantly contributing to the current body of literature for research into the chemistry teaching laboratory. The second aim, "The development of a rigorous methodology for the investigation and validation of laboratory teaching practices," is designed to directly address some of the limitations observed from the systematic review conducted in Section 1.4. The strength of the methodologies employed adds considerable weight to the findings and outcomes observed from this study. Furthermore, this aim was intended to provide a framework from which the wider community could draw upon to potentially strengthen their corresponding studies.

The third, "To explore the advantages and disadvantages of alternative teaching approaches in comparison to one another," and fourth, "To investigate the relationship between teaching approaches and the types of experiments undertaken," aims are intrinsically linked in
outcomes. To clarify, the third aim, when discussing the advantages or disadvantages observed, the context lies within finding which teaching method provides the optimal laboratory experience. Aligning this outcome with regard to the type of experiment undertaken, leads into the fourth aim. The type of experiment, means the skill associated with completion of this experiment rather than the specific branch of chemistry it may be connected to. For example, the difference between an observation or interpretation experiment to that of a hands-on skills focused synthesis.

Any findings for these latter two aims will contribute to the growing literature on effective teaching and learning methods in chemistry education, specifically laboratory teaching practices. The use of a rigorous methodology enables the findings of this study to have some transferability to other institutions.
Chapter 2 – Teaching Methods

Earlier in Chapter 1, Domin's 1999 review of implemented laboratory teaching styles was discussed with regards to distinguishing the most commonly used teaching approaches. Another exploration of the differences between some of these teaching approaches was provided by Pavelich and Abraham (1979) some twenty years prior to Domin's review. Pavelich and Abraham discuss three teaching approaches, Verification (otherwise known as Expository), Guided Inquiry, and Open Inquiry, with respect to the characteristics of teachers as seen below in Table 3 (Pavelich & Abraham, 1979, pp. 100).

Table 3. Characteristics of Laboratory Types

<table>
<thead>
<tr>
<th></th>
<th>Verification</th>
<th>Guided Inquiry</th>
<th>Open Inquiry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order</td>
<td>C à D</td>
<td>D à C</td>
<td>D à C</td>
</tr>
<tr>
<td>Choice of Experiment</td>
<td>T</td>
<td>T</td>
<td>S</td>
</tr>
<tr>
<td>Experiment Design</td>
<td>T</td>
<td>T</td>
<td>S</td>
</tr>
<tr>
<td>Data Analysis</td>
<td>T</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Data Explanation</td>
<td>T</td>
<td>S</td>
<td>S</td>
</tr>
</tbody>
</table>

* C: Concepts  D: Data  T: Teacher  S: Student

Pavelich & Abraham (1979, pp. 100) in the definition presented by Pavelich and Abraham, there are differences with regards to the components of a laboratory experiment being considered when compared to that of Domin (1999). However, once again the same theme is apparent. The more rigorously structured approach, Verification, is identified as teacher centric. As each teaching approach is considered from left to right in Table 3, a gradual shift occurs with an increasing focus on student input into the experiment process until Open Inquiry is reached where the experiment is centered...
Chapter 2 – Teaching Methods

20

Upon the student. In Open Inquiry, the teacher's role shifts to becoming a facilitator or a resource for the student rather than being a guide.

Further examples can be seen within the literature with a study by Fay, Grove, Towns, and Bretz (2007) where a rubric was designed to aid in identifying the level of inquiry being used in a laboratory activity (Table 4).

Table 4. Levels of inquiry across undergraduate chemistry laboratory experiments

<table>
<thead>
<tr>
<th>Level</th>
<th>Problem/Question</th>
<th>Procedure/Method</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Provided to student</td>
<td>Provided to student</td>
<td>Provided to student</td>
</tr>
<tr>
<td>1</td>
<td>Provided to student</td>
<td>Provided to student</td>
<td>Constructed by student</td>
</tr>
<tr>
<td>2</td>
<td>Provided to student</td>
<td>Constructed by student</td>
<td>Constructed by student</td>
</tr>
<tr>
<td>3</td>
<td>Constructed by student</td>
<td>Constructed by student</td>
<td>Constructed by student</td>
</tr>
</tbody>
</table>

Fay, Grove, Towns, & Bretz (2007, pp. 216). The significance of this study lies within the similarities observed between the varying levels of inquiry posed by Fay, Grove, Towns, and Bretz (2007), and the laboratory instruction styles proposed in Table 1 (Domin, 1999, pp. 543) and the laboratory types in Table 3 (Pavelich & Abraham, 1979, pp. 100). For example, to consider the Level 0 within Table 4; the Problem/Question, Procedure/Method, and Solution have all been designed or provided by the teacher. The classifications for Table 1 and Table 3 would designate these conditions as an Expository laboratory instruction style and a Verification laboratory type, respectively. This trend is observed when comparing higher levels of inquiry as defined by Fay, Grove, Towns, and Bretz (2007).
2.1 Study Design

The initial step in the process was to decide on suitable teaching approaches that would give varied results while remaining feasible given the environment provided at The University of Tasmania. After extensive consideration of the literature it was decided to consider three different teaching approaches, Expository, Guided Inquiry, and Problem Solving. Each of these is discussed in greater detail below. In comparing these teaching approaches, it must be acknowledged that each will have specific learning outcomes unique to that approach. The aim of this study focuses upon the core experiment-specific outcomes that remain the same regardless of the teaching approach used. The Expository approach was chosen as it relates most closely to the current laboratory methods used. Problem-based, on the other hand, was as far removed from the Expository approach as possible, allowing a comparison between two approaches at opposite ends of the spectrum. Guided Inquiry was treated as an intermediate between these two approaches, combining elements of both in a structured manner.

2.2 Expository Style

The Expository style of teaching has long been used as the traditional form of teaching, particularly within laboratory environments (Domin, 1999). It is characterised by a rigorous framework and strict instructions to create an environment where the student undertakes a specified pathway to achieve a predetermined result. To place this within the taxonomies defined earlier in Tables 3 and 4, Pavelich and Abraham (1979) would classify this as being a Verification style laboratory due to the concepts informing the data to be collected and all aspects of the laboratory being designed by the teacher. Similarly, Fay et al. (2007) would classify this style as a Level 0 Inquiry experience as the Problem/Question, Procedure/Method, and Solution are all provided for the student. A study by Montes and Rockley (2002)
investigated the perceptions teachers hold with regard to the advantages and disadvantages of Expository, or Verification, teaching experiments. The outcomes of this study indicated the advantages of Expository as a teaching approach fell into two larger categories: Firstly, the traditional nature of this approach provides teachers a sense of comfort and familiarity. Secondly, the perceived educational outcomes of which relate to chemistry content knowledge rather than practical laboratory experience.

The diversity of learning preference for students is broad and as such, a rigorously structured approach enables only one accepted method to complete the laboratory (Monteyne & Cracolice, 2004). In comparison to other teaching approaches, this limitation can severely disadvantage students who may not engage well with this approach. Studies have demonstrated the benefit for student learning gains in aligning teaching styles with individual students’ learning styles (Allinson & Hayes, 1996; Felder & Brent, 2005).

Given the long history of this teaching approach, little to no research has been undertaken with proposing Expository as a novel approach to laboratory education. However, there are examples in the literature, such as a study by Green, Elliott and Cummins (2004), in which they compared an Expository teaching approach to a Prompted Inquiry-Based approach. In this study, a Prompted Inquiry-based group project was run in conjunction with more traditional scripted laboratories for comparison.

Green et al. (2004) anecdotally determined that despite the promised potential of Inquiry, the Expository was preferred by educators for its effectiveness at linking theory with experience. This was noted to be particularly important at the introductory and first-year courses in order to cement understanding of fundamental concepts.
2.3 Guided Inquiry Style

As has been previously discussed, Guided Inquiry is just one example that fits beneath the umbrella of Inquiry as a teaching approach. This particular form of Inquiry is characterised by a blended approach utilising a framework to allow students some constraints whilst giving space for students to expand or personalise their experience (Gaddis & Schoffstall, 2007). The intermediate nature of this teaching approach was selected as it provides a medium between the Expository and Problem Solving approaches being investigated in this study. This aligns with the Guided Inquiry definitions given in Tables 3 and 4. Pavelich and Abraham (1979) describe Guided Inquiry as an experience where both the Data Analysis and Data Explanation sections of the experience are student-driven, whilst the Choice of Experiment and Experiment Design components are provided by the teacher. Furthermore, students utilise the data to discover concepts and explain these. Fay et al. (2007) provide an analogous classification, defining Guided Inquiry as a Level 1 Inquiry experience where both the Problem/Question and Procedure/Method are provided to the students and they generate the Solution themselves.

Given the flexibility of Inquiry as a teaching approach, a large volume of research has been published on varying approaches to incorporating Inquiry into the teaching laboratory. Mohrig et al. (2007) reported on a number of Guided Inquiry and continued to specify some of the most important factors to take into consideration when designing a successful Inquiry learning environment. These factors included:

- Conveying the goals and methods to all concerned
- Positive faculty participation
- Appropriate Teaching Assistant (TA) training
- Providing time for pre and post laboratory discussions
- Availability of modern instrumentation
• Availability of written background materials.

In an ideal world, control of all these aspects would be readily available and the limitations of funding and resources would not hinder the implementation of alternative learning experiences. By recognising these factors however, effort can be made wherever possible to ensure the implemented Inquiry approach has the highest chance of success.

A potential option for the incorporation of Inquiry-Based learning into a laboratory framework was proposed by Green et al. (2004). Within this study, a comparison was made between the more traditional Expository teaching approach and an Inquiry-Based approach. Green et al. highlight the strength of Inquiry in developing the process of scientific inquiry, a skill not associated with the Expository style. The conclusions from this study indicated that the optimal approach would be to maintain the rigorous structure previously used within Expository and combine elements of Inquiry-Based learning for the early years of tertiary chemistry education. Contrasting to his investigation, there are studies in which the conclusions drawn are far more black and white. Ricci and Ditzler (1991) advocate the replacement of all traditional laboratories with Guided Inquiry experiences. The crux of their argument lies in the desire to bring laboratories to the centre of chemistry learning and thus use lectures as a reinforcement instrument after concepts have been introduced in the laboratory. Positive feedback was reported from both staff and students involved in this study. The students specified that the collaborative and discovery nature of this experience were the highlights, the instructors on the other hand commented on the potential for merging their roles as teacher and scientist.
Examples of Inquiry-Based implementation have also been published in higher years of study. Hopkins and Samide (2013) implemented two thematic laboratory modules at Butler University, where the focus was to bring real work environmental issues into a second year chemistry laboratory. An aspect of particular interest to this study was the length of each module being five weeks and, furthermore, integrated into the lecture course as they progressed through the unit. Outcomes were determined through analysis of the specific chemistry knowledge learning gains, rather than investigating the full student experience or laboratory specific skills. At McGill University a study completed by Wilczek-Vera and Salin (2011) described the development of a Guided Inquiry experiment for an advanced analytical chemistry unit. This experiment is described as initially being a step-by-step process leading into student ownership of the experiment. An aspect of this laboratory that was highlighted was the use of discussion questions or points posed during the procedure to guide students towards developing their understanding throughout the process.

An expansion of the Inquiry-Based learning environment is to incorporate real world elements into the research being conducted in a teaching laboratory. Furthermore, there are examples where students perform their own literature studies before designing and implementing a research project of their choice (Iimoto & Frederick, 2011; Vyvyan, Pavia, Lampman, & Kriz, 2002). Often reported however, are the limitations on the number of students who can undertake these research modules as the resources required can be extensive and time consuming for both students and teachers.

An approach that has been used several times with the intent of enhancing the laboratory experience using Inquiry-Based learning is the redevelopment of pre-existing laboratories to incorporate or exemplify inquiry qualities. Two such articles (Barker, Allen, & Ramsden, 1986;...
Byrd & O’Donnell, 2003) discuss the modification of elements of laboratories to incorporate inquiry into their laboratories. Both reported positive feedback from students undertaking these laboratories in preference to experiments previously completed in their degrees. Gaddis and Schoffstall (2007) add further weight to this approach and additionally suggest the use of published laboratories rather than new development at every institute. The range of inquiry approaches available demonstrates the flexibility when adopting these approaches into the laboratory environment.

2.4 Problem Solving Style

Problem Solving when utilised as a teaching approach could be best described as the opposite end of the spectrum to the Expository style. True Problem Solving places the responsibility of the experiment squarely upon the student, with methods, problem, analysis, and outcomes undetermined (Lyle & Robinson, 2001; Domin, 1999). Some authors describe this type of approach as open-inquiry (Fay, Grove, Towns, & Bretz, 2007), however the terminology in the literature is somewhat confusing. For example, Domin (1999) defines both Inquiry Instruction (specifying the alternative name of open-inquiry) and Problem-Based Instruction (otherwise known as Problem Solving) as separate approaches. The definition provided by Fay and coworkers is further contrasted by the definition provided by Pavelich and Abraham (1979) in Table 3. Close similarities can be observed between Problem Solving and the Open Inquiry classification provided as all aspects of the laboratory experience are student generated and data collected informs the concepts understood.
Problem Solving within this study has been implemented using the more flexible definitions of Problem Solving discussed by Ashmore, Frazer and Casey (1979). Ashmore, Frazer and Casey (2007, pp 377) highlight the different definitions as:

- "problem solving is bridging a gap between a problem state and a solution state"
- "problem solving [occurs] as a result of assembling rules, already known, to create a new (to the solver) superior rule which is learned and which allows solution to the problem"
- "a form of discovery learning, bridging a gap between the learner's existing knowledge and the solution to the problem"

Kirschner, Sweller, and Clark (2006) suggest however, that the open-ended nature of true Problem Solving is not necessarily a beneficial experience. The Problem Solving environment can cause an overload for a learner's working memory leading to less effective learning (Kirschner, Sweller, and Clark, 2006). Based on these definitions, a large pool of studies have been completed utilizing various Problem Solving learning environments (Taconis, Ferguson-Hessler, & Broekkamp, 2000).

One of the driving factors behind the implementation of Problem Based Learning environments over traditional approaches is to enhance the quality of scientists graduating from universities. Gallet (1998) detailed concerns over the production of graduates who could only follow recipes rather than utilizing the scientific approach. In an effort to rectify this, Gallet (1998) devised a 4-week research project was undertaken by students with the intention that the full scientific research experience would be completed including research and design, implementation, and dissemination. Despite reported initial difficulties in getting students underway, the majority of students agreed this approach enhanced their ability to...
undertake an experiment and would prefer future implementation of this approach. The development of these skills outside of science-specific content knowledge was highlighted by a project initiated within Australia, led by Jones, Yates, and Kelder (2011), to develop threshold learning outcomes (TLOs) for science degrees within Australia. Of the five broad TLOs proposed by Jones et al. (2011, pp. 11), only one, TLO 2, specifically details content knowledge for science as a discipline. The remaining four encompass skills including: an understanding of the scientific method; inquiry and problem solving; communication skills; and a sense of personal and professional responsibility. It should be noted however, that problem solving in the context given within the TLOs is related but not the same as the problem solving laboratory approach defined within this thesis.

Laredo (2013) discusses this approach in depth with the development of laboratory manuals to represent Problem Solving laboratories with the intent to develop these higher-order thinking skills. Some of the key features of this study were a heavy emphasis upon student preparation before arriving at the laboratory and recognition of the worth of experimental design and scientific inquiry. Noted throughout the study completed by Laredo (2013), students who are well-versed in more traditional learning approaches may struggle with these alternative experiments, but, as familiarity increases, the preference for Problem Solving activities increases comparably. Another example of this type of investigation is described in the work by Zoller and Pushkin (2007) with an emphasis on the development of higher-order cognitive skills in a first-year organic chemistry unit is examined. In addition to the problem-based laboratory, an integrated homework approach was used to complement this development through the semester.
Examples of positively received Problem Solving implementations have been observed within the literature from several institutes. Browne and Blackburn (1999) at the University of Alberta implemented a laboratory centric chemistry unit in response to the calls for redevelopment of chemistry education. Initially the changes made to the chemistry unit and laboratories were found to be at a level too high for the majority of students. Through moderation and reduction of the workload expectations, a compromise was reached in which both staff and students found the experience to be engaging and effective. Kelly and Finlayson (2007) published another example of a successfully implemented problem-based laboratory. An interesting outcome of this study was the observation that as students had time to acclimatise to the laboratory approach being utilised, the number of students preferring Problem Based laboratories steadily increased. Further to this, at the time of dissemination, the laboratories had been running for a further two years with no adverse side effects or feedback.

One of the limiting factors as discussed for Problem Solving teaching environments is the volume of resources required for a full experience. In a rare case, Tomasik et al. (2013) describe a study where a series of Problem-Based laboratories were implemented with a large cohort of students. Some structure was provided in the form of guiding students in their designing of the experiment and data analysis techniques. Feedback was collected from students to investigate the learning gains in addition to their perceptions of the laboratory experience. Conversely, no significant differences were found between the Problem-Based laboratories and the traditional laboratories other than an interest in undertaking future research activities.

Vocational work experience is an avenue that has been proposed as a potential Problem Solving activity to develop those skills sought after in alternative teaching approaches. A study
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Completed by Benett (1993) at the University of Huddersfield investigated the perceptions of students for vocational work experience. Benett (1993) posed whether this may be an alternative to be pursued in laboratory courses going so far as to suggest that it may be counted as credit towards a degree.

Present in many Problem Based laboratories, the approach of creating small groups or collaborative experiences when tackling problems is common. Sandi-Urena et al. (2011) designed a cooperative Problem Based laboratory where emphasis was placed on the use of teamwork to collect data and interpret results. An interesting feature of these laboratories was the lack of focus on determining a concrete quantitative outcome. Rather, many of the results reported by students were qualitative in nature and detailed their experience in approaching the problem itself. This emphasised the importance of the process of scientific inquiry and encouraged reflection upon the methods used in tackling their respective laboratory problems.

When queried about their enjoyment of the laboratory, students responded that while they did not necessarily enjoy the experience, they recognised that significant development of their critical thinking skills had been achieved. Seery et al. (2007) at the Dublin Institute of Technology implemented a similar approach utilising real world problems within mini-projects to be tackled by small groups. This implementation was limited to a second year unit with student feedback indicating a preference for this approach. This preference stemmed from a student-reported increase in enjoyment, engagement, and morale when undertaking these mini-projects.
One key observation to be made from this discussion thus far is the prevalence of single teaching approach comparisons, where an alternative approach is proposed in place of the pre-existing or traditional approach previously used. One exception to this can be seen in a study completed by Pavelich and Abraham (1979) where three teaching approaches were compared in the chemistry teaching laboratory. Verification, Guided Inquiry, and Open Inquiry were compared in an effort to improve the laboratory experience, with specific research aims to:

1. Acquaint the student with fundamental laboratory techniques and procedures.
2. Give the student experience with aspects of scientific inquiry.
3. Enhance the student’s thinking ability toward more abstract thinking processes.

(Adapted from Pavelich & Abraham, 1979, pp. 100)

How the study presented within this dissertation differs to that of Pavelich and Abraham (1979) is the intention of the research aims. Where Pavelich and Abraham (1979) offer an investigation into the development of students specifically, my study aims to probe the interaction of these alternative teaching approaches with the types of experiments being conducted using student perceptions and learning gains to measure any differences.

Taking into account the findings from the systematic review in Chapter 1 and the range of studies detailed within Chapter 2, my study aims to complete a comparative investigation into the applicability of multiple teaching approaches within the chemistry teaching laboratory. Similar in nature to the study by Pavelich and Abraham (1979), the aims of the study within this dissertation follow a different pathway. These research aims will be discussed within Chapter 3, Methodologies Part 1: Logics.
This thesis describes the methodology of the research across two chapters. The first, Chapter 3, focuses upon the methodological framework within which this study lies and logistical considerations. The logistical considerations include the demographics of the cohorts, data collection and analysis methods, ethics considerations, and safety measures. The second, Chapter 4, specifically details the creation of the experiment procedures used in this research.

3.1 Research Methodology

This study is based within a pragmatist framework (Creswell, 2003). Pragmatism within educational research implies that through enacting actions upon an environment, progress can be made (Goldkuhl, 2012). This framework was chosen as the research question aligns with this definition as it centres on 'what works?' in a real-life setting, in this case, the chemistry teaching laboratory. The chemistry teaching laboratory is an opportune environment for enacting changes with a number of measurable variables. The pragmatist paradigm is founded on work of other researchers, including concepts discussed by Dewey (1938) in which research is completed by initiating actions to cause effects within the environments being studied (Goldkuhl, 2012). The methods chosen were consistent with pragmatism research. A mixed-methods approach was adopted (Cohen et al., 2011) that allowed an investigation in both a broad and in-depth sense. The design centred on a series of cross-sectional case studies completed over four years in a real-life setting. A cross-sectional study refers to the study of different samples at different instances of time (Cohen et al., 2011, pp. 267). Case studies have been described and widely accepted in education research for some time (Freewody, 2003; Yin, 2006; Cohen, et al. 2011). The cases in question for this doctorate study were bounded within...
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3.2 Research Questions

1. What are the advantages and disadvantages of implementing alternative teaching approaches within the chemistry teaching laboratory?

2. Do teaching approaches align differently with the type of experiments being undertaken (where type refers to the nature of that experiment being, for example, observational or interpretation based)?

3. Will a combination of teaching approaches be more effective than a single teaching approach in the development of a chemistry laboratory course?

To unpack these research questions with some further depth, the first question posed for this study, “What are the advantages and disadvantages of implementing alternative teaching approaches within the chemistry teaching laboratory?” was designed to address the lack of studies within the literature in this area. Given the wealth of research into implementing individual teaching approaches in favor of entrenched traditional practices, it is hypothesized that all teaching approaches have their place in the development of scientists. This links...
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3.1 Directly into the Third Research Question, “Will a Combination of Teaching Approaches Be More Effective Than a Single Approach in the Development of a Chemistry Teaching Laboratory Course?” Given the hypothesis that all teaching approaches will have value of some kind for the education of students, it is further hypothesised that a combination of these approaches throughout a tertiary degree would provide an optimal blend of learning outcomes.

The second research question, “Do teaching approaches align differently with the type of experiments being undertaken?” is aimed to investigate how these teaching approaches align with the experiment type. As alluded to in the question itself, the experiment type discussed here relates to the nature of the experiment, rather than the topic of chemistry and shall be further explained in Section 3.3. To provide an in-depth example, an organic synthesis of aspirin is used primarily to develop those hands-on skills required when undertaking syntheses. Whereas an experiment focused upon the investigation of organic functional groups and tests to identify these groups aims to develop observational and interpretation skills.

3.3 Experiment Types

To determine a primary and secondary type for each experiment included within this study, a typology was determined through discussion with the teaching staff. This included topic-specific lecturers, the laboratory coordinator, and the unit coordinator. This yielded four elements that were focused on to varying degrees within the experimental program.
### Table 5. Experiment Typology Descriptions

<table>
<thead>
<tr>
<th>Experiment Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observational</td>
<td>Focuses upon the use of observational skills to identify and recognize a range of scientific outcomes. This may include changes in temperature, colouration, opacity, formation, or dissolution of solids, and evolution of gases.</td>
</tr>
<tr>
<td>Interpretation</td>
<td>Requires students to utilize observations and results in the formation of reasonable conclusions and assumptions. This includes, but is not limited to, the identification of reactions and/or products, determination of the order of a reaction, the presence of functional groups, and collecting evidence to support known chemical theorems.</td>
</tr>
<tr>
<td>Hands-On</td>
<td>Focuses on the use of laboratory-specific hands-on skills. Some examples include performing accurate and precise titrations, the preparation of standard solutions, the use of distillation equipment, and operation of laboratory instruments such as spectrophotometers.</td>
</tr>
<tr>
<td>Calculations</td>
<td>Requires students to manipulate data collected during an experiment to demonstrate knowledge of and applying appropriate formulae to solve a range of chemical equations. Outcomes of these calculations include, but are not limited to, percentage yields, standardization of solutions, and application of Beer's Law and Hess's Law.</td>
</tr>
</tbody>
</table>
This typology was then used as a reference for determining experiment type for each of the laboratory experiments selected within this study. Chapter 4 provides a detailed summary of each experiment and the associated primary and secondary type.

3.4 Chemistry at the University of Tasmania

This study was undertaken by investigating multiple units (or subjects) offered within the discipline of chemistry at the University of Tasmania. These units included the foundation chemistry unit, KRA001; the first year unit, KRA113 Chemistry 1A; the second year unit, KRA223 Chemical Analysis; and the third year unit, KRA342 Catalysis and Reaction Processes. A summary of each unit’s description, intended learning outcomes, and associated assessment tasks can be found within Chapters 5, 6, and 7 (KRA001, KRA113, KRA223 and KRA342 respectively) or in the unit outlines (University of Tasmania, 2015a, 2015b, 2015c, 2015d).

Table 6. Variations in laboratory structure across chemistry units studied

<table>
<thead>
<tr>
<th>Unit</th>
<th>Cohort Size</th>
<th>Demographics</th>
<th>Laboratory Time per Experiment</th>
<th>No. of Labs</th>
</tr>
</thead>
<tbody>
<tr>
<td>KRA001</td>
<td>50</td>
<td>Very diverse</td>
<td>3 hours</td>
<td>6</td>
</tr>
<tr>
<td>KRA113</td>
<td>200</td>
<td>Very diverse</td>
<td>3 hours</td>
<td>8</td>
</tr>
<tr>
<td>KRA223</td>
<td>40</td>
<td>Chemistry minors and majors</td>
<td>4–8 hours</td>
<td>6</td>
</tr>
<tr>
<td>KRA342</td>
<td>20</td>
<td>Chemistry majors</td>
<td>4–8 hours</td>
<td>4</td>
</tr>
</tbody>
</table>

*The cohort size is listed as the average size per year. It can range by up to 50%.

Depending on the unit being discussed, the demographics of students undertaking that unit varies significantly. For example, the foundation chemistry unit, KRA001, typically attracts two...
types of students; students who have just completed pre-tertiary education and did not complete a chemistry topic at that level, and mature age students who are returning to university after a sojourn within the workforce or alternative area of study. KRA 001 typically attracts between 40 to 60 students per semester. KRA001 is offered as an alternative pathway into first year chemistry for those students who have not completed a pre-tertiary chemistry unit.

In comparison, one of the first year chemistry units offered, KRA113, is mostly composed of students continuing education from pre-tertiary subjects the year prior. The student cohort of KRA113 per semester is significantly larger attracting between 180 to 250 students. The large size of KRA113 is due to the requirements of many specialized degrees requiring first year chemistry as a prerequisite. Examples of degrees requiring KRA113 include, but are not limited to: the Bachelor of Pharmacy, Bachelor of Medical Research, Bachelor of Marine and Antarctic Science, and Bachelor of Agricultural Science.

Moving into the second and third year units, KRA223 and KRA342, the student groups suffer a significant drop in numbers and the composition of these cohorts become mostly composed of students taking chemistry as a minor or major.

3.5 Ethics

Ethics approval was granted in 2012 by the University of Tasmania Social Sciences Human Research Ethics Committee within the University of Tasmania (Ethics Reference Number: H0012564). The minimal risk application is detailed within Appendix I.
3.6 Data Collection Methods

Consistent with the pragmatist framework and mixed methods approach discussed in Section 3.1, both quantitative and qualitative data was collected. This was to give a greater depth of understanding of the effects of any changes made to the teaching approach used. Data collection occurred through three primary instruments: a student completed survey to be filled out upon completion of the experiment undertaken, a student completed quiz to test understanding, and a demonstrator awarded grade through the use of observation and a rubric. Figure 3 shows the data collection instruments were designed to address the research questions defined within Section 3.2.

Later in the project, the experiments considered expanded to include several experiments from a 2nd year Chemistry unit, KRA224, and a 3rd year Chemistry unit, KRA342. As these units were typically composed of much smaller class sizes, the data collection instruments were modified to allow more qualitative information to be collected. These modifications primarily focused upon the survey instrument with the addition of second-tier styled questions to the pre-existing Likert scale questions. This allowed a degree of depth to be collected in the areas of interest. The modified survey for these later years of study can be found within Appendix II.
3.6.1 Survey

The use of surveys to collect information from sample groups is a well-established practice, the benefits of this approach have been detailed by Cohen et al. (2011, pp. 256–266). The student-completed survey was designed with two purposes in mind: the first being the collection of quantitative data for a series of questions of interest, and second the collection of qualitative free-form feedback from the students on the strengths and weaknesses of the teaching method with respect to this laboratory.

A survey was selected as one of the data collection methods due to several advantages that the use of surveys would bring. The strength of surveys of this type has been demonstrated previously in a number of published studies (Abraham et al., 1997; Brew & Ginns, 2008; Hart, Mulhall, Berry, Loughran, & Gunstone, 2000; Herrington & Nakhleh, 2003; Kabel & Read, 2007).

From a logistical point of view, surveys are a familiar data collection instrument to both staff and students. University policies dictate the use of unit evaluation surveys given to students nearing the end of the unit. In addition to the familiarity, given the large number of students and the often full timetables they are committed to, surveys allow collection of data from a large number of students with minimal time and cost. Alternative methods such as interviews or focus groups, this would require students to volunteer time outside of their laboratory classes, which would reduce the number of samples considerably. One potential limitation of using surveys was the choice in using paper-based surveys. Online-based surveys are advantageous in minimising the data processing and analysis for both student and researcher convenience (Nulty, 2008). Paper-based surveys were chosen as there are no computers available within the laboratory for common use, and it avoided the need for students to log in outside of laboratory hours. Furthermore, the presence of the surveys within the laboratory environment increased the response rate. Whilst paper-based surveys gave immediate
feedback upon completion of the experiment, a significant amount of time was required to sort through and transcribe the data into a format compatible with the statistical methods chosen. With these in mind, it was hoped that the choice of a survey as a data collection method would provide a large number of responses with a mixture of qualitative and quantitative feedback. The quantitative and qualitative feedback could then be used in conjunction with one another to provide an in-depth investigation into the key areas of focus. A previous study by Pullen, Yates, and Dicinoski (2014) designed and implemented a survey-based on developing questions in the key areas of interest for this study. This included addressing questions such as:

- What is the level of engagement with the experiment that students have?
- Are the learning objectives clear and are they being fulfilled?
- Do the workload expectations match the amount of work completed during the experiment?
- How do the students perceive their level of understanding and how does that change through completion of the experiment?
- Do the students enjoy completing the laboratory?

Based on these areas, seven questions were devised for this doctorate study, with an additional question to give insight into the overall laboratory experience. No formal psychometric validation (Arjoon, Xu, & Lewis, 2013) was undertaken for the designed instrument. Assistance was sought from one of the supervisors of this study, Dr. Natalie Brown (Head of the Tasmanian Institute for Learning and Teaching), whose expertise in this area was invaluable. Furthermore, comparisons were made with published survey instruments with similar purposes to ensure the developed instrument was robust. For example, the survey...
instrument designed by the Advancing Science by Enhancing Learning in the Laboratory program (ASELL) (Yeung et al., 2011), the ASELL Student Learning Experience (ASLE) tool (Barrie et al., 2015), was designed with the similar intention of determining a students’ perceptions of their laboratory experience in the key areas discussed earlier. When comparing the structure of the ASLE with the survey used in this study, a number of similarities were identified. The full ASLE survey can be found within Appendix I. The inclusion of psychometric validation would greatly strengthen the validity of survey instruments in any future studies.

3.6.2 Quiz

A quiz was chosen as one of the data collection methods to give insight into the understanding attained by students upon completion of each experiment. The strength of quizzes (or questionnaires) as a measurement instrument is thoroughly described by Cohen et al. (2011, pp. 377-408). An example of implementing a post-experimental quiz to measure learning gains of students can be seen in the work by Ding and Harskamp (2011). The use of quizzes in this doctoral study was limited to a single instance post-laboratory assessment. As such, learning gains would be an inappropriate term for use there and instead, a snapshot of student understanding was the desired outcome. One flaw to account for in this approach is the possibility of students having existing knowledge of the concepts or techniques used within the experiments. As this quiz was administered to all members of each student cohort, it was assumed that any minority with pre-existing knowledge would be present in each cohort in equal numbers. Therefore any trends observed would not be compromised by these minorities. These quizzes were designed with the intention that each teaching method would deliver the same level of understanding of the key concepts and techniques to the students.
The student completed quiz was unique to each experiment and composed of a series of questions designed to represent the key concepts or techniques used within that particular laboratory. These questions provided insight into the student's understanding of these concepts and techniques. Each quiz was designed to be brief and was marked as correct, partially correct, incorrect, or did not attempt. This allowed for better comparison between quizzes and experiments without the complications of appropriate weighting and different quiz lengths.

3.6.3 Grade for Student Laboratory Performance

Finally, students were given a demonstrator-awarded grade, a practice that has been used within the University of Tasmania for some time. The purpose of this grade is to give an indication of their performance during the laboratory coupled with their presentation of data collected and any calculations or discussions associated. To assist in minimizing variability between demonstrators a rubric was designed and implemented to clarify the measures and standards used in the grading of students' work. Rubrics, or criterion referenced assessments, are an effective tool in their capability to give detailed information on the progress or lack thereof for students (McInerney & McInerney, 2010). The designed rubric was first developed as part of a post-graduate short course on higher education. The development of this rubric was guided by the examples provided by Biggs and Tang (2011). Validation of this rubric was completed in two phases: the first was through assessment (the criteria used for this can be found in Appendix I) by Higher Education experts who ran this course from the Tasmanian Institute of Learning and Teaching (TILT). TILT is a division of the University of Tasmania employed to assist in the education and development of higher education. The second form of validation was through consultation with the Teaching Learning Committee within the...
discipline of chemistry prior to implementation. The consultation with the Teaching Learning Committee aimed to align the rubric with the historical approach of assessment for the teaching laboratory at this institute. The key criteria for this lie within ensuring that safety within the laboratory, knowledge of chemical concepts, and laboratory performance were included. Furthermore, each of these criteria to the appropriate standard expected of chemistry students. The criteria have been discussed in further depth later in this Section.

Rubrics can be described as being made up of three components: criteria clearly stating the assessment areas; standards to define the level of attainment of each criterion; and descriptors of each standard to each criterion (University of Tasmania, 2011). To design this rubric, the outermost framework was constructed before moving onto the descriptors. As such, five standards were chosen for use, to complement the accepted assessment standards used within the University of Tasmania. These included the following: High Distinction (HD 80%), Distinction (DN 70%), Credit (CR 60%), Pass (PP 50%), and Unsatisfactory (NN < 50%). Some initial discussions raised the alternative of using four standards, with the removal of the NN standard, rather than five in an effort to simplify the rubric, but after consideration the NN grade was retained. The advantage of the NN standard was the clear definition of what would constitute a grade below 50% to both students and demonstrators. This avoided the associated problems of implying that a student’s work had not achieved a PP and allowed demonstrators to mark students to their appropriate level indicating where students may not have met the PP level.

With the standards determined, the next component to consider were the criteria to define what was being assessed. The designed rubric was intended to be a generic rubric appropriate to all first-year chemistry laboratories. It was imperative that the criteria were broad enough
to encompass the range of experiments offered, but specific enough to allow meaningful assessment. Some logistical considerations were also required to be addressed. As the demonstrators assess students during laboratory time, it was important to ensure the marking process was efficient and transparent in nature. Each laboratory only targeted a few key aspects from the overarching learning objectives further supported this decision, as an in-depth rubric would not be appropriate. The developed rubric for the KRA001 and KRA113 units can be found within Appendix II.

The use of criteria-based assessment on the learning outcomes of an activity is supported by Biggs and Tang (2011) and the Guidelines for Good Assessment Practices (University of Tasmania, 2011), which states “Criteria should be clearly based on the learning outcomes in a unit”. The unit outline for Chemistry 1A, KRA113 (University of Tasmania, 2015b), states that the learning objectives of the laboratory classes are:

1. Complement the lectures where possible.
2. Increase skills in the handling of chemicals and equipment.
3. Introduce you to basic laboratory techniques of synthesis and analysis.
4. Allow you to gain an appreciation of the need to carry out experiments with regard to the safety of yourself and others.

(University of Tasmania, 2015b)

With these in mind, it was determined that three criterion would be sufficient to encompass these learning outcomes. Using these learning outcomes the following criteria were designed with a weighting attached to each, 20%, 40%, and 40% respectively:
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1. Completion of pre-laboratory requirements and work safely and efficiently within a laboratory

2. Use of the correct techniques and calculations

3. Understanding of the concepts and principles

Figure 4. An illustration of the alignment of the criteria of the rubric with the learning objectives of the laboratory.

These criteria were then subjected to scrutiny from the Unit Coordinator at the time, the Chemistry Teaching and Learning Committee, and the supervisory team of this project. They decided these criteria sufficiently encompassed the learning outcomes intended for the laboratory in addition to complying with the expectations implied from the guidelines and exemplars available from University resources. To expand on one of these expectations, his meant excluding all use of quantifiers and qualifiers, and ensuring the criteria represented what students have to do during the assessment task to attain a grade (University of Tasmania, 2011).
With the standards and criteria defined, the focus turned to the descriptors for each level of each criterion. The purpose of a rubric is to clearly and succinctly define to both students and demonstrators what is being assessed and what is required at each level to achieve different grades. It was therefore imperative that the descriptors written were consistent not only within each criterion but also across the rubric itself. The process of writing each descriptor began with constructing what was expected at the 50% Pass (PP) level. From this base level, descriptors for the 60% Credit (CR), 70% Distinction (DN), and 80% High Distinction (HD) levels were constructed. These descriptors were conceived through communication with past and present demonstrators, students, teaching staff, and the Chemistry Teaching and Learning Committee. Once approval had been gained from the Unit Coordinator, progress began on each standard not yet addressed.

3.7 Sample Groups

The conditions of the ethics approval attained meant that all students must attend and complete each experiment as they would in a normal teaching semester so that the key elements of the experiments were largely unaffected. Therefore all students within any one cohort undertook the modified experiment and was offered the opportunity to volunteer to provide data for this study. Data collection was undertaken through 2013-2015 or each implementation of KRA001, was assigned a single teaching approach for all modified experiments: The Guided Inquiry approach was run in 2013, the Problem Solving approach was run in 2014, and the Expository approach was run in 2015. For example, one KRA113 experiment investigated a variety of functional organic groups and the use of small-scale tests to identify these groups. No matter which teaching method was used, the students would still be fulfilling the minimum learning objectives and using the same techniques and concepts to...
For data to be collected and retained for the purpose of analysis, students had to complete the provided surveys and quizzes with their student I.Ds written on each data collection instrument. This signified permission had been granted by the student for their responses to be de-identified and utilized in this study.

3.8 Analysis of Data

For all data analysis, the null hypothesis was used that no differences would be found between the three teaching methods considered for all experiments. A variety of methods were used in the comparison of data collected using the instruments discussed in Section 3.5.

3.8.1 Quantitative

For comparison of the quantitative data collected through the survey instrument and the demonstrator awarded grades, a one-way between-groups ANOVA with post-hoc tests was completed using IBM SPSS Statistics for Macintosh (Version 22.0). The post-hoc analyses included two test options available for use: the Games-Howell test and the Tukey HSD test. Levene’s test for homogeneity of variances was used to determine which of these tests were appropriate. Where the significance value (p) was greater than 0.05 in Levene’s test, the homogeneity of variances assumption is abided by and the Tukey HSD test may be used. For those comparison of variances where p was less than 0.05, the homogeneity of variances assumption has been violated and the Games-Howell test is used. For each comparison where significant differences were identified, the effect size (Cohen, 1988, pp. 284 - 287) was calculated. Effect sizes provide more depth to any comparison made by measuring magnitude of difference where statistically significant differences have been identified. The effect sizes within this thesis have been calculated as the sum of squares (between groups) divided by the
sum of squares (total). The data collected through the student-completed quizzes was compared quantitatively using a standard comparison of means using Microsoft Excel for Macintosh (2011).

3.8.2 Qualitative

A succinct definition of qualitative research is given by Weimer (2006): “Qualitative methodologies are multiple and diverse, but they share a commitment to study phenomena in naturalistic settings and to analyze results interpretively.” (Weimer, 2006, pp. 43)

In the context of this study, it was intended that the qualitative component of this investigation would encompass the free-text survey responses received describing the student perceptions of a number of aspects of the laboratory. The specific qualitative analysis methodology followed was a thematic analysis, a method that has been utilised previously (Miles, & Huberman, 1994). Individual responses are coded for themes and descriptive analyses are conducted upon this data. A hierarchal approach was used to first identify broad themes, before narrowing focus to determine sub-themes. A summary of the process followed is below:

- Transcribe all data into a Word document to match the free-text entry spaces on the surveys;
- Group the comments to represent common themes;
- Indicate information on the proportion of responses from each teaching method;
- Identify exceptions or points of interest from the data collected; and
• Compare with quantitative analysis outcomes to identify any correlation or contradictions.

To identify common themes, student responses were grouped into broad areas. For example, all responses that related to the information provided within the laboratory manual were placed together. From there, sub-themes are derived such as: responses indicating a lack of information, clarity of information provided, request for additional resources, and outdated or incorrect information. During the grouping stage of this process, particular care was taken to check and recheck the identified themes multiple times, with at least two rechecks for each comparison.

3.9 Participation by Demonstrators and Staff

Given the breadth of this project, significant interaction with both the teaching staff of the units considered within this study and the demonstrators teaching in the laboratories occurred. The teaching staff provided input and moderation of the content to be contained within each laboratory experiment considered in this study. Demonstrators, also known as teaching assistants, fill several roles within the teaching laboratory. These roles vary and require the demonstrator to be attentive to the students' needs while maintaining a professional relationship as a teacher and assessor.

The demonstrators are recruited each year with a mixture of new and experienced demonstrators drawn from the honours and postgraduate students, the postdoctoral research fellows, and the academic staff within the School. Approximately 70% of the demonstrators had prior experience with the experiments to be completed in each unit, either through previous experience as a demonstrator in that unit or as a past student. Each classroom typically contains one senior demonstrator and three...
demonstrators matched to a group of approximately 50 students. This allows a ratio of up to 16 students to teach demonstrator. Demonstrators were made familiar with the project through several mechanisms. During the first meeting of the semester, the lead investigator led an informative discussion, between 30 to 45 minutes each year, providing a briefing of the intentions behind this study with details on the role demonstrators' play and what outcomes were expected. Within this discussion, a number of key points were covered including:

- A brief explanation of each teaching method;
- The data collection instruments that would be utilized;
- An explanation of the ethics approval attained and the conditions of this approval;
- The role of the demonstrator within this environment and how this changed between teaching approaches; and
- An in-depth explanation of criterion referenced assessment in the context of the rubric designed for these laboratory experiments.

A demonstrator-training day was implemented within the School coinciding with the initiation of this project. This provided additional training for demonstrators who were new or requested a refresher course. The day covered general teaching principles and the practical application of such in a teaching laboratory. Weekly 30-minute meetings were held throughout the semester to act as a continuation of this training day and to ensure preparation for the following week's laboratory occurred. Finally, throughout the implementation of the modified laboratories, the student investigator was present as an observer and a resource to the demonstrators.
3.10 Safety

Safety is paramount in the chemistry laboratory and was therefore a major consideration in the design of this project. As modifications were being made to each experiment's structure, it was imperative that these modifications did not require students to step outside the bounds of safe laboratory procedures. One item of particular concern was the development of problem-solving versions of the existing experiments. A characteristic of problem-solving laboratory experiences is the opportunity for students to develop their own methods and explore alternative avenues to achieve the learning outcomes for that experiment. As some of the experiments required the use of hazardous materials or instruments, for example, strong acids or bases and the use of hotplates, this issue had to be considered when structuring the procedures for each teaching method variation of each experiment. The inclusion of a limited pool of reagents and equipment limited the accessibility of potentially hazardous and unrequired elements for each experiment. Further to this, for experiments with very specific methods, a basic approach was provided for students to expand upon or vary key variables.
Chapter 4 – Methodologies Part 2: Experiment Design

With the design of the experiments it is important to note that the intention was to take pre-existing experiments, well established and understood at the University of Tasmania, and modify each chosen experiment to versions representing each of the three teaching methods.

Before delving into the details of experimental design, it was important to first decide which experiments would be investigated as part of this study. The choice of these experiments would have a large influence on the meaningfulness of any data collected and compared. For example, the initial experiments within a standard chemistry course will have a focus on introduction to the laboratory. An analysis of an experiment at that level would draw away from the elements of teaching chemistry concepts and techniques. Another variable to be wary of was an over-exposure to similar chemistry concepts or techniques. Preferably, a range of experiments representing different types of experiments would be chosen. When discussing types of experiments it is important to highlight that distinguishing between experiments based on the concepts or techniques alone was not the intention of this study. It is important to note that the types of experiments can be described as being, for example, observational or synthetic in nature. An experiment centred around the observation of multiple spot-tests is very different from a hands-on multi-step synthesis with a particular target in mind. Both use observational and hands-on techniques but the focus is very different in nature. Each experiment was assigned a primary type and a secondary type. These were decided through collaboration with both the lecturers teaching the corresponding materials for each experiment and the Teaching Learning Committee. Focus was placed upon identifying the specific skills that were integral to this experiment including both assessed skills and to-be-learnt skills. With this in mind, the following experiments within Tables 7, 8, and 9 were selected:
### Table 7: Summary of experiments considered within the foundational KRA001 unit

<table>
<thead>
<tr>
<th>Unit</th>
<th>Experiment</th>
<th>Key Concepts/Techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>KRA001</td>
<td>The Analysis of a Solution by Measurement of its Density</td>
<td>• Familiarisation with the measurement of volume and mass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Basic glassware usage with accuracy and precision</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Use of appropriate significant figures</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Calculation</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Hands-on</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Interpretation</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Hands-on</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Calculation</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Observation</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Interpretation</strong></td>
</tr>
</tbody>
</table>

*Bolded represents the primary experiment type.*
<table>
<thead>
<tr>
<th>Unit</th>
<th>Experiment</th>
<th>Key Concepts/Techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>KRA113</td>
<td>Oxidation of Benzyl Alcohol: Synthesis of Benzoic Acid</td>
<td>• Fundamentals of an oxidation reaction in organic synthesis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• % Yield determination</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Vacuum filtration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Basic synthesis skills</td>
</tr>
<tr>
<td></td>
<td>Hands-on/Observation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Organic Functional Groups</td>
<td>• Chemical reactivity of certain functional groups</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Application of chemical reactivity knowledge to identify the presence of functional groups</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Small scale functional group tests</td>
</tr>
<tr>
<td></td>
<td>Observation/Interpretation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thermochemistry: Enthalpy of Neutralisation</td>
<td>• Construct and utilise a calorimeter for the measurement of the enthalpy of neutralisation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Perform calculations using experimental data to investigate Hess' Law</td>
</tr>
<tr>
<td></td>
<td>Calculation/Interpretation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Determination of the Freezing-Point Depression for Cyclohexane</td>
<td>• Understand the difference between molarity and molality</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Experimentally construct cooling curves</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Methods for the determination of molecular mass</td>
</tr>
<tr>
<td></td>
<td>Interpretation/Calculation</td>
<td></td>
</tr>
</tbody>
</table>

*Bolded represents the primary experiment type.*
### Table 9. Summary of experiments considered within the KRA223 and KRA342 units*

<table>
<thead>
<tr>
<th>Unit</th>
<th>Experiment</th>
<th>Key Concepts/Techniques</th>
<th>Experiment Type*</th>
</tr>
</thead>
<tbody>
<tr>
<td>KRA223</td>
<td>Determination of Copper and Arsenic in Treated Wood by Atomic Absorption Spectroscopy</td>
<td>• Theory of Atomic Absorption Spectroscopy • Concentration, conversion between different forms, dilutions • Use of calibration curves and standards</td>
<td>Calculation</td>
</tr>
<tr>
<td></td>
<td>Gravimetric Determination of Calcium</td>
<td></td>
<td>Hands on</td>
</tr>
<tr>
<td>KRA342</td>
<td>Palladium Cross-Coupling Reactions</td>
<td>• Establish an order for reactivity for a variety of aryl halides including any steric effects that occur • Investigate the effects of electron donor/withdrawing substituents during the rate determining step, oxidative addition • Analysis by GC-FID and using this information to estimate % yield formation of a target compound • Design the procedure to carry out a 5 mmol scale Suzuki-Miyuara reaction</td>
<td>Hands on/interpretation</td>
</tr>
</tbody>
</table>

*Bolded represents the primary experiment type.
Two approaches were taken in the development of the experiments for this study. The first was applied to the two units, KRA001 and KRA113. The second approach was used for the units KRA223 and KRA342. These two approaches will be discussed separately.

4.1 KRA001 and KRA113

The experiments for units KRA001 and KRA113 were designed to be completed within three hours, and presented to beginning undergraduate students. These experiments tend to be relatively straightforward and often centered around two to three core concepts and techniques. The first stage in the development of these modified experiments was to identify the key concepts and techniques. Regardless of the teaching method to be used, these key concepts and techniques must be covered as they are linked to the learning outcomes for each experiment.

Upon identifying the concepts and techniques for each experiment, these were summarized and circulated to the academic staff responsible for each component of the relevant unit. This allowed confirmation that the appropriate concepts and techniques had been listed and an additional check for any that had been missed. Development moved into the next stage of structuring each experiment into three modified experiments to represent each teaching method. The experiments in their traditional format largely coincided with the teaching approach formally known as Expository, or more commonly referred to as instruction-based or recipe-based learning. With some small exceptions this was the prevalent teaching method across all experiments for foundation and first year chemistry at the University of Tasmania. Conversion to the three teaching methods chosen, Expository, Guided Inquiry, and Problem Solving, began with Expository as this would be the most straightforward and would identify...
all aspects of the laboratory to be completed. The experimental procedures were considered and systematically reviewed to remove any elements of inquiry or problem solving. These elements were then adapted and integrated into the discussion and results component of the laboratory report template. The intended outcome of this was the production of a purely instruction-based experiment, with no possibility of students deviating from the provided method. All calculations, results, and discussions were contained within a single section and treated as work to be completed upon collection of all data for that experiment. Thereby students would be developing their understanding after completion of the experiment.

Using the methods previously used by Pullen et al. (2014), the Expository versions of each experiment were then treated as the foundation for the Guided Inquiry and Problem Solving versions of these experiments. The Expository version identified where to incorporate more complexity into the experiment. As Guided Inquiry has been defined in this project as an intermediate approach between Expository and Problem Solving, the conversion from Expository to Guided Inquiry required careful consideration of what stages of the experiment could be adapted to integrate hurdles or challenges. These hurdles would allow students to inquire into elements of the experiment previously only considered upon completion of the Results and Discussion section. By identifying these stages, inquiry-styled questions and discussions were interspersed throughout the experiment to break the perceived monotony of following pure instructions. This encouraged the development and consideration of a student’s understanding whilst the experiment was completed, rather than afterwards as expected in the Expository teaching method. Finally, to construct a Problem Solving activity, the experiment was broken down into broad sections. Each section was intended to be presented as a problem in itself or a facet of the experience that students could design and engage with.
4.2 KRA223

Within the time frame planned for this project, only two iterations of KRA223 would run. Therefore only two teaching methods could be used and compared. The nature of these experiments led to the decision that modifying these experiments to a Problem Solving alternative would not be feasible as the concepts or techniques being learnt did not lend themselves the freedom to explore and investigate as required. It was therefore decided that Expository and Guided Inquiry would be compared for the purpose of investigating any differences found between first and second year students for their experiences with alternative teaching methods.

Similar to the methodology employed in designing the modified experiments in KRA001 and KRA113, each experiment was broken down into the key concepts and techniques. After moderation by the appropriate academic staff, a pure instructional format was developed to represent the Expository teaching method. All calculations and discussions were compiled into a single section to be considered upon completion of the experiment.

The experiments completed in second year are considerably more advanced than first year; having more difficult concepts in addition to a longer time frame, four hours minimum, to complete the experiment. Therefore the expansion to a Guided Inquiry format had a greater number of areas possible for enhancement of the method. By integrating calculations and discussions through the method, students were provided assistance in writing their laboratory reports. The laboratory reports written by second year students are constructed without guidance in comparison to first year where provided templates are used.
At the third year level for undergraduate chemistry, the number of experiments completed per student decreases in favour of increasing the depth of each experiment. This allows for experiments to span over several laboratory sessions, widening the range and types of procedures beyond those possible given time constraints in first and second years. Given the extended length of the experiments, only a single experiment was chosen from KRA342 to be modified. This was an experiment focused upon palladium catalyzed cross-coupling reactions. Originally this experiment was delivered in a mixture of Expository and Guided Inquiry approaches giving a formal structure for students to follow, but allowing some exploration into the flexibility of this class of reactions. After some consideration of class sizes, a maximum of 20 per cohort, it was initially decided that comparing two teaching methods would lead to a sample group of insufficient size. As an extension of the project's larger goal it was decided that at the third year level only the Problem Solving approach would be studied. This was supported by the expectations that students at this level should have a thorough understanding of chemistry foundations and should be focusing instead upon the application of this knowledge.

With this in mind, a redevelopment of the current experiment was undertaken. Similar to the previous methodologies discussed, the core concepts and techniques were identified and moderated by the appropriate academic staff. In this case however, it was decided to redesign the overarching direction of the experiment to give greater freedom to students in exploring this reaction. As such, the experiment was separated into two distinct sections: the first an exploration at the micro-scale of a range of potential reactants for a Suzuki-Miyaura cross-coupling reaction to determine reaction efficiencies. The second a scaling up of the most efficient reaction as determined in section one, a process often used within research and...
development to minimize wastage of potentially expensive reagents or processes. An excerpt from the laboratory manual procedure (the full experiment can be found within Appendix II) has been given below detailing the nature of the experiment and its rough structure:

"This experiment will be completed in small groups with each student in that group investigating the reactivity of 2-3 different aryl halides. Prior to the laboratory, you should discuss with the other students completing the experiment, which aryl halides to analyse in order to produce a meaningful comparison. A meaningful comparison will require the analysis of 6-8 reactions across a broad range of aryl halides. Before beginning the experiment, justify your choices to the demonstrator. On completion of the laboratory work, results will be shared amongst the group to give further insight."
Chapter 5 – Results: Foundation Chemistry

5.1 Introduction about Foundation Chemistry

To give context as to the inclusion of a foundation chemistry unit at the University of Tasmania, a required prerequisite for first year chemistry is the completion of a Year 12 chemistry or equivalent. Foundation Chemistry is offered as an alternative pathway for those students who did not undertake a Year 12 chemistry unit or those students who are returning to study at a later stage of life. The inclusion of Foundation Chemistry units is supported by a recent revision of the guidelines for the structure of a Bachelor of Chemistry from the American Chemical Society (American Chemical Society, 2015).

The ACS Committee on Professional Training state that “Foundation course work provides breadth and lays the groundwork for the in-depth course work.” (2015, pp. 11).

5.1.1 Unit Objectives

From a practical point of view, this unit is designed to act as a prerequisite for the first year chemistry units, KRA113 and KRA114, offered at the University of Tasmania. This is not to say it is equivalent to the chemistry subjects offered in Grade 12 at pre-tertiary institutions. Specifically this unit will cover topics of direct relevance to KRA113 and KRA114 including: the nature of matter, the fundamentals of chemical structure, bonding and chemical reactions, the states of matter, an introduction to chemical analysis, acid base chemistry and organic chemistry. Taken directly from the unit outline for KRA001 at the University of Tasmania (2015a), the intended learning outcomes are:

• Demonstrate knowledge and understanding of chemical principles and theories;

...
Chapter 5 – Results: Foundation Chemistry

• Apply chemical principles and theories to predict and explain the chemical and physical properties of substances, their structure, and the interactions that take place between them;

• Display competence in working in an individual and team environment both within a learning space and a laboratory space;

• Demonstrate problem-solving skills from experimental and theoretical approaches, in addition to knowing when to accept evidence contrary to established beliefs.

(University of Tasmania, 2015a, pp. 2)

5.1.2 Unit Operation

The University of Tasmania has three main campuses across Tasmania: the Sandy Bay campus in Hobart, the Newnham campus in Launceston, and the Cradle Coast campus in Burnie. The foundation chemistry unit, KRA001, is offered at all three campuses in a variety of modes.

Table 10. The variety of formats KRA001 is offered as

<table>
<thead>
<tr>
<th>Campus</th>
<th>Semester 1</th>
<th>Semester 2</th>
<th>Semester 3 (Summer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy Bay</td>
<td>On Campus</td>
<td>On Campus</td>
<td>Online</td>
</tr>
<tr>
<td>Newnham</td>
<td>Online</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cradle Coast</td>
<td>On Campus</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Between campuses KRA001 effectively runs in the same fashion with the same experiments, assessment tasks, and content. Some small differences occur between different lecturers and...
demonstrators in teach campus. There are major differences however, between the unit offered within semesters 1 and 2 and the unit offered over the summer semester (3). The on-campus mode delivers the content over 13 weeks in the standard unit format with regular lectures and tutorials (2 x 1 hour lectures, and 1 x 1 hour tutorial per week) in addition to the laboratory course. The laboratory course consists of 6 three-hour experiments, i.e., one every two weeks through the semester. The summer semester iteration of KRA001 acts as an abridged version of the semester 1 and 2 counterparts, containing the same content and laboratory course delivered over a brief period of time. As an online mode, the summer semester version offers the majority of its content and assessment tasks over 7 weeks. The laboratory component of this unit fits into two laboratory days where 3 experiments are completed from 9am until 5pm each day.

As this unit runs through multiple semesters each year, implementation of modified teaching approaches occurred in multiple instances across the 4 year period of this study. The results collected from multiple instances of the same teaching approach were then pooled for analysis, based on the assumption that the student cohorts were similar. This assumption is supported by previous work by Pullen et al. (2014).

5.1.3 Laboratory course details

Table 11 below, provides a brief overview of the tasks undertaken and concepts focused upon in each experiment. Those experiments that were studied within this project have been shaded.
# Results: Foundation Chemistry

## Table 11.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Overview</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Safety</td>
<td>The first half of this session acts as an induction for safety within the chemistry laboratory. Upon completing the safety section, a range of activities are offered for students to explore some types of reactions.</td>
</tr>
<tr>
<td>The Analysis of a Solution by Measurement of its Density Using a variety of equipment</td>
<td>Students will first calculate the density of water and compare with a provided literature value to determine the method of most accuracy and precision. Using this identified method, students will then determine the density of a sodium chloride solution of unknown density.</td>
</tr>
<tr>
<td>Distillation as a Separation Technique</td>
<td>This experiment acts as an introduction to the equipment used in a standard distillation apparatus. A sample of hard water, water doped with a mixture of ions found commonly in water samples, is distilled to remove these ions from the water sample. Some simple spot tests are used on both hard water and the distilled product to indicate the presence of ions.</td>
</tr>
<tr>
<td>Preparation and Standardization of Sodium Hydroxide Solution</td>
<td>Students will prepare an approximate concentration of sodium hydroxide solution to be standardized with the use of a known acid, potassium hydrogen phthalate. The standardized sodium hydroxide is then stored to be used in the next experiment.</td>
</tr>
</tbody>
</table>
Identification of a Carboxylic Acid through titration against the standardized sodium hydroxide solution and the determination of any water of crystallization, students will identify one of two unknown acids assigned to them.

Properties of Solutions of Acids and Bases
Within this experiment students will explore the differences between a variety of acids and bases using universal indicators for pH, pH meters, and conductivity meters. Classification of each of these as acid or base, strong or weak, or a salt, will occur in addition to detailing the net ionic equations associated with each substance.

Shaded spaces within Table 11 indicate those experiments included within this study.

5.2 Results
The analysis of each experiment considered for the Foundation unit, KRA001, will be presented in this section. Each experiment will be discussed individually for each aspect considered within the analysis before the overarching outcomes are discussed for this unit. Section 5.2.1 will discuss the first of these,

The Analysis of a Solution by Measurement of its Density.
Sample sizes for the comparisons discussed throughout this Chapter can be found within Appendix I.

5.2.1 The Analysis of a Solution by Measurement of its Density
The Analysis of a Solution by Measurement of its Density experiment serves two primary purposes. As one of the earlier experiments completed during the laboratory course, it further familiarises students with the laboratory layout and basic equipment. Specific to this experiment, emphasis is placed upon the equipment used and the methods of measurement.
possible. Therefore, this experiment is primarily classified as a hands-on experience, with a minor focus on calculations.

During this experiment students use a variety of equipment including pipettes, measuring cylinders, burettes, and both bench and analytical balances to measure the density of water. Through comparison of these combinations, an ideal approach is determined before repeating this method to determine the density of a sodium chloride solution. Finally, their density is converted to both weight by weight and weight by volume values.

Using the experiment design process discussed in Chapter 4, three versions of this experiment were implemented to represent each teaching approach considered: Expository, Guided Inquiry, and Problem Solving. Analysis was completed through several mechanisms as detailed in Section 3.7.

5.2.1.1 Student perceptions – Survey
A one-way between-groups analysis of variance was conducted upon the collected survey responses, to explore the impact of alternative teaching styles on multiple cohorts of students undertaking the chemistry unit, KRA001. For this experiment, the Analysis of a Solution by Measurement of its Density, statistical analysis for the comparison between teaching methods (Expository, N = 86; Guided Inquiry, N = 42; Problem Solving, N = 62) yielded no differences at the p < 0.05 level in the directed questions asked within the survey. The discussion of these surveys has been structured to consider the findings at a broad level before gradually narrowing the focus to identify key sub-themes. The overarching broad themes are identified before inspecting the distribution of positive versus negative responses in each of these themes before finally identifying the specific sub-themes. Throughout Chapter 5 the three
5.2.1.2 Student perceptions – Survey comments

Within Figure 5, the combined, both positive and negative, student comments for The Analysis of a Solution by Measurement of its Density, have been categorized into five overarching themes. These themes are:

• Interaction with others
• Laboratory processes
• Engagement with information
• Overall laboratory experience
• Miscellaneous

What can be drawn from this representation is the proportion of comments made in each of these areas, and how these change between the teaching approaches used. Through a brief observation of the proportions, it is apparent that there are some key differences. For example, the Problem Solving iteration had a considerable increase for comments on the laboratory processes used and a decrease for the interaction with others theme. Where this proportion was changed for Expository and Guided Inquiry were for increases in the engagement with information, overall laboratory experience and interaction with others themes, respectively.
Chapter 5 – Results: Foundation Chemistry

Figure 5. Total distribution of types of survey comments for The Analysis of a Solution by Measurement of its Density experiment (Expository, N = 108; Guided Inquiry, N = 35; Problem Solving, N = 19).

When considering the proportions of positive versus negative comments the depth of conclusions that can be drawn from this greatly increases. For example, when analyzing for sub-themes common between all three teaching approaches of this experiment, the only themes common were comments centring upon the positive interaction with demonstrators and their capacity to run the experiment in an efficient manner. It is clear when considering the broad proportions within Figure 6, excluding the comments classified under the overall experience theme, that each overarching theme has an even balance of positive and negative comments. Investigating this further leads us to sub-themes present for both positive and negative comments.

[Graph showing distribution of survey comments]
Figure 6. The proportion of positive versus negative comments for the overarching themes in the Expository (N = 108) version of *The Analysis of a Solution by Measurement of its Density* experiment.

The sub-themes presented in Table 12 for the Expository version of the *Analysis of a Solution by Measurement of its Density* experiment indicated several areas students deemed as both positive and negative. Aligning with the teaching approach used, students found the clarity of the objectives to be one of the preferred aspects of this iteration. Conversely, students indicated there was a lack of background information that led to a reduced level of understanding upon completion of the experiment. The remaining sub-themes focussed upon aspects of the laboratory not directly related to the teaching approach used. For example, both being a hands-on laboratory and working as a group was a positive experience, while the use of pipettes and a lack of time were negative.
Table 12. Sub-themes observed for the Expository version of The Analysis of a Solution by Measurement of its Density

### Positive

- Hands-on experiment
- Clear objectives
- Group work

### Negative

- Students felt rushed, a lack of time
- Need more background information
- Not enjoying the use of pipettes

Additionally, demonstrators indicated that the key factor for making the Expository experience a positive and successful one was to couple the laboratory format with clear instructions from the provided manual through discussions. This allowed the demonstrators to expand upon the students' intended development of understanding through the experiment while providing a clear structure for the completion of the experiment.

Figure 7 for the Guided Inquiry version paints a far different picture to the proportions observed for the Expository version. Three areas in Figure 7 do not have balanced proportions between positive and negative responses. The laboratory process theme including all equipment, reagents, and processes involved within a laboratory space has a distinct increase of negative comments. Whereas comments within the overall experience theme had the reverse, with a distinct increase of positive comments. Whilst the miscellaneous comments are reported as being all positive, the number of miscellaneous comments was minimal (N = 1) and therefore can be considered as misleading.
Figure 7. The proportion of positive versus negative comments for the overarching themes in the Guided Inquiry (N = 35) version of The Analysis of a Solution by Measurement of its Density experiment.

The sub-themes in Table 13 for the Guided-Inquiry instance of this experiment did not elucidate many specific elements of the experiment. Aspects such as working individually and difficulty hearing demonstrators or peers are often personal preference for students and can be addressed easily. The difficulty hearing was an issue that has been raised previously by demonstrators attributed to the layout of the laboratory. One theme of note however, lies in the number of students listing an uncertainty about the difference between the teaching method used in this experiment, Guided-Inquiry, and other teaching methods they may be used to. Unfortunately, the comments were general and did not highlight any specific differences or similarities. Upon reflection, one potential explanation could lie in the nature of this experiment. Given that this experiment is the first experiment for a Foundation Chemistry unit, the concepts and processes contained could be at a standard that, regardless of teaching approach, may provide a similar experience.
Table 13. Sub-themes observed for the Guided-Inquiry version of the Analysis of a Solution by Measurement of its Density experiment

Positive
• The learning environment

Negative
• Preferred to work individually
• Difficult to hear the demonstrator over the general laboratory noise
• Not sure of the difference between this and other teaching methods

Demonstrators for this instance of the experiment observed that there was a distinct lack of preparation which led to students struggling with any discussions or questions required through the procedure. As this experiment is one of the first experiments undertaken by students in this unit, the importance of preparing for laboratory sessions has not taken hold. The procedure itself was observed to be successful otherwise.

Different once more to both Expository and Guided-Inquiry versions, Figure 8 illustrates the proportions of positive versus negative comments for the Problem-Solving version of this experiment. The two key indicators of difference lie in the responses categorized into the interaction with others, both peers and demonstrators, and the engagement with information overarching themes. In both cases, an increase in the negative comments was observed with a much larger effect for the engagement with information theme.
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Figure 8. The proportion of positive versus negative comments for the overarching themes in the Problem Solving (N = 19) version of The Analysis of a Solution by Measurement of its Density experiment.

The sub-themes for this teaching approach have been displayed within Table 14. The positive themes identified were based upon two aspects of the laboratory. One being the self paced approach to a Problem Solving experience allowing students to develop their own methods and implement them on their terms. The second being the group discussions held prior to the laboratory start. For the Problem Solving version of this experiment, particular care was given to allow students a chance to engage within these group discussions and voice concerns or ideas based on their plan. The negative sub-themes identified were aligned with concerns on the information within the laboratory. Both for the information and instructions in the laboratory manual, and the lack of chemistry knowledge of students prior to beginning the experiment. Interestingly, some student felt that the openness of the experimental information in the laboratory manual had caused them to over-prepare for the experiment, which was considered a negative effect. This finding is a direct contrast to one of the results obtained for Guided-Inquiry where a lack of preparation was observed.
Chapter 5 – Results: Foundation Chemistry

Table 14. Sub-themes observed for the Problem Solving version of the Analysis of a Solution by Measurement of its Density experiment

<table>
<thead>
<tr>
<th>Positive</th>
<th>Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Self-paced with an appropriate workload</td>
<td>• The information and instructions in the laboratory manual were lacking</td>
</tr>
<tr>
<td>• Group discussions prior to individual work</td>
<td>• Lack of chemistry knowledge to support this teaching approach</td>
</tr>
<tr>
<td>• Some students felt they had over-prepared</td>
<td>• Some students felt they had under-prepared</td>
</tr>
</tbody>
</table>

Demonstrators noted for the Problem Solving version of this experiment that while the experience overall was positive for both themselves and their students, the verbal explanations provided throughout the experiment were considerably more difficult than normal.

5.2.1.3 Student performance – Grade

Using the method discussed in Section 3.5.1, statistically significant differences at the p < 0.05 level were only found in the averages for each of the three criteria, but also in the overall grade given to students. Figure 9 displays the comparison of the three teaching approaches (Expository, N = 97; Guided Inquiry, N = 72; Problem Solving, N = 79) for the overall grade and the respective criteria. The three criteria have been discussed in detail within Section 3.5.3 and are defined as:

1. Completion of pre-laboratory requirements and work safely and efficiently within a laboratory
2. Use of the correct techniques and calculations

...
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3. Understanding of the concepts and principles

Figure 9. Comparison of grades between teaching methods for The Analysis of a Solution by Measurement of its Density experiment in KRA001. True values: Criterion 1 - 20, Criteria 2 and 3 - 40 scaled to percentage with percentage error represented as error bars. For the post-hoc analyses, two tests were available for use: the Games-Howell test and the Tukey HSD test. Which test is used is determined via use of Levene's test for homogeneity of variances. For those comparisons of variances where the significance value (p) was greater than 0.05, the homogeneity of variances assumption has not been violated and the Tukey HSD test may be used. For p values less than 0.05, the Games-Howell test is used. For each comparison where significant differences were identified, the effect size (Cohen, 1988, pp. 284-290).
Cohen classifies 0.01 as a small effect size, 0.06 as a medium effect and 0.14 as a large effect size. The summary of the analyses completed for The Analysis of a Solution by Measurement of its Density experiment can be found in Table 15. Post-hoc comparisons using the Games-Howell test for Criterion 1 indicated that the mean scores for both Expository ($\mu = 16.89, \sigma = 2.38$) and Problem Solving ($\mu = 16.56, \sigma = 3.03$) were significantly different to Guided Inquiry ($\mu = 14.875, \sigma = 4.72$). The effect size for Criterion 1, calculated using eta squared, was 0.07. An effect of this size is considered as a medium effect as defined by Cohen (1988, pp. 284-7).

Post-hoc comparisons using the Tukey HSD test for Criterion 2 indicated that the mean scores for both Expository ($\mu = 31.16, \sigma = 4.23$) and Problem Solving ($\mu = 29.68, \sigma = 4.56$) were significantly different to Guided Inquiry ($\mu = 27.04, \sigma = 5.24$). The effect size for Criterion 2 was 0.12, a size of which is considered as a large effect as defined by Cohen.

Post-hoc comparisons using the Tukey HSD test for Criterion 3 indicated that the mean scores for Expository ($\mu = 29.38, \sigma = 4.61$) were significantly different to both Guided Inquiry ($\mu = 26.125, \sigma = 5.51$) and Problem Solving ($\mu = 27.56, \sigma = 4.60$). The effect size for Criterion 3 was 0.07, a size of which is considered as a medium effect.

Post-hoc comparisons using the Games-Howell test for the overall Grade indicated that the mean scores for both Expository ($\mu = 77.53, \sigma = 8.94$) and Problem Solving ($\mu = 74.60, \sigma = 10.66$) was significantly different to Guided Inquiry ($\mu = 69.06, \sigma = 13.64$). The effect size for the overall Grade was 0.09, a size of which is considered as a medium effect.
Table 15. Post-hoc output of comparisons of students' overall grade yielding significant differences at a 95% confidence interval for the Analysis of a Solution by Measurement of its Density experiment.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Comparison</th>
<th>Post-Hoc*</th>
<th>Effect Size</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criterion 1</td>
<td>Expository &gt; Guided Inquiry</td>
<td>Games–Howell</td>
<td>0.07 (medium)</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Problem Solving &gt; Guided Inquiry</td>
<td>Games–Howell</td>
<td>0.07 (medium)</td>
<td>0.018</td>
</tr>
<tr>
<td>Criterion 2</td>
<td>Expository &gt; Guided Inquiry</td>
<td>Tukey</td>
<td>0.12 (medium)</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>Problem Solving &gt; Guided Inquiry</td>
<td>Tukey</td>
<td>0.07 (medium)</td>
<td>0.002</td>
</tr>
<tr>
<td>Grade</td>
<td>Expository &gt; Guided Inquiry</td>
<td>Games–Howell</td>
<td>0.09 (medium)</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>Problem Solving &gt; Guided Inquiry</td>
<td>Games–Howell</td>
<td>0.09 (medium)</td>
<td>0.011</td>
</tr>
</tbody>
</table>

*Post-Hoc tests determined by Levene's test for homogeneity of variances as discussed in Section 5.2.1.3.

5.2.1.4 Student Performance – Quiz

The post-laboratory quiz for the Analysis of a Solution by Measurement of its Density experiment contained a total of 5 questions to address the key concepts or techniques used within this laboratory. These questions have been summarised below:

Question 1a – Focuses upon the identification of significant figures in provided values.

Question 1b – Performs a calculation using the provided values in Question 1a.

Question 2 – Recognition and differentiation between analytical and top-loading balances.

Question 3 – Using provided values, students calculate density.

Question 4 – Using the density calculated in Question 3, students convert a provided % w/v composition to % w/w.
In the analysis of the data collected for these questions, responses were judged one of the following: correct, partially correct, incorrect, or did not attempt. For simplicity, the output of this analysis displays only the correct (in blue) and the partially correct (in red) responses. The pictorial comparison between teaching approaches for these questions have been summarised in Figure 10.

Figure 10. Percentage of correct (blue) and partially correct (red) responses to questions contained within the post-experiment quiz for The Analysis of a Solution by Measurement of its Density experiment (Expository, N = 86; Guided Inquiry, N = 38; Problem Solving, N = 56).

When considering the performance of students through the completion of a post-experiment quiz, the first most apparent outcome observed is the similarity between the Expository and Guided Inquiry approaches.
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Problem Solving versions of this experiment. Without delving into specifics of each question, concepts or techniques, both of these teaching methods not only had comparable correct responses but also partially correct responses for their respective cohorts. The Guided-Inquiry cohort appeared to be performing at a lower level of understanding for these concepts, but of most concern for questions 2 and 4. Respectively, these questions test for knowledge and understanding of the two types of balances used within the laboratory, and the conversion of % weight by volume (w/v) to % weight by weight (w/w). No obvious characteristic of Guided Inquiry could be identified as causing this lack of understanding. One potential explanation could be the wealth of information students engaged with when addressing both the discussion points and procedure at the same time. This may have led to an overloading of information causing misunderstandings or confusion when answering the post-experiment quiz.

5.2.1.5 Summary of results

With no differences observed within the survey questions posed to the student cohort it becomes necessary to assume all three teaching methods were achieving an approximately equal standard for the survey questions. Investigating further by considering the responses from students gives an indication of some differences however, between the teaching approaches. The overarching view of the distribution of comments, combining both positive and negative, indicated that between teaching methods there were differences in what themes were of most interest to the students upon completion of their experiment. The major difference lay within the proportion of comments relating to the laboratory process. On the whole the Expository style was fairly evenly distributed across each of the themes (interaction with others, laboratory process, engagement with information, overall, and miscellaneous) excepting the overall experience being all positive. Guided Inquiry and Problem Solving styles...
were found to have a large proportion shift to negative for the laboratory process and engagement with information themes respectively.

Looking at the comparison of grades between teaching methods there was a definitive increase for both Expository and Problem Solving over the Guided Inquiry approach. Whilst both Criterion 1 and 3 had only a medium effect size (as defined by Cohen), Criterion 2, the criterion allocated for performance in the use of calculations and techniques, was observed to have a large effect size. This indicates that students completing the Expository and Problem Solving versions were performing at a higher standard for the relevant calculations and techniques used within this experiment. Realistically however, despite there being an increase for both Expository and Problem Solving, the difference observed is the difference between a Distinction with an approximate grade of 70% for Guided Inquiry and both Expository and Problem Solving sitting around 75% and 80%.

Finally, the results observed for the comparison of quiz responses indicated that both Expository and Problem Solving were similar in the standard shown by students. Students completing the Guided Inquiry version however, were found to be performing at a lower standard for two of the concepts tested through this quiz. This result may have resulted from a perceived increase in workload by integrating discussion questions and challenges through the procedure.

Based on the collation of this data, it becomes apparent that in terms of which teaching approach had the most success for The Analysis of a Solution by Measurement of its Density experiment, Guided Inquiry can be definitively ruled out. The Expository and Problem Solving versions become more difficult to separate. In most comparisons, both teaching approaches...
were observed to be operating at a similar standard, the exception lying in the student free-text responses where Expository appeared to be better balanced in terms of student reception.

The final consideration to take into account is the realistic implementation of this experiment within the laboratory course it is offered in. Given that this experiment is typically the second experiment, the first true wet laboratory experiment. In addition to the nature of this unit being composed of many first time laboratory students. The additional workload and pre-knowledge required for the Problem Solving version makes it unfavourable in comparison to the Expository approach.

5.2.2 Distillation as a Separation Technique

The Distillation as a Separation Technique experiment focuses upon two learning objectives. Firstly to enable familiarity with the equipment and techniques associated with completing a distillation. Secondly, to describe the interactions between multiple molecules using ionic equations. As such, the primary focus on this experiment is the development of hands-on skills for both general and specialized equipment.

Students completing this experiment work in pairs initially to setup and run a steam distillation of a hard water sample to remove contaminants and collect a distilled water product. As this distillation is running, students individually complete small-scale spot tests to determine the presence of particular ion contaminants in a hard water sample. Upon completion of the distillation, individual tests are then completed on the distilled product to compare for the presence of the ion contaminants tested earlier. Finally, the observed outcomes of these spot-tests, or lack thereof, are described using ionic equations and discussion.
5.2.2.1 Student perceptions – Survey

A one-way between groups analysis of variance was conducted to explore the impact of alternative teaching styles on multiple cohorts of students undertaking the chemistry unit, KRA001. For this experiment, Distillation as a Separation Technique, statistical analysis for the comparison between teaching methods (Expository, N = 76; Guided Inquiry, N = 46; Problem Solving, N = 75) yielded no differences at the \( p < 0.05 \) level in the directed questions asked within the survey.

5.2.2.2 Student perceptions – Survey comments

Within Figure 11, the combined student comments, both positive and negative, for the Distillation as a Separation Technique have been categorized into five overarching themes as discussed in Section 5.2.1.2. Across all three teaching approaches the engagement with information, overall experience and miscellaneous themes appear to remain unchanged. The major differences can be seen clearly in the proportion of comments being submitted between the interaction with others and the laboratory process themes. For the interaction with others theme, the Guided Inquiry approach has the highest proportion of student comments before the Expository and finally Problem Solving approaches.
Figure 11. Total distribution of types of survey comments for the Distillation as a Separation Technique experiment (Expository, N = 56, Guided Inquiry, N = 49; Problem Solving, N = 58).

Only one sub-theme was consistent throughout all three teaching approaches: the positive experience of working in small groups for the initial setup of the full steam distillation equipment and the subsequent collection of distilled water.

The proportions of responses for each of the overarching themes for the Expository version of the Distillation as a Separation Technique experiment are within Figure 12. Consideration of these proportions indicated some imbalances for the overarching themes. The laboratory process theme was the one exception. Both interaction with others and the overall experience themes had solely positive student feedback for the free-form text comments, whilst the engagement with information theme had a distinct skew of more negative responses than positive. At this level of observation it can be surmised that while students enjoyed the physical actions and the interaction with both demonstrators and peers, a gap or problem of some kind existed within the information being provided leading to a negative experience.
Figure 12. The proportion of positive versus negative comments for the overarching themes in the Expository (N = 56) version of the Distillation as a Separation Technique experiment.

To investigate the students responses at a finer level, Table 16 details the sub-themes that were identified across all five overarching themes. The sub-themes identified continue to develop the idea that students are enjoying the hands-on physical aspect of this laboratory, whilst at the same time struggling with the concepts that are required for completion of the laboratory. Interestingly, there was a split of responses for both positive and negative experiences with the set up of the distillation itself. Ionic equations in particular were highlighted multiple times by students as a point of frustration and lack of understanding. A miscellaneous comment that was also prevalent was the indication from students that the addition of content to be completed during the distillation process would be welcomed. One resolution to this gap in the experiment would be the inclusion of information and activities to better improve the understanding of ionic equations.
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Table 16. Sub-themes observed for the Expository version of the Distillation as a Separation Technique experiment

<table>
<thead>
<tr>
<th>Positive</th>
<th>Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>- The setup of the distillation</td>
<td>- The setup of the distillation as a laboratory process</td>
</tr>
<tr>
<td>- The comparison of before and after distillation spot-tests</td>
<td>- Understanding the process of distillation as a concept</td>
</tr>
<tr>
<td>- General comments for the enjoyment of the laboratory</td>
<td>- The construction and use of ionic equations</td>
</tr>
</tbody>
</table>

In comparison to the student comment proportions observed for the Expository approach, the proportion in Figure 13 for the Guided Inquiry style displays a much more balanced range of comments. Solely positive responses were observed for the overall experience theme once again but a smaller skew of positive responses for the interaction with others can be seen.

Figure 13. The proportion of positive versus negative comments for the overarching themes in the Guided Inquiry (N = 49) version of the Distillation as a Separation Technique experiment.
The responses given by students within the free-text entry spaces of the surveys were varied such that only 2 sub-themes were identified, both of which were positive, as seen within Table 17. Any negative comments could be described as individual concerns rather than concerns that may influence the entire class. Demonstrators mirrored this with their comments reflecting on the positive overall experience for both demonstrators and the students completing this experiment. Some minor laboratory manual adjustments were noted by the demonstrators to reduce confusion for the recording of results.

Table 17. Sub-themes observed for the Guided Inquiry of the Distillation as a Separation Technique

<table>
<thead>
<tr>
<th>Positive</th>
<th>Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>• General comments for the enjoyment of the laboratory</td>
<td></td>
</tr>
<tr>
<td>• Interaction with the demonstrators specifically.</td>
<td></td>
</tr>
<tr>
<td>• No negative sub-themes were identified.</td>
<td></td>
</tr>
</tbody>
</table>

In Figure 14, the responses give an immediate indication of two very strong themes for the Problem Solving version of the Distillation as a Separation Technique experiment. Notably, all responses relating to interaction with peers or demonstrators were solely positive. Conversely, all responses relating to the engagement with information theme, through the laboratory manual, lectures, pre-readings, or provided information during the laboratory, were negative. Interestingly, the laboratory processes theme remained largely the same between all three teaching approaches.
A variety of sub-themes were identified for the Problem Solving version of this experiment as displayed in Table 18. Based on the comments received, the students responded well to the Problem Solving nature of the teaching approach and highlighted the ability to have some control of the experimental direction in their laboratory. There was a mix of comments relating to clarity within the laboratory manual with a reasonable split for those who found the manual clear and those who did not. One of the negative sub-themes observed indicated students felt there was not enough work, and that an expansion of this experiment would be feasible. While not specifically noted within this experiment, students from a number of Problem Solving versions of other experiments indicated an increased workload for Problem Solving as a negative sub-theme. The responses from demonstrators indicated a preference for the Problem Solving approach; the reasoning given conceded that whilst the Expository approach was rapid in its completion, the Problem Solving approach was both more enjoyable and allowed students to gain a better understanding of the concepts.
### Table 18. Sub-themes observed for the Problem Solving version of the Distillation as a Separation Technique

<table>
<thead>
<tr>
<th>Positive</th>
<th>Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>• General comments on the experiment</td>
<td>• Explanations and information provided during the experiment</td>
</tr>
<tr>
<td>• Clear layout within the laboratory manual</td>
<td>• Wording is vague, some of the questions posed in the laboratory manual</td>
</tr>
<tr>
<td>• Flexibility for students to design their experiments direction</td>
<td>• Not enough work for a three hour laboratory session</td>
</tr>
</tbody>
</table>

#### 5.2.2.3 Student performance – Grade

Statistically significant differences at the p < 0.05 level were only found in the averages for each of the three criteria, but also for the overall grade given to the students. The comparisons of the three teaching approaches (Expository, N = 96; Guided Inquiry, N = 69; Problem Solving, N = 78) for the overall grade and respective criteria is shown in Figure 15.
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Figure 15. Comparison of grades between teaching methods for the Distillation as a Separation experiment in KRA001. True values: Criterion 1 - 20, Criteria 2 and 3 - 40 scaled to percentage with percentage error represented as error bars.

The statistical analysis for the comparison of the teaching approaches for the grades is shown in Table 19. The post-hoc tests used were determined by Levene’s test for homogeneity of variances as discussed in Section 5.2.1.3. Post-hoc comparisons using the Games-Howell test for Criterion 1 indicated that the mean score for the Problem Solving (µ = 18.31, σ = 2.00) version was significantly different to both the Expository (µ = 16.77, σ = 2.86) and Guided Inquiry (µ = 17.09, σ = 2.71) versions. The effect size for Criterion 1, calculated using eta squared, was 0.06. An effect of this size is considered a medium effect. Post-hoc comparisons using the Games-Howell test for Criterion 2 indicated that the mean score for the Problem Solving version was significantly different to both the Expository and Guided Inquiry versions.
Solving ($\mu = 33.13, \sigma = 3.64$) was significantly different to both the Expository ($\mu = 31.09, \sigma = 4.95$) and the Guided Inquiry ($\mu = 29.57, \sigma = 3.62$). The effect size for Criterion 2 was 0.10, i.e., a medium effect. Post-hoc comparisons using the Tukey HSD test for Criterion 3 indicated that the mean score for Problem Solving ($\mu = 30.90, \sigma = 4.87$) was significantly different to the Guided Inquiry ($\mu = 27.87, \sigma = 4.53$). The effect size for Criterion 3 was 0.06, i.e., a medium effect. Post-hoc comparisons using the Tukey HSD test for the overall Grade indicated that the mean score for the Problem Solving ($\mu = 81.94, \sigma = 9.09$) was significantly different to both the Expository ($\mu = 77.47, \sigma = 10.69$) and the Guided Inquiry ($\mu = 75.30, \sigma = 9.19$). The effect size for the overall Grade was 0.07, i.e., a medium effect.

Table 19. Post-hoc output of comparisons of students' overall grade yielding significant differences at a 95% confidence interval for the Distillation as a Separation Technique experiment:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Post-Hoc*</th>
<th>Effect Size</th>
<th>Comparison</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criterion 1</td>
<td>Games–Howell</td>
<td>0.06</td>
<td>(medium)</td>
<td>Problem Solving &gt; Guided Inquiry &lt; 0.001, Problem Solving &gt; Expository 0.007</td>
</tr>
<tr>
<td>Criterion 2</td>
<td>Games–Howell</td>
<td>0.10</td>
<td>(medium)</td>
<td>Problem Solving &gt; Guided Inquiry &lt; 0.001, Problem Solving &gt; Expository 0.006</td>
</tr>
<tr>
<td>Criterion 3</td>
<td>Tukey</td>
<td>0.06</td>
<td>(medium)</td>
<td>Problem Solving &gt; Guided Inquiry &lt; 0.001, Problem Solving &gt; Expository 0.005</td>
</tr>
</tbody>
</table>

*Post-Hoc tests determined by Levene’s test for homogeneity of variances as discussed in Section 5.2.1.3.
5.2.2.4 Student performance - Quiz

The post-laboratory quiz for the Distillation as a Separation Technique experiment contained two questions to encompass the key concepts and techniques used within this laboratory. These questions, loosely adapted from the original, were:

Question 1 – Requires a description of the distillation process and how this is used to achieve separation.

Question 2 – Given a chemical reaction, students must provide the corresponding total and net ionic equations.

As discussed in Section 5.2.1.4, the results presented in Figure 16 below display the percentage of students who provided correct (blue) or partially correct (red) answers.

Comparing the standards achieved for each question between the three teaching approaches, no teaching approach clearly performs at a higher standard. For Question 1 both Expository and Problem Solving had a larger proportion of students correctly answering the question than...
Guided Inquiry. All three, however, had responses that were partially correct for the majority of the students who completed the quiz. For Question 2, Problem Solving had the largest proportion of students correctly giving the net and total ionic equations. When considering the partially correct responses, however, Guided Inquiry had a far higher percentage of students than both Expository and Problem Solving. The misconceptions causing partially correct responses were largely the same across all three teaching approaches.

The major misconceptions causing answers to be only partially correct for Question 1 was failing to recognize how distillation takes advantage of different boiling points. Students would often quote that the water would boil off because what was left behind could not transition to a gas. The partially correct responses for Question 2 were a mixture amongst the absence of identifying states of matter, failing to balance equations correctly, and correctly describing the net ionic equation but unable to describe the total ionic equation.

5.2.2.5 Summary of results
Analysis of the directed questions within the survey yielded no significant differences between the teaching approaches for the Distillation as a Separation Technique experiment. Analysis of the free text entry component of the survey provides some contrasting indication of differences between the teaching approaches. At the broadest level of analysis it was observed that for Expository, Guided Inquiry and Problem Solving there was a definite trend of a shift between comments being made within the interaction with others and laboratory process themes. The order of this trend for interaction with others having the most responses to the least was Guided Inquiry, Expository and finally Problem Solving. Responses for the laboratory...
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Guided Inquiry had a far better mixture of positive and negative comments referring to this theme. This outcome was despite the trend indicating more comments were made within the Guided Inquiry approach than both the Expository and Problem Solving approaches. The Expository and Problem Solving approaches were almost entirely negative when considering responses within the same theme. The sub-themes identified for each teaching approach also yielded some interesting outcomes. The Expository approach sub-themes, particularly the negative tones, were for the most part concerned with components of the laboratory that required understanding of the equipment or concepts utilized within the experiment. The Guided Inquiry approach, despite having varied responses, was identified as a mostly positive experience with no particular weak or confusing areas for students. Of most interest perhaps was the Problem Solving approach, as a contrast to the Expository approach responses; the sub-themes identified there were concerned with components of the laboratory that are easily accessible for amendment. For example, the explanations or information provided during the experiment, the structure and clarity of the laboratory manual, and the indication that students would like more work to complete during this laboratory session.

The performance of students during this laboratory as defined by the assessment provided by demonstrators. The grades, when compared afterwards, indicated the presence of significant differences between the three teaching approaches. To be specific, the grades for the Problem Solving approach were significantly higher than both Expository and Guided Inquiry approaches, though the effect size for these comparisons were of a medium size and therefore negligible. Furthermore, all three teaching approaches had calculated average grades within the DN and HD range, well above the standard required to pass this laboratory.
The post-experimental quiz to determine students' understanding of key techniques or concepts within this experiment did not yield any conclusive results for one teaching approach being superior. Question 1 centred upon demonstrating an understanding of the equipment used, with all three teaching approaches demonstrating similar responses. Question 2, however, which centred upon the demonstration of chemistry knowledge and application for net and total ionic equations, appeared to significantly favour the Guided Inquiry approach.

With these findings in mind, it is apparent that the Guided Inquiry approach has a slight edge in several areas. Firstly, the student experience, as determined via their free-text entry spaces, indicated that while both the Guided Inquiry and Problem Solving approaches were received well, the Guided Inquiry approach did not appear to have any specific weaknesses. Secondly, despite the grade awarded to students for their performance in the laboratory, as determined by the demonstrators, being relatively the same between the teaching approaches, the understanding demonstrated by the students through the post-experiment quiz indicated that the Guided Inquiry approach was superior. Within the laboratory course in current implementation, this is the third experiment of the course and aside from the set-up of the distillation equipment itself, features no new laboratory skills. It is therefore concluded that the Guided Inquiry approach was of most success for the Distillation as a Separation Technique experiment.
5.2.3 Identification of a Carboxylic Acid

The Identification of a Carboxylic Acid experiment is designed as a follow-on experiment to a previous experiment in which each student standardizes a unique sodium hydroxide solution. As the previous experiment focuses upon developing the technique of titration, this experiment focuses instead upon the application of the titration technique in conjunction with understanding and applying the concept of equivalent mass to identify their carboxylic acid provided. As such, this experiment falls under the thinking and interpretation category for experiment type.

This experiment contains two primary components that the students complete. Firstly, students identify whether their sample contains any water molecules within its crystal structure; a small sample is dried within an oven to identify any water of crystallization by change in mass. Secondly, during this drying time the technique of titration is applied using their standardized sodium hydroxide solution to determine the equivalent mass of their unknown carboxylic acid. Through the interpretation of these two components' results and provided information on a range of possible carboxylic acids, students can then identify their carboxylic acid.

5.2.3.1 Student perceptions – Survey

A one-way between groups analysis of variance was conducted to explore the impact of alternative teaching styles on multiple cohorts of students undertaking the chemistry unit, KRA001. For this experiment, Identification of a Carboxylic Acid, statistical analysis for the comparison between teaching methods (Expository, N = 74; Guided Inquiry, N = 30; Problem Solving, N = 40) yielded no differences at the $p < 0.05$ level in the directed questions asked within the survey.
5.2.3.2 Student perceptions – Survey comments
Unfortunately, the data for this component of the study was mislaid. If more time was available for this study, another iteration of this experiment would be run to collect new data for analysis and comparison.

5.2.3.3 Student performance – Grade
The average overall grades and respective criteria (Expository, N = 95; Guided Inquiry, N = 68; Problem Solving, N = 85) for the Identification of a Carboxylic Acid experiment are shown in Figure 17. Statistically significant differences at the p < 0.05 level were not found in the averages for each of the three criteria, but also the overall grade given to students.
Figure 17. Comparison of grades between teaching methods for the Identification of a Carboxylic Acid experiment in KRA001. True values: Criterion 1 - 20, Criteria 2 and 3 - 40 scaled to percentage with percentage error represented as error bars. The post-hoc tests were decided as discussed in Section 5.2.1.3. A summary of the statistical analyses can be found in Table 20. Post-hoc comparisons using the Games-Howell test for Criterion 1 indicated that the mean score for the Problem Solving (µ = 17.34, σ = 2.68) was significantly different to both the Expository (µ = 15.90, σ = 3.56) and the Guided Inquiry (µ = 15.59, σ = 3.72). The effect size for Criterion 1 was 0.05, i.e., a small effect. Post-hoc comparisons using the Tukey HSD test for Criterion 2 indicated that the mean score for the Problem Solving (µ = 30.52, σ = 4.19) was significantly different to the Guided Inquiry (µ = 28.26, σ = 4.65). The effect size for Criterion 2 was 0.04, i.e., a small effect. Post-hoc comparisons using the Games-Howell test for Criterion 3 indicated that the mean score for the Problem Solving (µ = 35.21, σ = 5.35) was significantly different to both the Expository (µ = 32.60, σ = 5.18) and the Guided Inquiry (µ = 32.19, σ = 5.32). The effect size for Criterion 3 was 0.06, i.e., a small effect.
Comparisons using the Tukey HSD test for Criterion 3 indicated that the mean score for the Problem Solving ($\mu = 30.52, \sigma = 3.76$) was significantly different to the Guided Inquiry ($\mu = 27.99, \sigma = 4.92$). The effect size for Criterion 3 was 0.03, i.e. a small effect. Post-hoc comparisons using the Tukey HSD test for the overall Grade indicated that the Problem Solving ($\mu = 77.77, \sigma = 8.87$) was significantly different to the Guided Inquiry ($\mu = 72.61, \sigma = 11.78$). The effect size for the overall Grade was 0.04, i.e. a small effect.

Table 20. Post-hoc output of comparisons of students' overall grade yielding significant differences at a 95% confidence interval for the Identification of a Carboxylic Acid experiment.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Post-Hoc*</th>
<th>Effect Size</th>
<th>Comparison</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criterion 1</td>
<td>Games–Howell</td>
<td>0.05 (small)</td>
<td>Problem Solving &gt; Expository</td>
<td>0.006</td>
</tr>
<tr>
<td>Criterion 2</td>
<td>Tukey</td>
<td>0.04 (small)</td>
<td>Problem Solving &gt; Guided Inquiry</td>
<td>0.007</td>
</tr>
<tr>
<td>Criterion 3</td>
<td>Tukey</td>
<td>0.03 (small)</td>
<td>Problem Solving &gt; Guided Inquiry</td>
<td>0.033</td>
</tr>
<tr>
<td>Grade</td>
<td>Tukey</td>
<td>0.04 (small)</td>
<td>Problem Solving &gt; Guided Inquiry</td>
<td>0.006</td>
</tr>
</tbody>
</table>

*Post-Hoc tests determined by Levene's test for homogeneity of variances as discussed in Section 5.2.1.3.

5.2.3.4 Student performance – Quiz

The Identification of a Carboxylic Acid post-laboratory quiz contained four questions covering the key concepts and skills used in this experiment. A summary of each question has been listed below:
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Question 1 – Students must demonstrate an understanding of what is required to identify an unknown compound, with examples.

Question 2 – Back calculation utilizing molar equivalence and titration.

Question 3 – Defining the term diprotic.

Question 4 – Students must provide the empirical formula for a variety of molecular representations provided.

The post-laboratory quiz responses are displayed in Figure 18. As discussed in Section 5.2.1.4, the percentage of correct (blue) and partially correct (red) are pictorially compared for each question.
When considering the comparison of standards achieved by students completing each teaching approach for the Identification of a Carboxylic Acid experiment, similar proportion of correct or partially correct responses occur for all teaching approaches. To be specific, both student cohorts who completed the Expository and Problem Solving versions of this experiment performed to a similar standard. The Guided Inquiry cohort by comparison appeared to have performed at a higher standard in all four questions posed. This finding is direct contrast to the Analysis of a Solution by Measurement of its Density experiment in Section 5.2.1.4. Two possible explanations come to mind: Firstly, that this particular cohort alternated in success when approaching these two experiments. Or secondly, Guided Inquiry

\[
\text{Figure 18. Percentage of correct (blue) and partially correct (red) responses to questions contained within the post-experiment quiz for the Identification of a Carboxylic Acid experiment (Expository, N = 80; Guided Inquiry, N = 21; Problem Solving, N = 33).}
\]
as a teaching approach was more aligned with the learning outcomes intended for the experiment. One partial exception to this lies in Question 2 where no students who completed the Guided Inquiry post-experimental quiz gave a correct answer, whereas both the Expository and Problem Solving cohorts did.

5.2.3.5 Summary of results

A major limitation for this particular experiment is the lack of data concerning the student experience as provided through the free-text entry spaces of the survey. Analysis of the directed questions posed on the survey indicated no statistically significant differences between the three teaching approaches for this experiment. Furthermore, upon analysis of the average grades for each teaching approach, despite statistically significant differences being observed, the calculated effect sizes for each variable was of a small size and therefore negligible. Finally, the data collected from students on their understanding of the core techniques and concepts through the post-experimental quiz indicated that the Guided Inquiry cohort of students achieved a higher standard in each of the questions posed. While it could be argued that all three teaching methods perform to a similar standard. The understanding demonstrated by students within the post-experimental quiz by the Guided Inquiry student cohort indicates that would be the most beneficial teaching approach. Given the limited data however, this would require further implementation to confirm this conclusion.
5.2.4 Properties of Solutions of Acids and Bases

The experiment differs from the other experiments within the KRA001 laboratory course as it is completed in small groups of 4 to 5 students. The primary focus of this experiment is the development and practice of observational skills, including the use of pH measuring tools and conductivity measurement. Using the observations and data collected, students then classify a range of solutions based on their pH and conductivity. Finally, the ionic equations for both dissociation and hydrolysis, where applicable, are detailed for each solution.

5.2.4.1 Student perceptions – Survey

A one-way between groups analysis of variance was conducted to explore the impact of alternative teaching styles on multiple cohorts of students undertaking the chemistry unit, KRA001. For the Properties of Solutions of Acids and Bases experiment, statistical analysis for the comparison between teaching methods (Expository, N = 69; Guided Inquiry, N = 41; Problem Solving, N = 46) yielded no differences at the p < 0.05 level in the directed questions asked within the survey.

5.2.4.2 Student perceptions – Survey comments

The distribution of comments amongst the broad themes previously discussed in this Chapter for the Properties of Solutions of Acids and Bases experiment are displayed within Figure 19. Inspection of these distributions yields no clear trends. There are however some interesting changes between each teaching approach. The majority of the comments given by the student cohort who completed the Expository version of this experiment lie within the interaction with others and the laboratory process themes. The Guided Inquiry teaching approach data gave a balanced distribution between three of the themes, interaction with others, engagement with the content, and problem solving.
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Information, and the overall laboratory experience. The laboratory process theme in comparison to the Expository iteration was considerably reduced. The Problem Solving version of this experiment was dominated by comments within the engagement with information theme with an equal spread amongst the other themes excepting the miscellaneous comments.

Figure 19. Total distribution of types of survey comments for the Properties of Solutions of Acids and Bases experiment (Expository, N = 39; Guided Inquiry, N = 28; Problem Solving, N = 23).

Two sub-themes were identified that were common across all three teaching approaches. These included a positive response to the experiments being completed in small groups rather than individual tasks. In addition to this, all student cohorts reported their respective teaching approach versions of the experiment as an overall positive laboratory experience. Being the final laboratory of the course however, this may have influenced their experience in comparison to other laboratories.
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The proportion of comments for each broad theme when broken down to the positive versus negative, shown in Figure 20, gives a strong indication of the Expository teaching approach’s strengths and weaknesses. Interaction with others, the overall laboratory experience, and the comments within the miscellaneous themes all mostly consisted of positive responses from students. Conversely, both the laboratory processes and the engagement with information themes mostly consisted of negative comments.

![Figure 20](image)

Figure 20. The proportion of positive versus negative comments for the overarching themes in the Expository \((N = 39)\) version of the *Properties of Solutions of Acids and Bases* experiment

The sub-themes identified for the Expository version of the *Properties of Solutions of Acids and Bases* experiment have been summarised within Table 21. The majority of comments made throughout the themes were quite varied with no distinct positive sub-themes being identified and only one negative sub-theme. Interestingly, the negative sub-theme centred upon students requesting more content for the experiment. The reasoning varying between an inclination for more to do and further content to deepen their understanding beyond the
Demonstrators reported a mixture of student efficiency, with some finishing well within the timeframe while others struggled with the calculations and conclusions component of the experiment and using the full time allotted.

Table 21. Sub-themes observed for the Expository version of the Properties of Solutions of Acids and Bases experiment

Positive
• No positive sub-themes were identified.

Negative
• Students reported a preference for an increase in content for this experiment.

Interestingly, when the results within Figure 21 are compared with the respective results obtained for the Expository iteration of this experiment, a very similar trend is observed. The proportion of positive to negative comments has reduced by a small margin and no comments were identified for the broad miscellaneous theme.
Figure 21. The proportion of positive versus negative comments for the overarching themes in the Guided Inquiry (N = 28) version of the Properties of Solutions of Acids and Bases experiment.

The comments for the Guided inquiry approach were similar to the Expository iteration in being quite varied and only negative sub-themes were identified, as seen in Table 22. Of these, the first relating to the laboratory manual is interesting, as the tables in question had not been altered from the Expository version of this experiment. This would suggest that because of the straightforward nature of the instructions provided within the Expository procedure, student understanding of the tables was greater than the student cohort completing the Guided Inquiry version. The other two sub-themes were related in that many students who quoted a lack of engagement similarly asked for further background information to help not only with their understanding but also clarify the content of the experiment.
### Table 22: Sub-themes observed for the Guided Inquiry version of the Properties of Solutions of Acids and Bases

<table>
<thead>
<tr>
<th>Positive</th>
<th>Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>• No positive sub-themes were identified.</td>
<td>• The tables within the laboratory manual were confusing</td>
</tr>
<tr>
<td>• More background information for the mathematics, equations and concepts</td>
<td>• Students felt they were not engaged by this teaching approach.</td>
</tr>
</tbody>
</table>

It can be observed from the results in Figure 22 that both interaction with others and the overall laboratory experience retained a high proportion of positive to negative comments. This outcome follows the trend from the two previous teaching approaches discussed, Expository and Guided Inquiry. The laboratory process and engagement with information themes however, further shifted to a balance between positive and negative comments.
Figure 22. The proportion of positive versus negative comments for the overarching themes in the Problem Solving (N = 23) version of the *Properties of Solutions of Acids and Bases* experiment

The sub-themes for the Problem Solving version of this experiment are displayed in Table 23. Despite the increase of negative sub-themes observed in comparison to both the Expository and Guided Inquiry versions of this experiment, the sub-themes for the Problem Solving version largely relate to superficial problems within the laboratory that are easily addressed. One common response indicated an insufficient amount of space provided within the laboratory manual for writing, particularly considering this experiment required a large number of observations and calculations. Additionally, students requested more information within the laboratory manual. Two possible explanations for this are an increased level of engagement leading to students wanting to deepen their understanding, or with greater freedom in the development and undertaking of this experiment students felt a greater pool of information would assist in completion of this experiment. The number of comments received concerning the amount of equipment and reagents available was noteworthy.
considering the proportions of equipment and reagents to students remained the same throughout all three iterations of this experiment.

Table 23. Sub-themes observed for the Problem Solving version of the Properties of Solutions experiment

<table>
<thead>
<tr>
<th>Positive</th>
<th>Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>• The experimental method was clear.</td>
<td>• Not enough laboratory manual space</td>
</tr>
<tr>
<td>• More information within the laboratory manual</td>
<td>• An increase in the amount of equipment and reagents available for use.</td>
</tr>
</tbody>
</table>

5.2.4.3 Student performance – Grade

Statistically significant differences at the p < 0.05 level were not only found in the averages for each of the three criteria, but also for the overall grade given to students. Figure 23 shows the comparisons for the overall average grades and respective criteria for the three teaching approaches (Expository, N = 95; Guided Inquiry, N = 63; Problem Solving, N = 84).
Figure 23. Comparison of grades between teaching methods for the Properties of Solutions of Acids and Bases experiment in KRA001. True values: Criterion 1 - 20, Criteria 2 and 3 - 40 scaled to percentage with percentage error represented as error bars.

The post-hoc test used for each comparison was determined using Levene's test for homogeneity of variances as discussed in Section 5.2.1.3. A summary of the statistical analyses completed for the Properties of Solutions of Acids and Bases are within Table 24.

Post-hoc comparisons using the Games -Howell test for Criterion 1 indicated that the mean score for both Guided Inquiry (\( \mu = 17.89, \sigma = 2.67 \)) and Problem Solving (\( \mu = 18.69, \sigma = 2.08 \)) were significantly different to Expository (\( \mu = 16.58, \sigma = 3.22 \)). The effect size for Criterion 1 was 0.10, i.e. a medium effect. Post-hoc comparisons using the Tukey HSD test for Criterion 2 indicated...
that the mean score for Problem Solving (µ = 32.36, σ = 4.24) was significantly different to both Expository (µ = 30.72, σ = 4.26) and Guided Inquiry (µ = 29.25, σ = 4.93). The effect size for Criterion 2 was 0.07, i.e. a medium effect. Post-hoc comparisons using the Tukey HSD test for Criterion 3 indicated that the mean score for Problem Solving (µ = 30.62, σ = 4.77) was significantly different to Guided Inquiry (µ = 28.35, σ = 4.36). The effect size for Criterion 3 was 0.04, i.e. a small effect. Post-hoc comparisons using the Tukey HSD test for the overall Grade indicated that the mean score for Problem Solving (µ = 81.67, σ = 9.39) was significantly different to both Expository (µ = 75.82, σ = 12.15) and Guided Inquiry (µ = 75.86, σ = 9.33). The effect size for the overall Grade was 0.06, i.e. a medium effect.

Table 24. Post-hoc output of comparisons of students’ overall grade yielding statistically significant differences at a 95% confidence interval for the Properties of Solutions of Acids and Bases

<table>
<thead>
<tr>
<th>Variable</th>
<th>Post-Hoc*</th>
<th>Effect Size</th>
<th>Comparison</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criterion 1</td>
<td>Games-Howell</td>
<td>0.10 (medium)</td>
<td>Guided Inquiry &gt; Expository</td>
<td>0.017</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Problem Solving &gt; Expository</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Criterion 2</td>
<td>Tukey</td>
<td>0.07 (medium)</td>
<td>Problem Solving &gt; Guided Inquiry</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Problem Solving &gt; Expository</td>
<td>0.038</td>
</tr>
<tr>
<td>Criterion 3</td>
<td>Tukey</td>
<td>0.04 (medium)</td>
<td>Problem Solving &gt; Guided Inquiry</td>
<td>0.006</td>
</tr>
<tr>
<td>Grade</td>
<td>Tukey</td>
<td>0.06 (medium)</td>
<td>Problem Solving &gt; Expository</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Problem Solving &gt; Guided Inquiry</td>
<td>0.002</td>
</tr>
</tbody>
</table>

*Post-Hoc tests determined by Levene’s test for homogeneity of variances as discussed in Section 5.2.1.3.
5.2.4.4 Student performance – Quiz

The post-laboratory quiz for the Properties of Solutions of Acids and Bases experiment was composed of a total of four questions to probe the student cohorts’ understanding of the key concepts and techniques used within this laboratory. A summary of these four questions is:

Question 1 – Students are asked to define pH.

Question 2 – Students are asked to define conductivity.

Question 3 – For acid and base examples, students provide the ionic equations for dissociation in water in addition to the neutralisation reaction between the two.

Question 4 – Conversion of concentration to pH.

The visual comparison of the three teaching methods for the post-laboratory quiz is in Figure 24. Each comparison presents the percentage of correct (blue) and partially correct (red) responses, as discussed in Section 5.2.1.4.
Figure 24. Percentage of correct (blue) and partially correct (red) responses to questions contained within the post-experiment quiz for the Properties of Solutions of Acids and Bases experiment (Expository, N = 50; Guided Inquiry, N = 27; Problem Solving, N = 78).

Figure 24 gives a strong indication that Questions 1, 2, and 4 were all completed to a similar standard for all three teaching approaches. Question 3 appears to indicate a slight advantage of the Guided Inquiry and Problem Solving approaches over Expository, but this is by no means definitive.

5.2.4.5 Summary of results

Once more, the analysis of the directed questions within the student-completed survey yielded no statistically significant differences between the teaching approaches. The analysis of the...
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free-text entry comments however, gave a far more interesting look into the student experience of Properties of Solutions of Acids and Bases experiment. Comparing the number of negative comments relating to the laboratory process and engagement with information themes, it was found that Expository was least favoured, followed by Guided Inquiry and finally Problem Solving. The interaction with others and the overall experience themes both mostly consisted of positive comments for all three teaching approaches. The analysis of the grades given by demonstrators to students for their in-laboratory performance yielded statistically significant differences between the teaching approaches, but the effect size of these comparisons were of small to medium size and are therefore negligible. Furthermore, the understanding demonstrated by students through the post-experimental quiz indicated that across all four questions the student cohorts of all three teaching approaches performed to a similar standard. Taking the results from each of the data sources, Expository, Guided Inquiry, and Problem Solving, into account, there does not appear to be any significant difference between these teaching approaches with regard to their laboratory process or demonstrated understanding upon completion of the experiment. There is, however, differences observed when inspecting student perception of the laboratory experience as described by the free-text entry component of the student-completed survey. These responses indicated students preferred the structure of the Problem Solving approach. While some concerns were detailed by students, these concerns were largely logistical in nature and can be addressed by minor adjustments.
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5.3 Final Thoughts

This chapter has presented the results obtained from analysis of four of the experiments undertaken by students as part of the Foundation Chemistry unit, KRA001. The experiments were chosen to represent a mixture of experiment types including: hands-on, observational, calculations and interpretive skills. As KRA001 runs in three semesters per year, multiple instances were used for data collection with student cohorts being combined based on the assumption of homogenous student cohorts. To consider all four experiments, the two data collection instruments that yielded the most differences were the student-completed survey and the student-completed post-laboratory quiz. The comparisons of grades in all cases, while some statistically significant differences were identified, were negligible for the overall laboratory experience. The four experiments discussed previously within Chapter 5 have been summarised in turn. Table 25 provides the recommended teaching approach for each experiment:

Table 25. A summary of the recommended teaching approach for each experiment in KRA001.

<table>
<thead>
<tr>
<th>Name of Experiment</th>
<th>Type of Experiment</th>
<th>Recommended Teaching Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Analysis of a Solution by Measurement of its Density</td>
<td>Calculation/Hands-on</td>
<td>Expository</td>
</tr>
<tr>
<td>Distillation as a Separation Technique</td>
<td>Hands-on/Interpretation</td>
<td>Guided Inquiry</td>
</tr>
<tr>
<td>Identification of a Carboxylic Acid</td>
<td>Hands-on/Calculation</td>
<td>Guided Inquiry</td>
</tr>
<tr>
<td>Properties of Solutions of Acids and Bases</td>
<td>Observation/Interpretation</td>
<td>Problem Solving</td>
</tr>
</tbody>
</table>
The Analysis of a Solution by Measurement of its Density experiment (Calculation/Hands-on) was the most preferred by students to be run as either Problem Solving or Expository versions. The analysis of the post-laboratory quiz mirrored the student preference, with both Expository and Problem Solving approaches attaining a similar standard. Given the earliness of this experiment within the laboratory course, Expository was deemed the most appropriate for this experiment.

The Guided Inquiry version of the Distillation as a Separation Technique experiment (Hands-on/Interpretation) was not only preferred by students through analysis of the student-completed survey, but also demonstrated a higher level of understanding through the post-laboratory quiz. Guided Inquiry was therefore deemed most appropriate for this experiment. The major strengths demonstrated by the Guided Inquiry version were based within interactions with peers and demonstrators and the overall laboratory experience.

The Identification of a Carboxylic Acid experiment (Hands-on/Calculation) was considerably limited by the lack of data pertaining to the student perception of their experience in this laboratory. Analysis of both the directed survey questions and the grades indicated no differences between the teaching approaches. The post-laboratory quiz analysis however, suggested students who completed the Guided Inquiry version of this experiment attained a higher level of understanding for those questions asked. Based on the limited data, Guided Inquiry would appear to be the most beneficial teaching approach. A repeat of this experiment would be required to confirm this assertion.

The Properties of Solutions of Acids and Bases experiment (Observation/Interpretation) indicated that all three teaching approaches achieved a similar standard with regard to
scholarly outputs. The responses from students on their experience indicated, however, that while all three teaching approaches were received well, the Problem Solving iteration in particular appeared to be favoured. As no disadvantage for the understanding developed by students was observed, the Problem Solving approach for this experiment was decided as the most advantageous.

When considering these experiments in the context of the overall laboratory structure, an interesting theme becomes apparent. As students progress through their laboratory course, a transition from the more structured teaching approaches such as Expository to Guided Inquiry to the open-ended experiences such as Problem Solving seem to be favoured. As KRA001 as a unit is an exception to ordinary undergraduate degrees, this may be an outcome observed due to the experience of students undertaking this unit. For students with little to no laboratory experience, the gradual increase in student responsibility for their learning and scientific investigation skills may be a natural progression as they gain confidence in the laboratory skills and scientific thinking.
Chapter 6 – Results: First Year Chemistry

6.1 Introduction to First Year Chemistry

6.1.1 Unit Objectives

The chemistry unit studied from the first year component of the bachelor's degree offered at the University of Tasmania was Chemistry 1A. This unit is one of two units (Chemistry 1A and 1B, KRA113 and KRA114 respectively) that are compulsory for students who are intending to major in Chemistry or undertake second year chemistry units for their Bachelor of Science. Additionally, these units act as a prerequisite for many degrees offered at the University of Tasmania including, but not limited to, geology, marine science, pharmacy, agricultural science, and medical research. Within this unit fundamental chemistry topics are covered including chemical bonding and chemical structure, organic chemistry, structure and reactions, and thermodynamics and colligative properties. Further information for this unit can be found within the KRA113 2015 Unit Outline (University of Tasmania, 2015 b). Taken directly from the 2015 Unit Outline for KRA113, the Intended Learning Outcomes for this unit are:

- Demonstrate knowledge and understanding of chemical principles and theories and in so doing be able to appreciate the unifying themes in chemistry.
- Apply chemical principles and theories to predict and explain the chemical and physical properties of substances, their structure and the interactions that take place between them.
- Demonstrate an understanding of the central role of chemistry in other branches of natural science, such as biology, geology and physics and to recognize the central role that chemistry has in understanding the natural world.
- Demonstrate problem solving skills from experimental and theoretical approaches.

Ichkeb Bhujel
• Know when to accept evidence contrary to established beliefs.

Demonstrate awareness that chemistry is a living and rapidly developing science. (University of Tasmania, 2015b, pp. 2)

6.1.2 How Does It Run?

Despite first year chemistry being offered across all three campuses, Cradle Coast, Newnham, and Sandy Bay, KRA113 in the format of the unit included in this study was only provided on-campus at the Sandy Bay campus. As KRA113 runs as one half of the first year chemistry units offered, this unit is always undertaken during Semester 1, KRA114, the follow-on unit, runs in Semester 2. The unit is composed of three major components: a series of face-to-face lectures and Problem Solving sessions, 4 per week totaling 49 over the course of the semester; a series of online activities to be completed outside of compulsory contact time; and a laboratory course composed of 8 three-hour experiments on-campus. A standard student cohort totals 200 to 250 students, with a large variety of students including chemistry majors, 15 – 20% and a diverse range of other disciplines requiring chemistry as a pre-requisite for further studies.

Given the size of the student cohort, the laboratory sessions are limited to approximately 50 students with a laboratory running on each day during the week.

6.1.3 Laboratory Course Details

An overview of the laboratory course for the first year chemistry unit, KRA113, has been summarised within Table 26. Those experiments that were considered as part of this study have been shaded for identification.
Table 26. The full laboratory course completed as part of the first year chemistry unit, KRA113, indicating which experiments have been modified for this study

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Overview</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recrystallisation of a Solid, Safety Induction and Locker Check</td>
<td>The introductory laboratory to familiarise students with the laboratory setting and basic equipment. Students recrystallise crude benzoic acid using vacuum filtration and slow cooling.</td>
</tr>
<tr>
<td>Preparation and Standardisation of Sodium Hydroxide Solution and Determination of Acetic Acid in Vinegar</td>
<td>The technique of titration and standardisation is introduced with emphasis upon precision and accuracy. Students will first standardise a sodium hydroxide solution they prepare before determining the concentration of acetic acid present in a vinegar solution provided.</td>
</tr>
<tr>
<td>SN1 Substitution: Synthesis of t-Butyl Chloride</td>
<td>During this SN1 substitution synthesis, students will be exposed to both the solvent extraction and purification via distillation techniques.</td>
</tr>
<tr>
<td>Oxidation of Benzyl Alcohol: Synthesis of Benzoic Acid</td>
<td>An expansion of the first experiment, students first synthesise benzoic acid from a provided benzyl alcohol sample through oxidation, followed by cleaning and recrystallising to a pure product.</td>
</tr>
<tr>
<td>Organic Functional Groups</td>
<td>Students are introduced to the concept of using small-scale tests for identification of functional groups including: alkenes, phenols, aldehydes, ketones, and carboxylic acids. Finally, students use a combination of these skills to identify a provided unknown from a selection of compounds.</td>
</tr>
</tbody>
</table>
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Determination of Unknown Concentration by Spectroscopy

Students are introduced to their first experience using spectroscopy to identify the concentration of a copper sulfate solution. Within this experiment, students construct a calibration curve and apply Beer's Law.

Thermochemistry: Enthalpy of Neutralisation

To complement the theory given on Hess's Law, students construct a basic calorimeter and measure the enthalpy of: neutralisation of HCl and NaOH solutions, dissolution of NaOH solid pellets, and the combined processes.

Determination of the Freezing-Point Depression Constant for Cyclohexane

This experiment explores the difference between molarity and molality before constructing cooling curves to determine the freezing point constant of cyclohexane. Finally, through use of this constant, the determination of the molecular mass of an unknown solid is calculated.

Shaded spaces within Table 2 indicate those experiments included within this study.

6.2 Results

Section 6.2 will discuss the outcomes for the comparison of the three teaching approaches, Expository, Guided Inquiry, and Problem Solving, for the four experiments considered from KRA113. The structure to this discussion will mirror that of Chapter 5. The first experiment presented below is the Oxidation of Benzyl Alcohol: Synthesis of Benzoic Acid experiment.

Sample sizes for the comparisons discussed throughout this Chapter can be found within Appendix I.
6.2.1 Oxidation of Benzyl Alcohol: Synthesis of Benzoic Acid

This experiment serves to reinforce the recrystallization techniques previously covered in earlier KRA113 experiments, in addition to applying these to a full synthesis of benzoic acid from benzyl alcohol. As such the skills being practiced in this laboratory are primarily hands-on skills, requiring familiarity and proficiency in the handling of equipment used for synthesis experiments.

Individually, students collect a pre-measured sample of potassium permanganate solid to be dissolved and heated before reaction with benzyl alcohol. Upon formation of the insoluble manganese dioxide, deionized water, 50% sulfuric acid, and 20% sodium sulfite solution are added to produce the crude final product. Repeating the techniques used in an earlier KRA113 experiment, the crude benzoic acid is then recrystallized and collected via vacuum filtration. Final calculations are performed to determine the yield, and a small-scale test for the presence of a carboxylic acid functionality is used to ensure the intended product was formed.

6.2.1.1 Student perceptions – Survey

Using the method discussed in Section 5.2.1.1, a one-way between groups analysis of variance was conducted to compare the three teaching approaches (Expository, N = 98; Guided Inquiry, N = 194; Problem Solving, N = 157). The discussion of these surveys has been structured to consider the findings at a broad level, before gradually narrowing the focus to identify key sub-themes. The overarching broad themes are identified before inspecting the distribution of positive versus negative responses in each of these themes, before finally identifying the specific sub-themes. The three teaching approaches, Expository, Guided Inquiry, and Problem Solving, have been abbreviated to EX, GI, and PS respectively. Statistically significant
Chapter 6 – Results: First Year Chemistry

Differences at the p < 0.05 level were found in a number of the questions posed to students through the survey. These included:

Question 1 – This learning format was an engaging experience.

Question 2 – The learning objectives were clearly defined.

Question 4 – I further developed my practical skills in the laboratory by completing the experiment in this format.

As discussed in Chapter 5, two post-hoc analysis tests were available for use: the Games-Howell test and the Tukey HSD test. Which test is used is determined via Levene’s test for homogeneity of variances. For those comparisons of variances where the significance value was greater than 0.05, the homogeneity of variances assumption has been abided by and the Tukey HSD test may be used. For violations of this assumption, the Games-Howell test is used.

A summary of the statistical analysis for this experiment can be found in Table 27. Post-hoc comparisons using the Tukey HSD test for Question 1 indicated that the mean score for Problem Solving (µ = 7.36, σ = 1.79) was significantly different to both Expository (µ = 6.61, σ = 2.01) and Guided Inquiry (µ = 6.85, σ = 1.79). The effect size for Question 1 was 0.03, i.e., a small effect. Post-hoc comparisons using the Tukey HSD test for Question 2 indicated that the mean scores for both Expository (µ = 7.56, σ = 1.96) and Guided Inquiry (µ = 7.46, σ = 1.91) were significantly different to Problem Solving (µ = 6.91, σ = 2.16). The effect size for Question 2 was 0.02, i.e., a small effect. Post-hoc comparisons using the Tukey HSD test for Question 4 indicated that the mean score for Problem Solving (µ = 8.07, σ = 1.54) was significantly different to Guided Inquiry (µ = 7.63, σ = 1.70). The effect size for Question 4 was 0.01, i.e., a small effect.
### Table 27: Post-hoc output of comparisons of students’ survey responses yielding statistically significant differences at a 95% confidence interval for the Oxidation of Benzyl Alcohol: Synthesis of Benzoic Acid experiment

<table>
<thead>
<tr>
<th>Variable</th>
<th>Post-Hoc*</th>
<th>Effect Size</th>
<th>Comparison</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Question 1</td>
<td>Tukey</td>
<td>0.03</td>
<td>(small)</td>
<td>Problem Solving &gt; Expository</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Problem Solving &gt; Guided Inquiry</td>
</tr>
<tr>
<td>Question 2</td>
<td>Tukey</td>
<td>0.02</td>
<td>(small)</td>
<td>Expository &gt; Problem Solving</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Guided Inquiry &gt; Problem Solving</td>
</tr>
<tr>
<td>Question 4</td>
<td>Tukey</td>
<td>0.01</td>
<td>(small)</td>
<td>Problem Solving &gt; Guided Inquiry</td>
</tr>
</tbody>
</table>

*Post-Hoc tests determined by Levene's test for homogeneity of variances as discussed in Section 5.2.1.3.

Despite the findings displayed above, the small effect size for each instance where statistically significant differences were found implies that these differences are negligible. This is not to say that no differences exist. Rather further fine-tuning of the questions being asked and a larger sample size are needed so that these differences may eventually become more distinct outcomes. To consider these findings however, two clear outcomes are apparent. Firstly, students indicated that Problem Solving as a learning experience was more engaging than both Expository and Guided Inquiry. This could be attributed to the nature of each teaching method and as a natural progression given both Expository and Guided Inquiry provide a more structured approach to the procedures, whereas Problem Solving requires students to develop their own method. The second outcome related to the clarity of the learning objectives. The outcome observed directly contrasts the finding above, as students indicated that the clarity of learning objectives for both Expository and Guided Inquiry was higher than that of...
Problem Solving. An interesting outcome also observed indicated students felt their practical skills were further developed in the Problem Solving approach than with Guided Inquiry.

6.2.1.2 Student perceptions – Survey comments
For the analysis of the student free-response component of the survey, five overarching themes were identified.

- Interaction with others
- Laboratory processes
- Engagement with information
- Overall laboratory experience
- Miscellaneous

Expository, Guided Inquiry, and Problem Solving will be abbreviated to EX, GI, and PS respectively. In Figure 25 are the proportions of these comments, both positive and negative, of each of these themes. Using this data allows comparison between the teaching methods to determine what elements of the laboratory were of most interest to the students. When considering the proportions observed for the Oxidation of Benzyl Alcohol: Synthesis of Benzoic Acid experiment in Figure 25, there is a clear difference between each teaching approach. For example, as we transition from Expository to Guided Inquiry to Problem Solving, we observe an increase in responses discussing the engagement with information theme, a theme which encompasses the information provided in the laboratory manual, pre-readings, lecture material, and any information provided during the laboratory. As the engagement with information theme proportion increases, we can note a corresponding decrease in the overall laboratory experience theme; a theme that encompasses all general comments about the students’ experience in that laboratory with no specifics given. The three remaining themes,
interaction with others, laboratory process, and miscellaneous themes all remained at a similar volume.

Figure 25. Total distribution of types of survey comments for the Oxidation of Benzyl Alcohol: Synthesis of Benzoic Acid experiment (Expository, N = 215; Guided Inquiry, N = 211; Problem Solving, N = 131).

To better understand the responses from each student cohort, it is important to increase the depth of analysis for each of these themes and to identify specific elements that students found important to give as responses. Two sub-themes were common amongst all three teaching approaches. The first was concern for both the length of waiting times through the experiment and the length of the experiment itself. Given the nature of a synthetic experiment, often steps require heating, cooling, or time for a reaction to occur which may require students to wait. The second sub-theme identified related to the connection, or lack thereof, between the lecture material and the laboratory experiment. Students indicated that the chemistry concepts were more difficult to grasp due to a lack of definition between theory and practice.
Figures 26 through 28 continue this exploration into the sub-themes of each broad overarching theme by detailing the proportion of positive to negative responses for each broad theme. In addition, sub-themes specific to each teaching approach have been identified and will be discussed.

Figure 26 is the breakdown of each of the broad overarching themes into the positive versus negative response proportions. One theme seems distinctly skewed in favour one way; the engagement with information theme appears to a higher proportion (approximately 80%) of negative comments in comparison to positive comments within this theme.

![Chart showing the proportion of positive versus negative responses for each theme.]

**Figure 26.** The proportion of positive versus negative comments for the overarching themes in the Expository (N = 215) version of the Oxidation of Benzyl Alcohol: Synthesis of Benzoic Acid experiment.

Table 28 gives insight into the sub-themes that were identified specific to this teaching approach iteration. A number of positive sub-themes were identified for the Expository
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version of the Oxidation of Benzyl Alcohol: Synthesis of Benzoic Acid experiment. These sub-themes varied across a number of elements within a laboratory ranging from the clarity of the laboratory manual in its current form, specific hands-on procedures applied within this experiment, and of particular interest, the application of theory to a laboratory environment. Many of the positive sub-themes observed indicates that the strength of this teaching approach is to provide an experience that matches what is presented within the structure. Where this potentially becomes an issue is the expansion into linking this laboratory with the wider body of chemistry concepts available and providing space for students to develop their knowledge outside of the specifics in that experiment. The negative sub-themes identified indicates that the student concerns were mostly directed towards improving aspects outside the scope of the experiment itself. For instance, the availability of pre-reading or background information for the purpose of preparation and greater understanding, and a lack of pre- and post-experiment structure. The majority of responses relating to pre- and post-laboratory structure related to the lack of activities or the opportunity to engage with demonstrators or lecturers with respect to preparation and reflection upon the experiment. This point in particular raises a concern with the nature of the Expository teaching approach, given the structured procedures and templates for discussion of the experiment, students may feel there is little space to develop or expand their knowledge. In addition to this, there could be little to no incentive for students to prepare for the laboratory session given the transparency of this experiment.
### Table 28: Sub-themes observed for the Expository version of the Oxidation of Benzyl Alcohol:

**Synthesis of Benzoic Acid**

<table>
<thead>
<tr>
<th>Positive</th>
<th>Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>• The procedural instructions were clear and easy</td>
<td>• The availability of equipment and reagents</td>
</tr>
<tr>
<td>• Specific hands-on components of the laboratory; small-scale tests,</td>
<td>• Further background information on both the reagents and the reactions</td>
</tr>
<tr>
<td>recrystallization, oxidation, were a positive experience</td>
<td>• The lack of structure of both pre- and post-experiment</td>
</tr>
<tr>
<td>• Interaction with the demonstrators was beneficial and enjoyable</td>
<td></td>
</tr>
<tr>
<td>• The application of lecture materials to a laboratory environment</td>
<td></td>
</tr>
<tr>
<td>• The intended learning outcomes were clear and achieved</td>
<td></td>
</tr>
<tr>
<td>• The individual nature of the work involved in this experiment.</td>
<td></td>
</tr>
</tbody>
</table>

One particular student comment of interest raising an important aspect of the laboratory, but standing outside of the sub-themes identified, was:

"I think we should be encouraged to ask questions. At this point we are deincentified to improve our understanding through the tutor as we lose marks for it. I think we should have a minor pretest based on procedure and basic background theory, then have a major post test after the lab to check our understanding. eg 20% pre test, 40% on post test, 40% for yield (not for the little help we need)."
A common misconception that has been noted by demonstrators on multiple occasions is the perception by students that assessment is based upon the amount of assistance given within the laboratory environment. There is a small amount of truth in that demonstrators must ascertain the depth of understanding of each student in addition to their performance within the laboratory. Questions, however, are encouraged so long as these questions are constructive or meaningful. A student who requires continual assistance throughout the laboratory and struggles to grasp the fundamental aspects of an experiment will of course score a lower grade than a student whose questions demonstrate an understanding of the content and further still expands into new concepts. One interesting facet of this survey response lies in the proposed marking scheme to give a more formal structure to pre- and post-experiment activities, a concept that was observed as one of the negative sub-themes for this experiment.

Figure 27 shows three interesting changes to the results observed for the Expository iteration in Figure 26 when considering the proportions for the Guided Inquiry instance presented within. Whilst the Expository iteration indicated an excess of negative comments for the engagement with information theme and equal footing for the laboratory process theme; the Guided Inquiry iteration appeared to reverse these results, with an excess of negative comments on the laboratory process and an approximately equal amount of positive and negative comments for the engagement with information theme. The final point of interest lies in the responses collected for the overall laboratory experience. Guided Inquiry as a teaching approach received purely positive responses for this category.
Figure 27. The proportion of positive versus negative comments for the overarching themes in the Guided Inquiry (N = 211) version of the Oxidation of Benzyl Alcohol: Synthesis of Benzoic Acid experiment.

One of the key features for a Guided Inquiry approach as a teaching tool is the development of understanding throughout the experiment. As such, the questions interspersed throughout the procedure were a key element to guide students towards glimpses of the underlying concepts and principles. Table 29 shows the sub-themes identified for the Guided Inquiry version of this experiment. Perhaps unsurprisingly, given the possibility of not having experienced this teaching approach before, both a positive and negative sub-theme was identified concerning the questions introduced into the procedure. The positive responses were directed towards the interest generated by the presence of these questions and upon completion, an increase in the development of each student's understanding. Whether this is perceived or actual understanding cannot be determined as will be discussed further later. The remaining positive sub-themes were quite varied, indicating a number of positive elements within the laboratory experience. These included: the lecture materials being connected to the concepts within the laboratory experiment, the demonstrators, and the development of practical skills. The
negative responses focused upon the increased sense of pressure students felt when completing the experiment. Despite the majority of these questions being drawn from what was previously the post-experiment discussion, students still felt there was a noticeable increase in the workload expected. The remaining negative sub-themes, excepting the responses concerning the clarity within the laboratory manual, raised some thought-provoking ideas and concerns. A large proportion of students commented on a lack of background information, a response observed within many of the iterations undertaken as part of this study. Further to this concern, some of the student comments indicated a potential solution through the inclusion of online tutorials and how-to videos as additional resources. One crucial concern that has been observed in several instances throughout Chapters 5 and 6, lie in students' misinterpretation and experiences with assessment within the laboratory environment. The key element within each response is largely the lack of clarity in the process and interpretation of assessment. This was confusing for the students and perceived as confusing for the demonstrators. Responses from the demonstrators themselves indicated that the Guided Inquiry approach to this experiment improved the engagement of students and assisted with filling the waiting times that were a concern for the Expository. Furthermore, the presence of these questions assisted with the assessment process and offered more opportunities to discuss the chemistry concepts and techniques applied in this experiment.
Table 29. Sub-themes observed for the Guided Inquiry version of the Oxidation of Benzyl Alcohol: Synthesis of Benzoic Acid experiment

**Positive**
- Engagement with the questions interspersed throughout the procedure. Students described these questions as an opportunity to better develop understanding.
- Lecture materials linked to the laboratory experiment.
- Demonstrators were engaged with assisting and approachable.
- Development of practical skills.

**Negative**
- Questions interspersed throughout the procedure increased the pressure to complete the experiment.
- Interest in the provision of online tutorials or how-to videos.
- The laboratory manual was unclear and questions were not prominent.
- Misconceptions concerning laboratory assessment. Clarity for both students and demonstrators.

Contrary to both the Expository and Guided Inquiry approaches, the proportions of positive and negative responses for the Problem Solving approach found in Figure 28, indicated a more balanced volume of responses for the laboratory process and engagement with information themes. The interaction with others theme was once more equal in proportion, mirroring the proportions found in both Expository and Guided Inquiry. The overall experience theme was entirely composed of positive responses, whilst the few comments in the miscellaneous theme were negative.
Figure 28. The proportion of positive versus negative comments for the overarching themes in the Problem Solving (N = 131) version of the Oxidation of Benzyl Alcohol: Synthesis of Benzoic Acid experiment.

The sub-themes for the Problem Solving approach iteration of the Synthesis of Benzoic Acid experiment are within Table 30. The total responses for this approach were varied, leading to a smaller number of sub-themes being identified. Both positive sub-themes identified outcomes often associated with Problem Solving activities; the benefits of writing their own procedures and an increased focus upon self-directed learning. As may be expected, despite the number of responses concerning the writing of their own method, a similar number of negative responses were given with regards to this process being confusing. Whether this is derived from a lack of experience with the construction of a method for experiments or from a genuine dislike is indeterminate at this stage. In addition, the student cohort indicated that further background information is required for this teaching approach. Many reasons were given for this; the underlying theme however, suggested that with further information and better prior understanding, the preparation of their methods would come with ease. Finally, students found that their interactions with demonstrators was considerably different to
regular laboratory experiences, with demonstrators being described as less approachable and evasive in their responses to questions. The demonstrators themselves noted an increased need for direction to get the students started and motivated for the experiment. The conclusions drawn by many demonstrators suggested that designing a suitable Problem Solving activity for synthesis laboratories, particularly for first-year students, was perhaps more difficult than it was worth. The benefits, however, were clear with demonstrators observing a notable improvement in the engagement of students with why an experiment occurs in contrast to simply following instructions.

Table 30. Sub-themes observed for the Problem Solving version of the Oxidation of Benzyl Alcohol: Synthesis of Benzoic Acid experiment

<table>
<thead>
<tr>
<th>Positive</th>
<th>Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>• The opportunity to write their own procedure gave students the chance to prepare and take ownership of the experiment.</td>
<td>• Writing their method was confusing.</td>
</tr>
<tr>
<td>• Self-directed learning at each student's own pace.</td>
<td>• The demonstrators were perceived as less approachable and evasive.</td>
</tr>
<tr>
<td></td>
<td>• The laboratory manual was confusing.</td>
</tr>
<tr>
<td></td>
<td>• Students would like more background information including mechanisms and diagrams.</td>
</tr>
</tbody>
</table>

6.2.1.3 Student performance – Grade

Using the same statistical analysis method as that for the comparison of teaching approaches (Expository, N = 104; Guided Inquiry, N = 238; Problem Solving, N = 226) for the student-completed survey, statistically significant differences at the p < 0.05 level were found in the...
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Averages for the overall grade, and also in all three criteria. Figure 29 compares the three teaching methods for the total grade and the respective criteria.

**Figure 29. Comparison of grades between teaching methods for the Oxidation of Benzyl Alcohol: Synthesis of Benzoic Acid experiment in KRA001.** True values: Criterion 1 - 20, Criteria 2 and 3 - 40 scaled to percentage with percentage error represented as error bars.

Two post-hoc tests were available for use in this analysis: the Games-Howell test and the Tukey HSD test. Levene’s test for homogeneity of variances was used to determine which test was appropriate for each comparison. For those comparisons of variances where the significance value was greater than 0.05, the homogeneity assumption has not been violated and the Tukey HSD test may be used. For violations of this assumption, the Games-Howell test was used.
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is used. A summary of the analysis of the comparison of grades for the Oxidation of Benzyl Alcohol: Synthesis of Benzoic Acid experiment is contained within Table 31. Post-hoc comparisons using the Tukey HSD test for Criterion 1 indicated that the mean score for Problem Solving ($\mu = 18.57$, $\sigma = 1.85$) was significantly different to Expository ($\mu = 17.91$, $\sigma = 2.10$). The effect size for Criterion 1 was 0.01, i.e. a small effect. Post-hoc comparisons using the Games-Howell test for Criterion 2 indicated that the mean scores for both Expository ($\mu = 32.63$, $\sigma = 2.91$) and Problem Solving ($\mu = 33.34$, $\sigma = 3.53$) were significantly different to Guided Inquiry ($\mu = 31.67$, $\sigma = 4.01$). The effect size for Criterion 2 was 0.04, i.e. a small effect. Post-hoc comparisons using the Games-Howell test for Criterion 3 indicated that the mean score for Problem Solving ($\mu = 33.42$, $\sigma = 3.05$) was significantly different to both Expository ($\mu = 32.53$, $\sigma = 2.71$) and Guided Inquiry ($\mu = 30.95$, $\sigma = 4.18$). Additionally, Expository was significantly different to Guided Inquiry. The effect size for Criterion 3 was 0.09, i.e. a medium effect. Post-hoc comparisons using the Tukey HSD test for the overall Grade indicated that the mean score for Problem Solving ($\mu = 85.33$, $\sigma = 6.69$) was significantly different to both Expository ($\mu = 83.07$, $\sigma = 6.50$) and Guided Inquiry ($\mu = 80.79$, $\sigma = 8.00$). Additionally, Expository was significantly different to Guided Inquiry. The effect size for the overall Grade was 0.07, i.e. a medium effect.
### Table 31.
Post-hoc output of comparisons of students’ overall grade yielding statistically significant differences at a 95% confidence interval for the Oxidation of Benzyl Alcohol: Synthesis of Benzoic Acid experiment.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Post-Hoc*</th>
<th>Effect Size</th>
<th>Comparison</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criterion 1</td>
<td>Tukey</td>
<td>0.01</td>
<td>Problem Solving &gt; Expository</td>
<td>0.039</td>
</tr>
<tr>
<td></td>
<td>Games–Howell</td>
<td>0.04</td>
<td>Expository &gt; Guided Inquiry</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>Games–Howell</td>
<td>0.09</td>
<td>Expository &gt; Guided Inquiry</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Problem Solving &gt; Expository</td>
<td>0.023</td>
</tr>
<tr>
<td>Grade</td>
<td>Tukey</td>
<td>0.07</td>
<td>Expository &gt; Guided Inquiry</td>
<td>0.021</td>
</tr>
</tbody>
</table>

*Post-Hoc tests determined by Levene’s test for homogeneity of variances as discussed in Section 5.2.1.3.

Of these comparisons, the Grade variable is of most interest given the medium effect size. This would suggest the differences observed between the teaching approaches are of significance. When placed within the context of the assessed values awarded students, both the Problem Solving and Expository average grades were in the HD region, with the Guided Inquiry average grade approaching a HD.
6.2.1.4 Student performance – Quiz

To allow enough time for students to complete the post-laboratory quiz, all quizzes for the four experiments for KRA113 were limited to three questions to cover the key concepts and principles.

Summaries of the post-laboratory quiz questions for the Oxidation of Benzyl Alcohol: Synthesis of Benzoic Acid experiment are:

Question 1 – Determining the oxidation products of a variety of starting materials.

Question 2 – Demonstrate an understanding of crystal growth and the reasoning behind recrystallization.

Question 3 – Combination of conversion and yield calculations.

To assess these questions for analysis, responses were judged as one of the following: correct, partially correct, incorrect, or did not attempt. This approach allowed a means to compare the teaching approaches without having to assign specific number values for each question and furthermore allowed comparison between experiments for the level of understanding gained for their respective questions.

In Figure 30 are the percentage of correct (blue) and partially correct (red) responses for each question. Incorrect and did not attempt responses were omitted to allow clarity in the analysis of this data.
Figure 30. Percentage of correct (blue) and partially correct (red) responses to questions contained within the post-experiment quiz for the Oxidation of Benzyl Alcohol: Synthesis of Benzoic Acid experiment (Expository, N = 130; Guided Inquiry, N = 220; Problem Solving, N = 104).

The results presented within Figure 30 indicate a clear trend through all three questions. Both Expository and Problem Solving approaches yielded near identical standards for the understanding demonstrated by students for each concept and technique covered in the experiment. The Guided Inquiry approach, however, in each suggested a minor improvement on both Expository and Problem Solving approaches across all questions. When considering the misconceptions or miscalculations attributing to the production of partially correct responses, all three teaching approaches tended towards similar mistakes. Question 1 required students to predict the oxidation products from a variety of starting materials; the majority of students demonstrated a basic understanding of oxidation of alcohol groups to ketones or carboxylic acids but often misidentified the number of carbons and the nature of oxidation in modifying the functional group rather than the carbon skeleton. The discussions provided by students for Question 2 to describe the process of recrystallization were of a sufficient standard to discuss improper crystal formation through agitation, but often lacked...
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descriptions of the importance of slow cooling. Finally, Question 3 posed the workings of a hypothetical student incorrectly calculating their yield. Students are required to first repeat the calculation and then indicate where the hypothetical student had gone wrong. The most common mistake for this question was due to the correct yield being calculated but an incorrect explanation of the source of the hypothetical student's error.

6.2.1.5 Summary of Results

The directed Likert-style question component of the student completed survey yielded several statistically significant differences based on analysis of the responses received. The Problem Solving responses for Question 1, This learning format was an engaging experience, were significantly higher than those of both Expository and Guided Inquiry responses. In contrast to this finding, analysis of responses for Question 2, The learning objectives were clearly defined, indicated that Problem Solving was significantly lower than those of Expository and Guided Inquiry. Question 4, I further developed my practical skills in the laboratory by completing the experiment in this format, showed statistically significant differences indicating that Problem Solving as a teaching approach scored significantly higher than the Guided Inquiry approach.

Despite these differences being observed, the effect size of all three comparisons are of a small size, and are therefore to be considered carefully before drawing conclusions.

Alternatively, by repeating these measurements or increasing the sample size, changes in effect size may be observed.

The other component to the student completed survey, the free-text entry spaces, yielded some interesting outcomes. At the broadest level with both positive and negative responses combined and divided into the five broad themes as discussed in Section 6.2.1.2, differences between the teaching approaches were apparent. Perhaps most thought provoking is the...
similarity in the proportion of comments for the Guided Inquiry and Problem Solving approaches. Both presented a large component (over 50%) of comments that were within the engagement with information theme, a medium component (approximately 25%) of comments within the laboratory process, and the rest of the comments distributed amongst the remaining themes. By contrast, the Expository teaching approach had a significant increase for responses on the overall laboratory experience with a corresponding decrease in responses for the engagement with information. Closer inspection of the proportions of positive and negative responses and the sub-themes observed within the broad themes, indicated some interesting outcomes from each teaching approach. All three teaching approaches were similar with regards to two key sub-themes: the waiting times incurred through the synthetic steps, and the disjoint between lecture materials and the chemistry topics covered in laboratories. The Expository teaching approach whilst appearing to engage students for the laboratory processes undertaken and allowing transparency of the intended learning outcomes, appeared to be limited in the development of understanding. This was apparent through the number of responses from students requesting further information for the purpose of understanding what they had achieved. The Guided Inquiry approach in comparison appeared to remedy some of the concerns from students with regards to the engagement with information. The presence of the questions interspersed throughout the laboratory procedure gave students the opportunity to further develop their understanding of the chemistry content, despite the perceived increase in workload and subsequent increase of pressure felt by students. Complementing this, the demonstrators noted a definitive improvement in the engagement of students with the chemistry concepts and principles underlying this experiment. Furthermore it was noticed that the waiting times normally associated with this laboratory prior to this study were remedied. The Problem Solving approach gave the most balanced proportions between positive and negative comments for...
the interaction with others, laboratory process, and engagement with information themes. When investigating the specific responses given, only a small number of sub-themes were identified. These included expected benefits and disadvantages in using Problem Solving as a teaching approach, an enhanced preparation for the laboratory, and the positive experience of self-directed learning coupled with an equal number of students who disliked the workload demand of preparing a method. A sub-theme leading on from this identified a need for further background information including mechanisms and diagrams to aid in the student's preparation and understanding of the chemistry concepts and principles within this experiment. One concerning sub-theme however, was that students felt that their demonstrators were less approachable and evasive in regards to questions on the process or concepts.

Given the breadth of responses across all three teaching approaches, no one teaching approach appeared to stand above the others from the data collected from the survey instrument. The analysis of the grades given by demonstrators for each student's performance during the laboratory yielded multiple statistically significant differences between all three teaching approaches. In summary, Problem Solving was significantly higher than both Expository and Guided Inquiry; additionally, Expository was significantly higher than Guided Inquiry. The effect size of these comparisons however was small to medium; therefore indicating the meaningfulness of these results is reduced.

The comparison of the responses given by the student-completed quiz was perhaps the most informative with regards to which teaching approach was providing the optimal learning environment. For all quiz questions, Guided Inquiry had an increased number of students...
answering either correctly, or partially correctly. No apparent differences between Expository and Problem Solving were observed.

Given the results discussed above, no teaching approach clearly stands above across the various aspects of the laboratory investigated. Based on the student opinions, both Guided Inquiry and Problem Solving were flawed but generated a positive overall experience. Based on the student-completed quiz, Guided Inquiry would most likely give the most consistent positive experience balanced with the development of understanding for the chemistry concepts and principles. Whilst Problem Solving was warmly received, the application of this teaching approach for a synthesis experiment was particularly challenging for demonstrators to manage and would require considerable adjustment to maximise its potential.
6.2.2 Organic Functional Groups

The Organic Functional Groups experiment focuses upon two major goals: the investigation of the chemical reactivity of certain functional groups, and the development of observational skills to identify and interpret chemical reactions. Using a series of tests, each student will investigate tests for different functional groups to observe both positive and negative results, culminating in the identification of an unknown sample using the same tests.

6.2.2.1 Student perceptions – Survey

A one-way between groups analysis of variance was conducted upon the three teaching approaches (Expository, N = 117; Guided Inquiry, N = 169; Problem Solving, N = 76). Statistically significant differences at the p < 0.05 level were found in all of the questions posed to students. These included:

Question 1 – This learning format was an engaging experience.

Question 2 – The learning objectives were clearly defined.

Question 3 – The learning objectives were fulfilled through completion of this experiment.

Question 4 – I further developed my practical skills in the laboratory by completing the experiment in this format.

Question 5 – The workload expected was acceptable.

Question 6 – I deepened my understanding of chemistry through completion of the experiment in this format.

Question 7 – I put effort into completing this learning procedure.

Question 8 – I found the experiment in this format to be both interesting and enjoyable.

Overall rating for experiment in this format.
Levene's test for homogeneity of variances was used to determine the appropriate post-hoc test for each analysis. A summary of the analysis of the comparison of grades for the Organic Functional Groups experiment is in Table 32 below. Post-hoc comparisons using the Games-Howell test for Question 1 indicated that the mean scores for both Expository ($\mu = 7.80, \sigma = 1.54$) and Guided Inquiry ($\mu = 7.52, \sigma = 1.64$) were significantly different to Problem Solving ($\mu = 6.46, \sigma = 2.32$). The effect size for Question 1 was 0.07, i.e., a medium effect. Post-hoc comparisons using the Games-Howell test for Question 2 indicated that the mean scores for both Expository ($\mu = 8.15, \sigma = 1.51$) and Guided Inquiry ($\mu = 8.06, \sigma = 1.54$) were significantly different to Problem Solving ($\mu = 6.63, \sigma = 2.25$). The effect size for Question 2 was 0.11, i.e., a medium effect. Post-hoc comparisons using the Games-Howell test for Question 3 indicated that the mean scores for both Expository ($\mu = 8.04, \sigma = 1.63$) and Guided Inquiry ($\mu = 7.92, \sigma = 1.54$) were significantly different to Problem Solving ($\mu = 6.68, \sigma = 2.25$). The effect size for Question 3 was 0.08, i.e., a medium effect. Post-hoc comparisons using the Games-Howell test for Question 4 indicated that the mean scores for both Expository ($\mu = 8.12, \sigma = 1.65$) and Guided Inquiry ($\mu = 7.82, \sigma = 1.82$) were significantly different to Problem Solving ($\mu = 7.00, \sigma = 2.43$). The effect size for Question 4 was 0.04, i.e., a small effect. Post-hoc comparisons using the Games-Howell test for Question 5 indicated that the mean scores for both Expository ($\mu = 8.34, \sigma = 1.84$) and Guided Inquiry ($\mu = 8.43, \sigma = 1.72$) were significantly different to Problem Solving ($\mu = 6.04, \sigma = 2.58$). The effect size for Question 5 was 0.19, i.e., a large effect. Post-hoc comparisons using the Tukey HSD test for Question 7 indicated that the mean scores for both Expository ($\mu = 8.45, \sigma = 1.25$) and Guided Inquiry ($\mu = 8.40, \sigma = 1.88$) were significantly different to Problem Solving ($\mu = 7.88, \sigma = 1.94$). The effect size for Question 7 was 0.19, i.e., a large effect.
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was 0.02, i.e. a small effect. Post-hoc comparisons using the Games-Howell test for Question 8 indicated that the mean scores for both Expository ($\mu = 7.78, \sigma = 1.87$) and Guided Inquiry ($\mu = 7.83, \sigma = 1.83$) were significantly different to Problem Solving ($\mu = 6.53, \sigma = 2.48$). The effect size for Question 8 was 0.07, i.e. a medium effect. Post-hoc comparisons using the Games-Howell test for the overall rating for this experiment indicated that the mean scores for both Expository ($\mu = 8.14, \sigma = 1.30$) and Guided Inquiry ($\mu = 7.88, \sigma = 1.47$) were significantly different to Problem Solving ($\mu = 6.57, \sigma = 2.29$). The effect size for the overall rating was 0.12, i.e. a large effect.
Table 32: Post-hoc output of comparisons of students' survey responses yielding statistically significant differences at a 95% confidence interval for the Organic Functional Groups experiment.

<table>
<thead>
<tr>
<th>Question</th>
<th>Test</th>
<th>1st Variable</th>
<th>2nd Variable</th>
<th>Effect Size</th>
<th>Comparison</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Games–Howell</td>
<td>Expository</td>
<td>Problem Solving</td>
<td>0.07</td>
<td>medium</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Guided Inquiry</td>
<td>Problem Solving</td>
<td>0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Games–Howell</td>
<td>Expository</td>
<td>Problem Solving</td>
<td>0.11</td>
<td>medium</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Guided Inquiry</td>
<td>Problem Solving</td>
<td>0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Games–Howell</td>
<td>Expository</td>
<td>Problem Solving</td>
<td>0.08</td>
<td>medium</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Guided Inquiry</td>
<td>Problem Solving</td>
<td>0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Games–Howell</td>
<td>Expository</td>
<td>Problem Solving</td>
<td>0.04</td>
<td>small</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Guided Inquiry</td>
<td>Problem Solving</td>
<td>0.029</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Games–Howell</td>
<td>Expository</td>
<td>Problem Solving</td>
<td>0.19</td>
<td>large</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Guided Inquiry</td>
<td>Problem Solving</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Games–Howell</td>
<td>Expository</td>
<td>Problem Solving</td>
<td>0.04</td>
<td>small</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Guided Inquiry</td>
<td>Problem Solving</td>
<td>0.008</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Games–Howell</td>
<td>Expository</td>
<td>Problem Solving</td>
<td>0.07</td>
<td>medium</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Guided Inquiry</td>
<td>Problem Solving</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Games–Howell</td>
<td>Expository</td>
<td>Problem Solving</td>
<td>0.07</td>
<td>medium</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Guided Inquiry</td>
<td>Problem Solving</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Post-Hoc tests determined by Levene's test for homogeneity of variances as discussed in Section 5.2.1.3.
6.2.2.2 Student perceptions – Survey comments

Figure 31 displays the proportions of student comments for the student-completed survey within the broad themes in Section 6.2.1.2. All three teaching approaches were distributed similarly to one another. In all three, approximately half of the student comments were concerning the laboratory process, a quarter were concerning the engagement with information, and the remaining comments distributed amongst the two themes; interaction with others and the overall laboratory experience.

Figure 31. Total distribution of types of survey comments for the Organic Functional Groups experiment (Expository, N = 144; Guided Inquiry, N = 141; Problem Solving, N = 96).

Three sub-themes were common across the teaching approaches compared: the positive experience of identifying an unknown using the skills and concepts practiced early in the experiment, the presence of clear instructions within the laboratory manual and concerns for laboratory resources including gloves, reagents, equipment, and space. Perhaps most interestingly was the shared sub-theme of clear instructions within the laboratory manual.
has been discussed in Chapter 5, there were sub-themes identified for Problem Solving versions of experiments that related to a lack of clarity for the procedure structure. The Problem Solving version of the Organic Functional Groups experiment perhaps differed as the steps for each small-scale test were given as part of the introduction and the student component required the structuring of suitable positive and negative examples of each tests.

The two other sub-themes can be both attributed to the nature of the experiment itself. The challenge of applying their tests to determine an unknown is a procedure that would appeal to most students. The downside of this experiment however, lies with the large number of reagents required, therefore causing some confusion with equipment and reagents.

Figure 32 shows the proportions of positive and negative comments made for each broad theme for the Expository version of the Organic Functional Groups experiment. For three of the themes; interaction with others, laboratory process, and engagement with information, there are approximately equal positive to negative comments. The one exception to this was for the overall laboratory experience responses, where all were positive.
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Figure 32. The proportion of positive versus negative comments for the overarching themes in the Expository (N = 144) version of the Organic Functional Groups experiment.

The sub-themes identified within Table 33, highlight a number of key aspects to the laboratory that students noted. Of these, the majority of the sub-themes identified focused upon laboratory specific aspects of the experiment. For example, a large proportion of students found the use of a large number of small-scale tests to be a useful practice in developing interest and maintaining engagement. An equal number of students indicated that the presence of so many small-scale tests resulted in an increased workload that contributed negatively to the laboratory experience. Furthermore, the reliability was questioned due to a lack of understanding of the nature of these tests. Given the nature of the Expository teaching approach, this belief may be attributed to a lack of development of understanding through completion of the provided instructions. Two responses from students were of particular interest. The first:

“System only works when in conjunction with demonstrator interaction. The extra info from them helps with understanding the chemistry rather than just following steps.”
The second comment of interest related to the course structure completed by students: “By only doing these experiments once a week, any understanding is lost by the next week.”

Table 33. Sub-themes observed for the Expository version of the Organic Functional Groups experiment.

<table>
<thead>
<tr>
<th>Positive</th>
<th>Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>• General feedback relating to the overall laboratory experience</td>
<td>• The unknown analysis was difficult and/or confusing.</td>
</tr>
<tr>
<td>• The variety of small-scale tests used</td>
<td>• The workload was too much for the time period allocated.</td>
</tr>
<tr>
<td>• The length of each test being short in conjunction with no waiting times for equipment and resources</td>
<td>• Insufficient background information on how the reactions occur and general theory.</td>
</tr>
<tr>
<td>• The repeatability of the tests and the presence of false positives and negatives</td>
<td>• The repeatability of the tests and the presence of false positives and negatives</td>
</tr>
</tbody>
</table>

Figure 33 presents the proportions of positive to negative responses for the Guided Inquiry iteration of the Organic Functional Groups experiment. It provides an almost exact replica of the proportions observed for the Expository iteration. The one exception to this was the presence of several comments classified as being within the miscellaneous theme.
A number of positive sub-themes were identified for the Guided Inquiry version of the *Organic Functional Groups* experiment (Table 34). Two of these focused towards the specifics of this experiment rather than the teaching approach. The large variety of interesting tests are inherently linked providing an experience with work to do throughout. A further advantage is the avoidance of waiting times seen within other experiments. Perhaps the most interesting positive sub-theme related directly to the teaching approach where students first identified, before responding in a positive fashion to the semi self-directed nature of Guided Inquiry. These comments included reference to the provision of a structured procedure with a focus on understanding aspects of the experiment throughout the experience rather than piecing it all together at the end en masse. The one negative sub-theme identified conflicted with one of the common sub-themes found throughout all three teaching approaches. The comments with concerns for the space allotted for taking notes and observations are logistical issues that can be solved in the next iteration of this unit. The clarity of information however, was vague on
whether it was directed at the information given within the procedural instructions or at the background information provided about each test and the underlying chemistry themes.

Table 34. Sub-themes observed for the Guided Inquiry version of the Organic Functional Groups experiment

<table>
<thead>
<tr>
<th>Positive</th>
<th>Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>• A large variety of interesting tests.</td>
<td>• Clarity of information provided and additional space within the laboratory manual needed.</td>
</tr>
<tr>
<td>• Semi self-directed nature of the teaching approach.</td>
<td></td>
</tr>
<tr>
<td>• The demonstrators were approachable.</td>
<td></td>
</tr>
<tr>
<td>• No excessive wait times, always work to complete.</td>
<td></td>
</tr>
</tbody>
</table>

To contrast the proportions observed in the Expository and Guided Inquiry, the Problem Solving version of this experiment did not have equal proportions for positive and negative responses for all overarching themes (Figure 34). Both interaction with others and the overall laboratory experience were skewed to an approximate 70/30 percentage favouring positive responses. Conversely, both the laboratory process and engagement with others themes were similarly skewed favouring negative responses.
Only a small number of sub-themes were identified for the Problem Solving version of the *Organic Functional Groups* experiment (Table 35). The two positive sub-themes were strongly related to the nature of Problem Solving as a learning experience. As students were required to construct the finer details of the experiment many students responded to this positively as having greater independency. This independency thereby allowed greater engagement with the chemistry being undertaken. Furthermore, one focus for the demonstrators in teaching the Problem Solving laboratory was to develop an environment where students would seek out discussion with both peers and demonstrators to help inform their experiment design. As with any student cohort however, for a group of students who may enjoy one learning environment, there will be a student group of an opposing opinion who may not have engaged as well or may have simply had a different experience. As seen in the Expository version of this experiment, students indicated that the large number of tests increased the workload too much, causing the experiment to be stressful and a struggle to complete.
Table 35. Sub-themes observed for the Problem Solving version of the Organic Functional Groups experiment

<table>
<thead>
<tr>
<th>Sub-themes</th>
<th>Positive</th>
<th>Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Independence in engaging with the experiment with encouragement to interact with peers and demonstrators.</td>
<td>• The number of tests increased the workload too much.</td>
</tr>
<tr>
<td></td>
<td>• This laboratory was more engaging, better than other experiments, and students said they learned more.</td>
<td>• A lack of direction and guidance from both laboratory manual and demonstrators.</td>
</tr>
</tbody>
</table>

Two comments were of particular interest when considering the advantages and disadvantages of Problem Solving as the teaching approach. The first related to the laboratory experience being a positive one: "I believe that the [practical] was set out well with easy to follow instructions, and I believe that being able to see that the [practical] had real world functions made it engaging." The first half of this response falls within one of the positive sub-themes already discussed earlier. The second half however, is one to which links to one the primary purposes of the teaching laboratory. Given the teaching laboratory aims to develop those skills that would be used outside of a learning environment, to further expand this to applications of the tests being undertaken, is an outcome highly desired by both students and teachers. The second comment conversely raises an important consideration for those students who may not be as easily engaged with a Problem Solving environment.
"I really want to learn chemistry. This means I need to be taught. This format requires me to teach myself. It is totally operating in the dark and I don't feel like I'm getting my money's worth."

This response indicates that the purpose of a Problem Solving experience has not been adequately conveyed to the student prior to their undertaking the activity. As seen within this comment, this can have drastic effects on their perception of the laboratory. The demonstrators for this laboratory provided some insight into their experience and indicated that teaching this Problem Solving laboratory was a more difficult challenge than the regular laboratories. In particular, they commented upon an increased workload for both themselves and the students, and that more direction was required for students prior to the laboratory. Despite this, some demonstrators reported an increased engagement and enjoyment of the challenge in undertaking the Problem Solving version of this experiment.

6.2.2.3 Student performance – Grade

Using the same methods discussed in Section 6.2.2.1, statistically significant differences at the p < 0.05 level were found in a number of the components of grades awarded to students. Figure 35 compares the overall grade and respective criteria for the three teaching approaches (Expository, N = 199; Guided Inquiry, N = 233; Problem Solving, N = 109).
Figure 35. Comparison of grades between teaching methods for the Organic Functional Groups experiment in KRA113. True values: Criterion 1 - 20, Criteria 2 and 3 - 40 scaled to percentage with percentage error represented as error bars.

A summary of the statistically significant analyses is within Table 36. Post-hoc comparisons using the Tukey HSD test for Criterion 2 indicated that the mean score for Expository ($\mu = 33.42, \sigma = 3.59$) was significantly different to Guided Inquiry ($\mu = 32.07, \sigma = 4.32$). The effect size for Criterion 2 was 0.02, i.e. a small effect. Post-hoc comparisons using the Games-Howell test for Criterion 3 indicated that the mean scores for both Expository ($\mu = 33.65, \sigma = 3.78$) and Problem Solving ($\mu = 33.09, \sigma = 3.18$) were significantly different to Guided Inquiry ($\mu = 31.80, \sigma = 4.62$). The effect size for Criterion 3 was 0.04, i.e. a small effect. Post-hoc comparisons using the Games-Howell test for the overall Grade indicated that the mean scores for both
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Expository ($\mu = 85.03, \sigma = 8.08$) and Problem Solving ($\mu = 84.12, \sigma = 6.68$) were significantly different to Guided Inquiry ($\mu = 81.81, \sigma = 9.23$). The effect size for the overall Grade was 0.03, i.e. a small effect.

Table 3. Post-hoc output of comparisons of students’ overall grade yielding statistically significant differences at a 95% confidence interval for the Organic Functional Groups experiment

<table>
<thead>
<tr>
<th>Variable</th>
<th>Post-Hoc*</th>
<th>Effect Size</th>
<th>Comparison</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criterion 2</td>
<td>Tukey</td>
<td>0.02</td>
<td>Expository &gt; Guided Inquiry</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Criterion 3</td>
<td>Games-Howell</td>
<td>0.04</td>
<td>Expository &gt; Guided Inquiry</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Problem Solving &gt; Guided Inquiry</td>
<td>0.008</td>
</tr>
<tr>
<td>Grade</td>
<td>Games-Howell</td>
<td>0.03</td>
<td>Expository &gt; Guided Inquiry</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Problem Solving &gt; Guided Inquiry</td>
<td>0.025</td>
</tr>
</tbody>
</table>

*Post-Hoc tests determined by Levene’s test for homogeneity of variances as discussed in Section 5.2.1.3.

6.2.2.4 Student performance – Quiz

The Organic Functional Groups experiment post-laboratory quiz questions were:

- Question 1 – Recognition of multiple types of observations.
- Question 2 – Theoretical problem requiring knowledge of the tests from the experiment to draw conclusions on the functional groups in compound X.
- Question 3 – Using the conclusions from Question 2, identify the structure of the compound X.
As discussed in Section 6.2.1.4, Figure 36 compares the three teaching approaches for each question with blue indicating the percentage of correct responses and red, the partially correct responses.

**Question 1**
Probing understanding of the types of observations that can be taken, indicates all three achieve a similar standard with respect to correct responses, with a small advantage for the Guided Inquiry cohort with respect to the partially correct responses. Question 2, requiring students to use the theory behind each of the tests within this experiment, gives perhaps the greatest difference between teaching approaches. While only a small percentage of students achieved a correct response, the majority of students giving partially correct responses meaning they understood a sufficient number of the tests to logically work out the correct answer. The components of responses that were not correct were awarded for misidentification of positive

![Graph comparing teaching approaches]

10% of students in the Expository cohort received a perfect score, indicating all students achieved correctness, while only 1% of students in the Guided Inquiry cohort achieved this. Question 3, requiring students to identify the type of tests and the conditions under which they should be used, gives perhaps the greatest difference between teaching approaches. While only a small percentage of students achieved a correct response, the majority of students giving partially correct responses meaning they understood a sufficient number of the tests to logically work out the correct answer. The components of responses that were not correct were awarded for misidentification of positive
and negative results for one or more of the tests given within the question. Based on this, the Guided Inquiry cohort had the most success in answering this question, closely followed by the Expository teaching approach cohort. Question 3, requiring students to select the compound discussed in question 2 from a range of possibilities, once again indicated a slight advantage to those who completed the Guided Inquiry experiment. A large number of the partially correct responses for all three teaching approaches seemed to have attained a correct or near correct answer for question 2 but chose not to utilise this information in answering question 3.

6.2.2.5 Summary of results
The post-laboratory survey provided students an opportunity to give feedback on their perceptions on the teaching approach undertaken and the general laboratory experience. Despite analysis of the Likert-based questions producing statistically significant differences in all questions asked, the effect size of the majority of these comparisons were of a small to medium size and are therefore negligible. Three questions however, indicated the presence of more substantial differences. Upon investigation of these differences, a definitive trend was observed. Both Expository and Guided Inquiry was preferable as a teaching approach to students over Problem Solving with regards to: clarity of the learning objectives, the acceptability of the workload, and the overall laboratory experience. This trend is observed throughout the remainder of the questions, but, as previously stated, the effect sizes of these comparisons reduce their meaningfulness. When considering the responses made by students outside of the guided questions, a number of themes were identified. At the broadest level of investigation that the proportion of comments, positive and negative combined, for each teaching approach were similar. Shifting to the next depth of investigation, both Expository and Guided Inquiry had an approximately equal proportion of positive to negative comments within the overarching themes discussed. The proportions observed for the Problem Solving
iteration, however, saw positive responses with regards to the interaction with others and the overall laboratory experience themes. The laboratory process and the engagement with information themes, however, were negative. Individually each teaching approach had a number of sub-themes identified. The strengths of Expository as perceived by the students related mostly to the timings within the laboratory and the variety of small-scale tests used. In contrast, students indicated that there was a lack of information, and due to this undertaking analysis of an unknown compound was difficult and confusing. The Guided Inquiry experiment appeared to encompass the strengths discussed for the Expository version. In addition, students positively commented on the self-directed nature of the teaching approach.

Furthermore, the one negative sub-theme identified was phrased in the context of expanding their knowledge rather than amending a lack of. Finally, the Problem Solving iteration of the Organic Functional Groups experiment results indicated a split of students for the enjoyment of this laboratory. A number of students indicated that the learning environment prompted a greater depth of engagement and enjoyment with the content. Others found the required student initiative to be confronting and confusing.

Analysis of the average grades given to students through assessment of their performance indicated statistically significant differences were found in the criteria and the overall grade. These comparisons however, had small effect sizes and are therefore not reliable. The average grades however, for each teaching approach all reached an approximately High Distinction level, 80%.

The post-laboratory quizzes completed by students to test understanding of the key concepts and techniques used within the laboratory did not provide a definitive conclusion on which teaching approach provided the best learning environment. Closer inspection of each question indicated a slight advantage may be apparent for the Guided Inquiry cohort of students. These findings align with the student perceptions of their understanding, Expository...
students found that a lack of information was impeding their development of understanding, whereas those students within the Guided Inquiry instance asked for further expansion on the information provided.

Initially, the student responses within the survey seemed to indicate an advantage of both the Expository and Guided Inquiry instances over the Problem Solving instance. While this may have appeared to be the case at the surface level, upon closer inspection it became apparent that the preference of students for the Expository teaching approach lie within the simplicity of its instructions. The students within the Guided Inquiry cohort, however, indicated that the increased level of student involvement in the experimental procedure led to the perception of a greater level of understanding attained.

Whilst analysis of the demonstrator awarded grades did not result in any conclusive evidence, this finding was further supported by the analysis of the post-laboratory quiz. From this quiz, the Guided Inquiry teaching approach developed the understanding of the key concepts and techniques to a higher standard than that of the Expository or Problem Solving experiments. Based on these findings, Guided Inquiry appears as a teaching approach of most benefit for this experiment. A special mention should be given to Problem Solving that was received positively by a significant proportion of students undertaking the laboratory. Conversely, an equally significant proportion of students found the Problem Solving experience to be confronting. With modification and fine-tuning of the laboratory manual and overall experience, Problem Solving could potentially be appealing and more beneficial to the student cohort.
6.2.3 Thermochemistry: Enthalpy of Neutralisation

The Thermochemistry: Enthalpy of Neutralisation segment centres on the investigation of Hess's Law in application to the neutralisation of sodium hydroxide pellets with hydrochloric acid. During this experiment students construct a makeshift calorimeter to measure the enthalpy of both the combined process and individual processes in this neutralisation. The focus however, lies within the calculation and interpretation of the data collected.

6.2.3.1 Student perceptions - Survey

Using the method discussed within Section 6.2.1.1, a one-way between-groups analysis of variance was conducted upon the three teaching approaches (Expository, N = 87; Guided Inquiry, N = 121; Problem Solving, N = 53). One statistically significant difference at the p < 0.05 level was found in the Likert-based questions posed to students within the survey:

Question 3 – The learning objectives were fulfilled through completion of this experiment.

As discussed previously, Levene’s test for homogeneity of variances was used to determine the appropriate post-hoc test. A summary of the analysis of the comparison of grades for the Thermochemistry: Enthalpy of Neutralisation experiment is in Table 37. Post-hoc comparisons using the Games-Howell test for Question 3 indicated that the mean score for Guided Inquiry (μ = 8.19, σ = 1.42) was significantly different to Expository (μ = 7.50, σ = 2.42). The effect size for Question 3 was 0.02, i.e. a small effect.
### Table 37. Post-hoc output of comparisons of students’ survey responses yielding statistically significant differences at a 95% confidence interval for the Thermochemistry: Enthalpy of Neutralisation experiment

<table>
<thead>
<tr>
<th>Variable</th>
<th>Post-Hoc*</th>
<th>Effect Size</th>
<th>Comparison</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Question 3</td>
<td>Games–Howell</td>
<td>0.02 (small)</td>
<td>Guided Inquiry &gt; Expository</td>
<td>0.050</td>
</tr>
</tbody>
</table>

*Post-Hoc tests determined by Levene’s test for homogeneity of variances as discussed in Section 5.2.1.3.

#### 6.2.3.2 Student perceptions – Survey comments

Figure 37 shows the proportions of responses, both positive and negative, students provided outside of the structured survey questions. After assignment of each response to one of the overarching themes discussed earlier in this Chapter, we can see a distinct difference between the Expository teaching approach and the Guided Inquiry and Problem Solving approaches. The Expository proportions are considerably skewed towards comments on the laboratory process. In contrast, both Guided Inquiry and Problem Solving approaches saw a decrease in comments relating to the laboratory process and a corresponding increase in the comments relating to the engaging with information theme. The three remaining themes, interaction with others, overall laboratory experience, and miscellaneous, were independent of the teaching approach used.
After investigating further into the responses provided by students, sub-themes were identified for each teaching approach. Through comparison of these, two sub-themes were identified as being common between all three. The first, regardless of teaching approach, was an overall enjoyable student experience. These comments listed a broad number of vague reasons with the focus being upon the overall laboratory. The second sub-theme common amongst all three teaching approaches was the negative perception of the quality of the calorimeter used. The calorimeter in question is constructed from two styrofoam cups and with care can be an effective tool for the measurement of enthalpy. The high number of student responses however, quoting poor quality calorimeters as the cause of faulty results or a lack of understanding was surprising. Whether this perception is initiated from the materials used, the information within the laboratory manual, or through communication with demonstrators or peers is uncertain. One example of a previous similar response from...
students concerning "simple" equipment has been presented by Crisp, Kable, Read, and Buntine (2011).

Figure 38 increases the depth of analysis by inspecting the proportions of positive and negative responses for each of the overarching themes. It is apparent that certain aspects within the Expository teaching approach were favoured by students over others. The interaction with others, engagement with information and overall laboratory experience themes were all skewed in favour of positive responses. The exception was the laboratory process theme, with an almost entirely negative response from students.

![Figure 38](image)

**Figure 38.** The proportion of positive versus negative comments for the overarching themes in the Expository (N = 71) version of the *Thermochemistry: Enthalpy of Neutralisation* experiment.

As discussed previously, a number of sub-themes were identified that were not common across all three teaching approaches. The sub-themes, both positive and negative, that were identified for the Expository version of this experiment are shown in Table 38. One sub-theme
is the clarity of the method within the laboratory manual that was identified as both a positive and negative theme. Inspection of the volume of responses for each shows a discrepancy with negative comments being in excess. The discontent with the information included not only the background information, but also the discussion questions posed upon completion of the experiment. Whether this was due to a lack of development of understanding of the principles behind this experiment, or due to a misinterpretation of the methods is uncertain. Perhaps the most intriguing sub-theme identified related to the students' perception of Hess' Law. Hess' Law states that the individual enthalpies in a series of reactions will equal the enthalpy of the combined reactions. Through observations within the laboratory and analysis of the comments made on the surveys, it became clear that students interpreted Hess' Law to mean the compared enthalpies must be exactly equal, completely disregarding the potential for experimental uncertainty within the laboratory. This demonstrates a lack of understanding not only of Hess' Law, but also of the nature and complications of practical laboratory work.
Table 38: Sub-themes observed for the Expository version of Thermochemistry:

**Positive**
- The step by step instructions coupled with the clear templates to record data.
- Working in pairs.

**Negative**
- The method and information provided in the laboratory book lack clarity.
- The questions asked in the discussion were confusing.
- The length of the experiment was too long and was not engaging.
- Hess's Law did not work and the individual enthalpies did not exactly match that of the combined enthalpy.

A number of individual responses stood out from the survey responses, though these did not fit within any of the sub-themes identified. One positive comment that has been observed throughout multiple experiments was the point that using new equipment and learning new techniques were critical for engaging and generating interest from students in the experiment being undertaken.

There were two comments however, that raised some concerns with the interactions with demonstrators and the quality of the laboratory experience itself:
- "I felt my demonstrator did not completely understand the course of calculations. They even said "I don't know" when I approached them with a question. This made it hard to feel I could ask more questions to further my understanding."
"I am being very discouraged from continuing with chem because of these labs."

Whilst these may be interpreted as 'once-off' occurrences, the first response in particularly is alarming. A large amount of effort is put into the training and maintaining of demonstrator quality throughout each semester. Furthermore, a key focus of the chemistry teaching laboratories is to engage and interest students, potentially for them to progress through to second and third year chemistry units. It is precisely because of these concerns that it is so important to continually reflect upon the teaching practices used and aim to maintain a high standard of teaching whilst being aware of the changing needs of students.

Figure 39 shows the Guided Inquiry version of the Thermochemistry: Enthalpy of Neutralisation experiment proportions of positive to negative responses for the overarching themes. Similar to the Expository iteration (Figure 39), both the interaction with others and laboratory process themes remained largely unchanged at this level. The engagement with others and overall laboratory experience themes however, shifted considerably towards a close balance of positive to negative responses.
Figure 39. The proportion of positive versus negative comments for the overarching themes in the Guided Inquiry (N = 65) version of the *Thermochemistry: Enthalpy of Neutralisation* experiment.

For the most part, the sub-themes, within Table 39, identified for the Guided Inquiry version related to those themes found within the Expository version discussed for Table 38. A divide of opinions was observed with respect to the quality of instructions and structure in the laboratory manual, though the overall proportions for Guided Inquiry (Figure 39) were far more balanced than seen in Expository (Figure 38). One point of interest was the notable lack of responses concerned with the application of Hess’s Law to a practical situation. Where Expository saw a large number of students misunderstanding Hess’s Law and the nature of an experimental environment, the Guided Inquiry cohort did not seem to have this problem.
Table 39. Sub-themes observed for the Guided Inquiry version of the Thermochemistry:

<table>
<thead>
<tr>
<th>Positive</th>
<th>Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>• The instructions and tables within the laboratory manual were clear</td>
<td>• Too much work to get through</td>
</tr>
<tr>
<td>• Interaction with both demonstrators and peers.</td>
<td>• Inconsistencies within laboratory book for both questions and tables</td>
</tr>
</tbody>
</table>

One particular response was given with regards to the information within the laboratory manual that may be related to the often seen concern with how much background information is within the laboratory manual.

"Some information on whiteboards and not in the [practical] notes. This leads to, in the heat of the moment of forgetting this info. It would be useful if all info required is in the [practical] book."

Recording information and notes within a laboratory manual or book is a key element to conducting work in an experimental environment. This comment would seem to indicate an overreliance upon what is provided in the laboratory manual. Demonstrator provided information is staggered as the laboratory progresses both to avoid information overload, and as an expansion relevant to that particular group. Despite these efforts, it may be necessary to more clearly state the importance of recording notes within their laboratory manual.

From the feedback received from demonstrators, one tangential response with regard to the structure of teaching into this laboratory was:
Instead of me asking questions, I split them into 2 groups to think together and come up with questions creatively. After 5 – 10 minutes each one in one group ask one from the other group. Evaluation based on quality of the question asked and the answer.

It is common and encouraged for demonstrators to hold a pre-experiment group discussion, and depending on the experiment hold several of these meetings to discuss particular aspects or procedures. This expansion described by the demonstrator above gives a potential avenue for students to not only be challenged on aspects of the laboratory, but also challenge students to generate questions based off of their understanding of the laboratory.

Figure 40 shows the Problem Solving version of the Thermochemistry: Enthalpy of Neutralisation experiment once more saw differences in the proportions when compared to both Expository (Figure 38) and Guided Inquiry (Figure 39). The interaction with others theme, similar to both Expository and Guided Inquiry, was entirely positive. Differences were observed in the other themes considered however. Both laboratory process and the overall laboratory experience themes neared an equal balance of positive to negative responses. The engagement with information theme conversely indicated an increase in the percentage of negative comments. This last point in particular is of interest as progressing from Expository through to Problem Solving there was a definitive trend of increasing negative responses for the engagement with information theme.
Table 40 shows the sub-themes identified for the Problem Solving version of this experiment. A number of both positive and negative sub-themes were observed. Inspection of these shows commonality for a number of sub-themes with the Problem Solving experiences previously discussed through this Chapter. For example, student responses suggested that the encouragement for time management and the development of their own method were aspects of this laboratory that strengthened the experience. Conversely, a large proportion of comments found the instructions within the laboratory manual were not clear, and that additional background information and pre-reading materials were needed. These are not necessarily insurmountable challenges to address but would require a considerable redevelopment of the expectations students have for the laboratory experience. One of the issues in a number of responses relating to clarity within the laboratory manual was the misinterpretation of what was required of students both prior and during the experiment session. One negative sub-theme of particular interest however, stated that students felt that...
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The level of chemistry within this experiment was too low and due to this was not interesting or engaging. The self-perception of understanding becomes significant when compared to the results obtained from the post-laboratory quiz, which shall be discussed later in this chapter.

Table 40. Sub-themes observed for the Problem Solving version of Thermochemistry:

<table>
<thead>
<tr>
<th>Enthalpy of Neutralisation experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Positive</strong></td>
</tr>
<tr>
<td>• The layout within the laboratory manual was clear.</td>
</tr>
<tr>
<td>• Individual time management.</td>
</tr>
<tr>
<td>• Learning and practicing the equations and calculations for this experiment.</td>
</tr>
<tr>
<td>• Writing their own method.</td>
</tr>
<tr>
<td><strong>Negative</strong></td>
</tr>
<tr>
<td>• The instructions within the laboratory manual were not clear.</td>
</tr>
<tr>
<td>• The chemistry in this experiment was not interesting or too easy.</td>
</tr>
<tr>
<td>• More background information and pre-laboratory reading materials.</td>
</tr>
</tbody>
</table>

One common point of feedback obtained from the demonstrators was that the fundamental mathematics were a considerable problem for a large number of students. These included basic algebra, calculator operations and units of measurement.

6.2.3.3 Student performance – Grade

Statistically significant differences at the p < 0.05 level were found in a number of the components of grades awarded to students. Figure 41 shows below is the comparison of the three teaching approaches (Expository, N = 188; Guided Inquiry, N = 230; Problem Solving, N = 79) for both the overall grade and the respective criteria for the Thermochemistry: Enthalpy of Neutralisation experiment.
Figure 41. Comparison of grades between teaching methods for the Thermochemistry: Enthalpy of Neutralisation experiment in KRA113. True values: Criterion 1 - 20, Criterion 2 and 3 - 40 scaled to percentage with percentage error represented as error bars. The post-hoc test for each comparison was selected using Levene's test for homogeneity of variances. A summary of the statistically significant comparisons are in Table 41. Post-hoc comparisons using the Games-Howell test for Criterion 2 indicated that the mean score for Problem Solving ($\mu = 33.57, \sigma = 2.72$) was significantly different to Guided Inquiry ($\mu = 32.34, \sigma = 3.76$). The effect size for Criterion 2 was 0.01, i.e. a small effect. Post-hoc comparisons using the Games-Howell test for Criterion 3 indicated that the mean score for Problem Solving ($\mu = 34.29, \sigma = 2.72$) was significantly different to both Expository ($\mu = 33.16, \sigma = 3.50$) and Guided Inquiry ($\mu = 32.11, \sigma = 3.72$). Additionally Expository was significantly different to Guided Inquiry.
Inquiry. The effect size for Criterion 3 was 0.05, i.e., a small effect. Post-hoc comparisons using the Tukey HSD test for the overall Grade indicated that the mean score for Problem Solving ($\mu = 86.43, \sigma = 5.70$) was significantly different to Guided Inquiry ($\mu = 82.85, \sigma = 6.81$). The effect size for the overall Grade was 0.03, i.e., a small effect.

Table 41. Post-hoc output of comparisons of students' overall grade yielding statistically significant differences at a 95% confidence interval for the Thermochemistry: Enthalpy of Neutralisation experiment.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Post-Hoc*</th>
<th>Effect Size</th>
<th>Comparison</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criterion 2</td>
<td>Games–Howell</td>
<td>0.01</td>
<td>(small)</td>
<td>Problem Solving &gt; Guided Inquiry</td>
</tr>
<tr>
<td>Criterion 3</td>
<td>Games–Howell</td>
<td>0.05</td>
<td>(small)</td>
<td>Expository &gt; Guided Inquiry</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Problem Solving &gt; Expository</td>
<td>0.014</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Problem Solving &gt; Guided Inquiry</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Grade</td>
<td>Tukey</td>
<td>0.03</td>
<td>(small)</td>
<td>Problem Solving &gt; Guided Inquiry</td>
</tr>
</tbody>
</table>

*Post-Hoc tests determined by Levene's test for homogeneity of variances as discussed in Section 5.2.1.3.

6.2.3.4 Student Performance – Quiz

The post-laboratory quiz questions for the Thermochemistry: Enthalpy of Neutralisation are:

Question 1 – Requires students to give an explanation of the calorimeter used in this experiment, in addition to its purpose and any flaws associated.

Question 2 – Explaining from what source energy is derived when the release of energy is observed.
Question 3 – Students must explain Hess’ s Law and how it was applied in this experiment.

As detailed in Section 6.2.1.4, Figure 42 below compares the three teaching approaches for each question. The blue percentage indicates the correct responses received whilst the red indicates partially correct responses.

Figure 42. Percentage of correct (blue) and partially correct (red) responses to questions contained within the post-experiment quiz for the Thermochemistry: Enthalpy of Neutralisation experiment (Expository, N = 87; Guided Inquiry, N = 185; Problem Solving, N = 52).

Unfortunately, due to a printing error, the data set for the Question 3 responses in Guided Inquiry was compromised and therefore no comparison could be made. At first inspection, Figure 43 indicates similarities between each question, with a slight increase for Problem Solving in each case. Question 1 had one outcome of particular interest. Nearly all students within the Guided Inquiry cohort gave a response that was only partially correct. The Guided Inquiry responses almost all correctly explained the purpose of a calorimeter, but failed to identify the flaws associated with the calorimeter used. Both the Expository and Problem Solving approaches had higher percentages of correct responses compared to the Guided Inquiry approach.

\[ Q'B' (\%) = \text{Percentage of correct responses} \]

\[ \text{Percentage Response} \]

\[ 0 \quad 20 \quad 40 \quad 60 \quad 80 \quad 100 \]

\[ \text{EX} \quad \text{GI} \quad \text{PS} \]

\[ 0 \quad 20 \quad 40 \quad 60 \quad 80 \quad 100 \]

\[ \text{EX} \quad \text{GI} \quad \text{PS} \]
Solving cohorts indicated a mixture of correct, partially correct, and incorrect responses from students who could correctly identify both the purpose and flaws of the calorimeter used. The most common mistake made by those awarded a partially correct response was a failure to identify flaws in the calorimeter. A number of the responses given quoted flaws such as "bad quality" or "cheap calorimeter" that were treated as insufficient. Question 2, requiring students to explain the source of energy during these reactions, had similar proportions of response types for all three teaching approaches. It could be cautiously stated that the Guided Inquiry responses were of a higher standard than both Expository and Problem Solving, with Expository being those of lowest. To consider the responses themselves, a significant number of responses for all three teaching approaches were partially correct due to identifying the source of the energy as the reactants and products rather than specifying the formation and breaking of bonds. As mentioned previously, the Guided Inquiry responses for Question 3 were compromised and so comparison to the other teaching methods was not possible. Comparing Expository and Problem Solving however, indicated a slight increase in the number of correct and partially correct responses for the Problem Solving cohort. Once more, the misconceptions responsible for partially correct responses were similar for both teaching approaches, and in this particular case related to students specifying that Hess's Law must apply as an exact summation of the enthalpies. Correct responses were those who elaborated on the impact of outside influences on the practical application of Hess's Law.

6.2.3.5 Summary of Results

The post-experimental survey responses for the Thermochemistry: Enthalpy of Neutralisation experiment yielded only one statistically significant difference for the Likert-style component of the survey. The Guided Inquiry cohort indicated that the learning objectives were fulfilled to a higher standard in comparison to the Expository cohorts perception (Question 3). The effect
size for this statistically significant difference was of small size, and is therefore questionable in its meaningfulness. Analysis of the less structured component of the post-experimental survey provided insight into a number of themes indicating differences between the teaching approaches. When considering the broad themes identified within the combined positive and negative written responses, one major shift was noted between teaching approaches. The Expository cohort written responses had a large proportion of comments (57%) focused upon the laboratory processes used within the experiment. Both Guided Inquiry and Problem Solving cohorts saw an approximate 20% shift of comments from laboratory processes to the engagement with information theme. Given that these broad themes are presented as the combined positive and negative responses, further analysis was required to identify the more subtle differences. After identifying sub-themes for each teaching approach, a number of these sub-themes were common amongst all three, and could be attributed to characteristics of this particular experiment in its current form. The first of these two common themes were responses from students indicating an overall enjoyment of the laboratory experience. Whilst these comments were vague, the majority indicated the laboratory processes were enjoyable to undertake and contributed largely to the overall experience. The second common theme was the perception of students in all three teaching approaches that the quality of the calorimeters used was insufficient and inappropriate for a university laboratory class. The reasons given for these responses were often due to a misconception on their effectiveness and lie at the surface level interpretation by students. Each teaching approach had a number of sub-themes identified only within that version of the experiment. One major note of interest for the Expository teaching approach was the proportions of positive to negative responses observed for each of the broad themes. Interaction with others, engagement with information, and the overall laboratory experience themes were heavily weighted by positive responses, whereas the laboratory process theme had a large majority of negative responses.
The strengths of this teaching approach, Expository, as perceived by students lay in the step-by-step nature of the process and the ability to work in pairs. A number of negative sub-themes were identified. Several of these however, were small in number. These included discontent with both the information provided in the laboratory manual and the questions posed in the discussion component of the experiment. Of far larger quantity were responses indicating the length of the experiment was inappropriate (too long) and furthermore, not engaging to complete. One sub-theme of particular interest indicated a misunderstanding by students of applying Hess' Law in an experimental environment.

As discussed earlier, the Guided Inquiry approach saw a considerable shift in the proportion of comments from the laboratory process to the engagement with information. This was also reflected in the sub-themes identified for each of broad themes. Interestingly, both the engagement with information and overall laboratory experience were weighted similarly for positive to negative responses. Interaction with others and laboratory processes themes had similar positive to negative proportions to the Expository style. Similar to the Expository approach, the strengths of Guided Inquiry as a teaching approach were the instructions and tables within the laboratory manual and the interaction with others, this time including the demonstrators. Students indicated however, that the sheer volume of work was too much for the timeframe allotted. In addition, students noted a number of inconsistencies in the laboratory manual, and the presence of these caused some confusion. One sub-theme of particular interest absent from this teaching approach was the application of Hess' Law. No responses from students indicated that Hess' Law was a problem, a very different response to that scene for the cohort who undertook the Expository instance.
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The Problem Solving instance of the Thermochemistry: Enthalpy of Neutralisation experiment once more shifted in the proportions of positive to negative comments when compared to the Expository and Guided Inquiry styles. Different to the Expository and Guided Inquiry approaches, the laboratory process broad theme saw a far more balanced proportion of positive to negative, whereas an increase in the negative comments relating to the engagement with information theme was observed. A number of strengths were identified for this teaching approach, of which several relate directly to characteristics of a Problem Solving activity. These included a focus upon individual time management, writing their own method, and preparation through practice of the equations used in this experiment. Found to be a sub-theme for both positive and negative responses, the clarity of the instructions within the laboratory manual was raised. Two other negative sub-themes were identified, though upon closer inspection these themes can be interpreted in a positive light. Firstly, students indicated that the chemistry within this experiment was too easy and therefore not particularly interesting. Whilst this is a negative outcome, this was not observed for either Expository or Guided Inquiry instances and could imply that students were better prepared for the experiment. Secondly, students requested more background information and pre-laboratory reading materials. Taken at a surface level this would appear to be a negative outcome. When considering the context within these responses however, it becomes apparent that the students requested further information to expand upon their knowledge base. As opposed to suggesting there was a insufficient information for the experiment, this further interest in the chemistry behind the experiment is the type of engagement that is needed to draw students into the field, rather than browsing at a surface level.

The analysis of the grades awarded to each student cohort found a number of statistically significant differences lie in both the individual criterion and the overall grade. Upon...
calculating the effect sizes of these grades and placing these differences into the context of overall grades, that these results were largely irrelevant. Finally, turning to the comparison of the responses for the post-experimental quiz, some minor differences were observed. As mentioned in Section 6.2.3.4, the Guided Inquiry instance of this quiz lacked data for Question 3, therefore making it difficult to draw conclusions for the strength of this teaching approach. Considering the Expository and Problem Solving approaches however, there appears to be a clear advantage for the Problem Solving approach in all three questions. As no quantitative analysis was conducted for this comparison, the advantage is merely suggestive.

Taking these findings into consideration, it seems clear that in most respects, the Expository approach was less effective as a teaching approach than both the Guided Inquiry and Problem Solving approaches. The strengths of Expository seemed to target surface level outcomes, whereas in Guided Inquiry and Problem Solving the students engaged with the chemistry behind the experimental techniques used. Comparing Guided Inquiry to Problem Solving, the major differences, as highlighted in previous experiments, lay within the student responses to the post-experimental survey. Based on these, Problem Solving seemed to have not only the most success, but furthermore the highest potential for the improvement of this experiment in future years.
6.2.4 Determination of the Freezing-Point Depression Constant for Cyclohexane

The determination of the freezing-point depression constant for cyclohexane experiment is split into two main components. The first emphasis is upon hands-on fundamental skills where students monitor the temperature of varying compositions of cyclohexane and naphthalene, and graph these temperature changes. The second, and more important aspect, is the interpretation of this data to identify and calculate the freezing-point depression constant.

6.2.4.1 Student perceptions – Survey

As discussed in Section 6.2.1.1, a one-way between-groups analysis of variance was conducted upon the data collected for the Likert-based questions of this survey (Expository, N = 99; Guided Inquiry, N = 137; Problem Solving, N = 49). Statistically significant differences at the p < 0.05 level were found in only one of the questions posed to students within the survey: Question 3 – I put effort into completing this learning procedure.

Levene’s test for homogeneity of variances was used to determine the appropriate post-hoc test (Section 6.2.1.1). A summary of the analysis of the comparison of grades for the Determination of the Freezing-Point Depression Constant for Cyclohexane experiment is in Table 42. Post-hoc comparisons using the Games-Howell test for Question 3 indicated that the mean score for Expository (µ = 7.93, σ = 2.19) was significantly different to Problem Solving (µ = 7.10, σ = 2.26). The effect size for Question 3 was 0.03, i.e., a small effect.
The combined, both positive and negative, responses provided from each teaching approach have been assigned to overarching themes and are in Figure 43. Some differences between the three teaching approaches can be observed upon inspection of the proportions observed in each overarching theme. Both Expository and Problem Solving are weighted more heavily for the engagement with information than Guided Inquiry. A corresponding increase can be observed for the laboratory process responses for the Guided Inquiry instance. The three remaining themes were mostly unchanged, excepting some minor shifts for the interaction with others and overall laboratory experience themes.
Figure 43. Total distribution of types of survey comments for the Determination of the Freezing-Point Depression Constant for Cyclohexane experiment (Expository, N = 114; Guided Inquiry, N = 76; Problem Solving, N = 78).

Breaking these overarching themes down to investigate the presence of sub-themes, both positive and negative responses yielded a number of themes specific to each teaching approach. One sub-theme was identified as being common amongst all three teaching approaches; a negative sub-theme relating to the presence of long waiting times during this laboratory, resulted in students finding the experiment to be boring and not an engaging experience. Given the nature of the experiment, monitoring change in temperature rates when freezing mixtures, it is not surprising to find a backlash from the students concerning this.

Shifting our focus to the next level of depth, Figure 44 details the proportion of positive and negative comments for each overarching theme within the Expository instance of this experiment. Immediately apparent are both the interaction with others and overall laboratory experience themes being mostly composed of positive responses. The laboratory process as an activity yields 91% positive responses and 10% negative responses. The overall laboratory experience yields 93% positive responses and 7% negative responses.
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The overarching theme is far more balanced, with a slight favouring of negative responses. The engagement with information theme is further weighted towards negative responses.

![Graph showing percentage responses]

Figure 44. The proportion of positive versus negative comments for the overarching themes in the Expository (N = 114) version of the Determination of the Freezing-Point Depression Constant for Cyclohexane experiment.

Upon further inspection, a number of sub-themes can be identified including both positive and negative themes. Both positive and negative sub-themes for the Expository teaching approach have been summarised within Table 43. As can be expected for this teaching approach, a large number of students indicated a preference for the straightforward nature of this experience, and furthermore the mathematics and graphs utilised as a part of the laboratory. As has been observed in a number of the experiments considered within this study, a high number of positive responses related to working in pairs were observed. Turning to the negative sub-themes observed; one sub-theme contrasts with students indicating a dislike for the graphs required as part of this experiment. The negative sub-theme relating to a lack of discussion or questions throughout the experiment was of particular interest. As discussed in Chapters 1 and
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1. One of the drawbacks of Expository as a teaching approach is the lack of discussion or probing throughout an experiment. Seeing this recognised by students as a negative outcome for this procedure would indicate an interest to deepen their understanding of the experiment. Furthermore, this could alleviate the common negative sub-theme discussed earlier of lengthy waiting times during this experiment. Finally, a large number of students detailed dissatisfaction with having to undertake the experiment prior to receiving the relevant lectures on this material. This arrangement was an unfortunate outcome of academic availabilities in that particular year, so would not be characteristic of a normal laboratory. The call for pre-reading materials was largely tied to the previous sub-theme.

Table 43. Sub-themes observed for the Expository version of the Determination of the Freezing-Point Constant for Cyclohexane experiment.

<table>
<thead>
<tr>
<th>Positive</th>
<th>Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>• The maths and graphs utilised within this experiment.</td>
<td>• The required graphs.</td>
</tr>
<tr>
<td>• Simple and straightforward instructions and experiment.</td>
<td>• More discussion and questions posed throughout the experiment rather than the end.</td>
</tr>
<tr>
<td>• Overall laboratory experience.</td>
<td>• Discontent with laboratory concepts not having been covered in prior lectures.</td>
</tr>
<tr>
<td>• Working in pairs.</td>
<td>• More pre-reading materials required.</td>
</tr>
</tbody>
</table>

The Guided Inquiry instance of the Determination of the Freezing-Point Depression Constant for Cyclohexane experiment, when broken into the positive vs negative proportions within Figure 45, paints a far more balanced picture than that of Expository above. With the
exception of the laboratory process theme, the themes of interaction with others, engagement with information, and the overall laboratory experience are almost even. The laboratory process theme itself is heavily weighted towards negative responses.

![Graph showing positive versus negative comments for the overarching themes in the Guided Inquiry (N = 76) version of the Determination of the Freezing-Point Depression of Cyclohexane experiment.](image)

Figure 45. The proportion of positive versus negative comments for the overarching themes in the Guided Inquiry (N = 76) version of the Determination of the Freezing-Point Depression of Cyclohexane experiment.

The positive and negative sub-themes identified for the Guided Inquiry instance of this experiment are summarised within Table 44. Of these, only a small number of positive sub-themes were identified. The content of these sub-themes were broadly distributed indicating that features such as the workload required, linkage with the lecture materials, group work, and the overall laboratory experience were positive. The negative sub-themes were far more numerous and specified a number of disliked aspects within the laboratory. These sub-themes encompassed requested changes to the laboratory manual for more space for recording information and the provided information contained within the manual, the removal of all graphing sections entirely, a lack of engagement with the chemistry concepts, and perhaps
most worryingly, negative interactions with the demonstrators. Inspecting these concerns for the demonstrators, the responses indicated that a number of demonstrators appeared to lack in knowledge and/or confidence for the chemistry being studied within this experiment. Upon consideration of the other experiments considered within this study, this theme was not observed otherwise so could be attributed to an anomaly from normal practice. One further negative sub-theme indicated a lack of linkage between the lecture materials and the experiment that directly contrasts with the positive sub-theme also observed. This could be due to a number of factors including the engagement for each student within lecture sessions or a failure to connect the materials from each with one another.
Table 44. Sub-themes observed for the Guided Inquiry version of the Determination of the Freezing-Point Depression Constant for Cyclohexane experiment

Positive
• Overall laboratory experience.
• Appropriate workload.
• Linked with lecture materials.
• Working in pairs.

Negative
• Greater detail in the explanation of method.
• More room for recording data and graphs.
• Too many waiting periods led to the experiment being boring.
• The experiment did not link with the lecture materials.
• Minimise or remove the graphing sections of this experiment.
• The interaction with demonstrators was not effective due to a lack of knowledge and/or confidence.
• This experiment was not engaging.

One comment made by a student summed up the strengths of the Guided Inquiry approach:
"Pre-lab questions relevant to method and that are engaging. Applying data collected to calculations helped me understand the learning objectives. The simplicity of the experiment allowed more energy to be spent on understanding the concept. Having explanations and diagrams printed before the experiment method and calculations page."
A number of the points raised in this comment align nicely with the positive sub-themes detailed in Table 45. Another perspective from another student highlights alternative perspective to undertaking this experiment and the areas that can create stumbling blocks, sometimes before the experiment even begins:

"I would like to see a fully worked example of each experiment with the relevant calculations. This would be useful for learning how to do prelabs, but I needed to google stuff to understand some information. I would like to see more info and worked examples in the lab manuals." 

Providing a full worked example of each experiment is at first a difficult concept to consider as it would defeat the purpose of students developing those skills to undertake these experiments. Considering this a bit further, however, in giving these experiments to students we assume that they have the necessary fundamental skills to research and prepare for laboratories. In those cases where students lack those skills, they are entering the laboratories immediately disadvantaged. The inclusion of further pre-reading information or preparatory information is a theme that has been observed on a number of times, whether due to a lack or for those students wishing to expand upon their current knowledge.

Figure 46 indicates considerable shifts in the positive vs negative proportions for the Problem Solving instance of this experiment. In fact, the proportions observed for this teaching approach closely resemble those for the Expository teaching approach. Both the interaction with others and the overall laboratory overarching themes were entirely positive and the laboratory process and engagement with information themes heavily weighted towards negative responses.
Figure 46. The proportion of positive versus negative comments for the overarching themes in the Problem Solving (N = 78) version of the Determination of the Freezing-Point Depression Constant for Cyclohexane experiment.

Table 45 summarises the positive and negative sub-themes identified for the Problem Solving instance of this experiment. Characteristic of this teaching approach a number of these sub-themes correspond with commonly observed themes, including positive responses to writing their own method and interactions with both peers and demonstrators, and negative responses such as the method being unclear. Contrary to previous experiments considered in this study as Problem Solving versions, positive sub-themes relating to a straightforward experience and calculations were observed. The remaining negative sub-themes are a mixture of easy to fix and perhaps more difficult to address. Problems such as more room for recording data and graphs and more information require only an adjustment to the laboratory manual. Minimisation of waiting periods during the laboratory would be more difficult. As these waiting periods couple with measurement taking and continual agitation of the mixture, it would be difficult to introduce extra content to engage students.
Table 4.5: Sub-themes observed for the Problem Solving version of the Determination of the Freezing-Point Depression Constant for Cyclohexane experiment.

**Positive**

- Writing their own method.
- The experiment was straightforward.
- The interaction with peers and demonstrators.
- The calculations undertaken in this experiment.

**Negative**

- The method was unclear.
- More information, specifically values such as mass and molecular weight.
- More room for recording data and graphing.
- Too many waiting periods led to the experiment being boring.

Further to the themes observed through analysis of the student responses, a number of demonstrators commented on the difficulties a large proportion of students had when tackling the mathematical problems.

6.2.4.3 Student Performance – Grade

A one-way between-groups analysis of variance was conducted upon the data collected for both the criteria used to grade and the combined total grade. Statistically significant differences at the p < 0.05 level were found in the averages for each of the three criteria, and also in the overall grade given to students. Figure 47 summarises the averages for this data for each teaching approach (Expository, N = 196; Guided Inquiry, N = 225; Problem Solving, N = 47).
Figure 47. Comparison of grades between teaching methods for the Determination of the Freezing-Point Depression Constant for Cyclohexane experiment. True values: Criterion 1 – 20, Criteria 2 and 3 – 40 scaled to percentage with percentage error represented as error bars. The appropriate post-hoc test was determined using the methods discussed in Section 6.2.1.1. A summary of the statistically significant differences determined are within Table 46. Post-hoc comparisons using the Tukey HSD test for Criterion 1 indicated that the mean scores for both Expository ($\mu = 18.60$, $\sigma = 1.81$) and Guided Inquiry ($\mu = 18.70$, $\sigma = 2.43$) were significantly different to Problem Solving ($\mu = 17.34$, $\sigma = 2.76$). The effect size for Criterion 1 was 0.03, i.e. a small effect. Post-hoc comparisons using the Games-Howell test for Criterion 2 indicated that the mean scores for both Expository ($\mu = 34.00$, $\sigma = 3.52$) and Problem Solving ($\mu = 33.68$, $\sigma = 2.55$) were significantly different to Guided Inquiry ($\mu = 31.80$, $\sigma = 4.12$). The effect size for Criterion 2 was larger.
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Criterion 2 was 0.08, i.e., a medium effect. Post-hoc comparisons using the Games-Howell test for Criterion 3 indicated that the mean scores for Expository (µ = 34.59, σ = 3.32) was significantly different to both Guided Inquiry (µ = 32.06, σ = 3.90) and Problem Solving (µ = 31.87, σ = 5.56). The effect size for Criterion 3 was 0.10, i.e., a medium effect. Post-hoc comparisons using the Tukey HSD for the overall Grade indicated that the mean score for Expository (µ = 87.18, σ = 7.44) was significantly different to both Guided Inquiry (µ = 82.56, σ = 7.59) and Problem Solving (µ = 82.89, σ = 6.91). The effect size for the overall Grade was 0.08, i.e., a medium effect.

Table 46. Post-hoc output of comparisons of students’ overall grade yielding statistically significant differences at a 95% confidence interval for the Determination of the Freezing-Point Depression Constant for Cyclohexane experiment.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Post-Hoc*</th>
<th>Effect Size</th>
<th>Comparison</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criterion 1</td>
<td>Tukey</td>
<td>0.03 (small)</td>
<td>Expository &gt; Problem Solving</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Guided Inquiry &gt; Problem Solving</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Criterion 2</td>
<td>Games–Howell</td>
<td>0.08 (medium)</td>
<td>Expository &gt; Guided Inquiry</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Expository &gt; Problem Solving</td>
<td>0.006</td>
</tr>
<tr>
<td>Criterion 3</td>
<td>Games–Howell</td>
<td>0.10 (medium)</td>
<td>Expository &gt; Guided Inquiry</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Expository &gt; Problem Solving</td>
<td>0.006</td>
</tr>
<tr>
<td>Grade</td>
<td>Tukey</td>
<td>0.08 (medium)</td>
<td>Expository &gt; Guided Inquiry</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Expository &gt; Problem Solving</td>
<td>0.001</td>
</tr>
</tbody>
</table>

*Post-Hoc tests determined by Levene’s test for homogeneity of variances as discussed in Section 5.2.1.3.
6.2.4.4 Student Performance – Quiz

The post-laboratory quiz given to students upon completion of the Determination of the Freezing-Point Depression Constant for Cyclohexane experiment was composed of the following questions:

Question 1 – Define the difference between molarity and molality.

Question 2 – Back calculation using a provided freezing point constant to find mass.

Question 3 – Demonstrating understanding of how freezing point changes with a different substance added.

The quiz responses were marked as correct, partially correct, incorrect, or did not attempt.

Figure 48 compares the responses for each question across all three teaching approaches where blue indicates correct responses and red indicates partially correct responses.

Figure 48. Percentage of correct (blue) and partially correct (red) responses to questions contained within the post-experiment quiz for the Determination of the Freezing-Point Depression Constant for Cyclohexane experiment (Expository, N = 99; Guided Inquiry, N = 206; Problem Solving, N = 73).
The results obtained from analysis of the responses for the post-experimental quiz varied drastically between each question posed as part of the quiz. Question 1 related to the difference between molality and molarity. When considering the combined correct and partially correct indicated similar levels of attainment for all three teaching approaches. To consider just the correct responses, however, it becomes apparent that the Problem Solving had far better success with developing knowledge of this distinction. The source of these partially correct responses was the identification of just one of the two terms in terms of units and failure to identify the second. This varied between both molality and molarity.

Contrasting strongly to Question 1, Question 2 indicated a reversal of this trend with the Expository cohort appearing to have the highest success, with a large number of students achieving partially correct answers. Despite this, the Guided Inquiry cohort obtained the highest percentage of correct responses. Misconceptions for this question varied, but were ultimately all calculation errors regarding unit conversion or minor misapplication of equations.

The third and final question caused a great deal of confusion for a number of students in the Guided Inquiry and Problem Solving approaches. Surprisingly, the students within the Expository instance attained a far higher percentage of students submitting correct responses.

6.2.4.5 Summary of Results

Bringing together the results obtained from analysis of this experiment, a number of key features stood out. The analysis of the structured component of the post-experimental identified one statistically significant difference for the amount of effort contributed by students where the Expository cohort was higher than Problem Solving. Upon calculation of the effect size of this comparison however, it was determined this effect size was small and therefore negligible.
The analysis of the unstructured component of the post-experimental survey yielded a much larger quantity of differences between the teaching approaches. Comparing at the broadest level for the combined positive and negative overarching themes identified, one notable shift between teaching approaches occurred. Both Expository and Problem Solving were weighted heavily towards comments within the engagement with information theme whereas the Guided Inquiry approach saw a decrease within the engagement with information and a corresponding increase within the laboratory process broad theme. The Expository approach was characterised by themes commonly found within Expository experiences. These themes included the straightforward nature of the experiment and calculations associated with whilst hindered by a lack of depth for the discussion of concepts and outcomes throughout the experiment. The Guided Inquiry approach identified a far larger number of negative sub-themes centred around the laboratory manual, the lack of engagement within the experiment, and the quality of the interaction with demonstrators. Balancing this, students of the Guided Inquiry cohort praised a number of broad components within the laboratory experience including the expected workload, linkage with the lecture materials, group work, and the overall laboratory experience. Finally, the analysis of the Problem Solving approach sub-themes identified a number of positive and negative themes. Strengths of this Problem Solving approach included students enjoying writing their own method and finding this experience to be a straightforward one including both the experiment and the calculations. Conversely, some students found the method to be unclear and the waiting periods during this Problem Solving experiment led to boredom and a lack of engagement. The remaining two sub-themes related to easily fixed laboratory manual components including some basic information on masses and molecular weights and the inclusion of more space for recording data and graphing.
The analysis of the grades awarded to each student cohort, as determined by their corresponding demonstrators, yield a number of statistically significant differences in both the individual criteria and the overall grade. Despite these differences, the effect size for these comparisons lie within a small to medium effect size. Furthermore, as the average grade of all three teaching approaches lies within the standard required for a High Distinction, the differences found were considered trivial.

From the comparison of the post-experimental quiz for the three teaching approaches, differences were observed in each question. Question 1 appeared to be relatively balanced between the three teaching approaches, with the one difference, Problem Solving, being a much higher proportion of students achieving a correct response when identifying the difference between molality and molarity. For both Questions 2 and 3, the Expository teaching approach responses were considerably higher than those of both the Guided Inquiry and Problem Solving approaches. Questions 2 and 3 relating to freezing point constant calculation and how freezing points change with a change in mixture respectively.

When placing these findings within the larger picture of which teaching method would be most appropriate for this experiment, it becomes apparent there are strengths and weaknesses associated with each. Both the structured survey component and the grades analysis did little to indicate a preferred teaching approach. The preference as dictated by the unstructured survey component indicated a broad variety of opinions on each teaching approach, with both the Expository and Problem Solving approaches appearing to be the most preferred teaching approaches. The Expository approach appeared to be a positive experience for students but these same students reported that not enough depth was provided during their experience. The cohort of the Problem Solving approach reported however, similar
The negative sub-themes identified were mostly those that can be easily remedied with minor laboratory manual adjustments. When considering the post-experimental quiz, the outcomes observed here appear more definitive with the Expository approach cohort attaining a higher level of understanding for Questions 2 and 3. With these in mind, whilst Problem Solving appeared to have some strengths, based on the preference and observed understanding of the student cohorts, the Expository approach seemed to be most favoured.

6.3 Final Thoughts

Chapter 6 has detailed the results obtained from the analysis of four of the experiments completed within the laboratory course undertaken by students as part of the First Year chemistry unit, KRA113 Chemistry 1A. Experiments were chosen to represent a number of different types of experiments including hands-on, observational, calculations based, and interpretation. Each teaching approach was implemented in a separate year: Guided Inquiry in 2013, Problem Solving in 2014, and Expository in 2015. The benefits of this approach allowed a single implementation for each approach with a large sample size for each group, approximately 200 students undertaking each experiment. This relied upon the previously discussed assumption that student cohorts from year to year are comparable. To collect data a number of instruments were used including a post-experimental student-completed survey, a post-experimental quiz, and a demonstrator awarded grade based on the performance of students during the laboratory. Similar to the results observed in Chapter 5 for the Foundation Chemistry unit, the two instruments of most use were the post-experimental survey and quiz.

Table 47 provides the recommended teaching approach for each experiment:
### Table 47. A summary of the recommended teaching approach for each experiment in KRA113.

<table>
<thead>
<tr>
<th>Name of Experiment</th>
<th>Type of Experiment</th>
<th>Recommended Teaching Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxidation of Benzyl Alcohol: Synthesis of Benzoic Acid</td>
<td>Hands-on/Observation</td>
<td>Guided Inquiry</td>
</tr>
<tr>
<td>Organic Functional Groups</td>
<td>Observation/Interpretation</td>
<td>Problem Solving</td>
</tr>
<tr>
<td>Thermochemistry: Enthalpy of Neutralisation</td>
<td>Calculation/Interpretation</td>
<td>Problem Solving</td>
</tr>
<tr>
<td>Determination of the Freezing-Point Depression for Cyclohexane</td>
<td>Interpretation/Calculation</td>
<td>Expository</td>
</tr>
</tbody>
</table>

The analysis of the results obtained from the Oxidation of Benzyl Alcohol: Synthesis of Benzoic Acid experiment were unclear for a particular teaching approach being the most appropriate for this experiment type (Hands-on/Observation). Whether due to the cohort itself or the nature of the experiment being a relatively fundamental experiment, the Guided Inquiry approach appeared to be potentially the most consistently positive experience and would therefore be the recommendation.

The Organic Functional Groups experiment (Observation/Interpretation) outcomes indicated that the teaching approach of most benefit was the Guided Inquiry approach with strengths lying in all three instruments used for analysis of the teaching approaches encompassing clarity of the experiment, enjoyment, and the development of understanding for the chemistry concepts and techniques. The Problem Solving approach was found to be appropriate by a...
component of the cohort undertaking this experiment, while an equally large group found it difficult to engage with thereby in its current form not suitable for recommendation. The analysis of the Thermochemistry: Enthalpy of Neutralisation experiment (Calculation/Interpretation) quickly removed Expository as a potential teaching approach for this laboratory. The Guided Inquiry and Problem Solving teaching approaches both displayed potential to be highly beneficial with Problem Solving more preferred through the post-experimental survey than Guided Inquiry. Based on these findings, the Problem Solving approach was determined to be of most benefit.

The Determination of the Freezing-Point Depression Constant for Cyclohexane experiment (Interpretation/Calculation) indicated mixed results with both Expository and Problem Solving approaches being preferred by students based on the post-experimental survey. When considering the post-experiment quiz and the understanding of key concepts, the Expository approach seemed of most benefit and is therefore the recommended approach for this experiment.

6.3.1 Concluding Thoughts

To consider these findings within the broader context of the full laboratory course undertaken within KRA113, the trend observed within Chapter 5 for the Foundation Chemistry unit KRA001 has not been followed there. Each KRA113 experiment type seems much more tailored to particular teaching approaches, rather than following a gradual increase in the amount of student ownership for each experiment. One explanation for this may lie in demonstrations of the students undertaking the KRA113 unit. The majority of students undertaking this unit have...
recently completed a pre-tertiary level chemistry unit, and have therefore obtained some familiarity and experience in a chemistry laboratory. This would indicate that when undertaking the laboratory course in this unit, students would be more concerned with the specifics of each experiment rather than the fundamentals taken for granted by those with experience such as recognizing equipment and identifying their functions. Based on these results it would then be plausible to suggest the teaching approaches found to be most appropriate for these types of experiments would be transferrable to experiments utilizing similar skills, i.e. hands-on, calculations, interpretation, and observations.
Chapter 7 – Results: Second and Third Year Chemistry

Moving into post-first year chemistry studies, significant changes occur to both the nature of the units undertaken and the student cohort itself. The student cohort in first year consists mostly of those undertaking chemistry as a pre-requisite for study in other areas or as an elective. From an initial student cohort of approximately 250 students in first year, the second year cohort reduces to between 50 to 100 across several units, and is further reduced moving into third year. Given this reduction in class numbers, the units shift to accommodate this by providing greater one-on-one interaction between students and their lecturers and demonstrators. The chemistry laboratory experiments transition from fast-paced three-hour laboratories to multiple four-hour laboratory sessions each week with opportunities for lengthier experiments.

Two units were considered from the range of units offered within both second and third year chemistry: KRA223 Chemical Analysis, and KRA342 Catalysis and Reaction Processes, respectively. Of these two units three experiments from KRA223 and one experiment from KRA342 were selected for investigation. As was discussed within Chapter 3, the approach taken to collecting data on these experiments were aimed towards qualitative data.

7.1 KRA223 Chemical Analysis

7.1.1 Unit Objectives

One of the major differences between the first year chemistry units offered versus the units offered in second and third year is the narrowing of scope. KRA223 Chemical Analysis (University of Tasmania, 2015c) focuses upon the analysis of aqueous systems relevant to...
206 topics of current interest, including environmental, industrial, and forensic sciences to name a few. As part of this unit, training and practice in a large number of analytical techniques is undertaken whilst building upon fundamental skills taught in first year. Some of these analytical techniques include spectrophotometric methods (AAS, UV/visible, fluorimetry), chromatography (IC, LC, GC), and electrochemistry (potentiometry, ion selective electrodes) (University of Tasmania, 2015c). In addition to these specific techniques, a large focus is upon the collection and reporting of accurate results and the consequential statistical analysis.

7.1.2 Unit Operation

The laboratory course for this unit has been designed such that each experiment focuses upon a single or small number of analytical instruments and/or techniques. Given the limited number of instruments and equipment available, students are assigned an order to complete the available experiments. Despite this structure, a number of students will, at times, undertake the same experiment. One disadvantage of this rotational approach to the laboratory course is the disconnection between lecture materials and the corresponding experiments. On average a student undertaking this unit may be expected to complete one to two experiments without the information provided through lectures. Aside from specialised equipment however, most practical skills required of students have been introduced through the first year chemistry units, KRA113 and KRA114.

7.1.3 Laboratory Experiment Details

Determination of Copper and Arsenic in Treated Wood by Atomic Absorption Spectroscopy

This experiment focused upon three key techniques: performing an extraction of copper and arsenic from a sample through the use of concentrated nitric acid, the preparation of a series
of accurate standards, and the use of an atomic absorption spectrometer. This experiment is completed upon two duplicate samples to give insight into the precision attained in this experience.

EDTA Titration of Calcium and Magnesium in Natural Waters

For this experiment, students are required to practice their hands-on skills when preparing accurate samples. Coupled with this, titrations are used to first determine the combined concentration of both calcium and magnesium ions in the unknown sample and a following titration is used after precipitating magnesium hydroxide to selectively identify the concentration of calcium ions. Through calculation and interpretation a quantitative value is found for the presence of both calcium and magnesium ions found within tap and sea water samples.

Spectrophotometric Determination of Phosphate in Natural Waters

The spectrophotometric determination of phosphate in natural waters experiment requires students to carefully prepare a calibration series of phosphate samples before measuring the absorbance using a spectrophotometer. After construction of this calibration curve, both a control and waste-water sample are measured using the same technique to allow calculation of the concentration of phosphate present in the waste water sample.

7.1.4 Results

It was decided during the project design that the benefit of using an Expository-based teaching approach would not be suitable for higher years of study. Therefore only Guided Inquiry and Problem Solving versions of these experiments would be investigated. The Guided Inquiry
version of these experiments was implemented in Semester 2, 2014 as individual experiments within the laboratory course. Before the implementation of the Problem Solving versions in Semester 2, 2015, changes were made to the structure of the laboratory course. The outcome of these changes resulted in the EDTA Titration of Calcium and Magnesium in Natural Waters and Spectrophotometric Determination of Phosphate in Natural Waters experiments being combined into one mini-project. Similar to this, the Determination of Copper and Arsenic in Treated Wood by Atomic Absorption Spectroscopy experiment was paired with an experiment not considered in this study, Gravimetric Determination of Calcium. These two instances of implementation will be discussed in turn.

The 2014 Guided Inquiry approach was implemented and data was received from 10 students of the 35 total students undertaking that unit. A broad variety of feedback was received through the post-experimental survey provided to students. Despite the presence of two-tiered response questions, where a number value is selected in response to a question and a follow-up justification question is posed to elaborate on that choice, students seemed hesitant to provide more than a brief justification of their response. As the phosphate and EDTA experiments were quite close in methodology, a number of students were confused on the use of the survey and completed one for both experiments combined. When asked whether the learning experience was an engaging one, the responses received varied in detail with some students enjoying the more realistic application of techniques they had been taught. For example: 

"A real world application that was applicable to other people, not just chemists was good. It was also enjoyable because the experiment was not too complicated to understand."
Whereas other students quoted more superficial strengths of this experiment such as the presence of observable changes using indicators: “The indicators gave the practical a more ‘easy to relate to’ and understandable feel’ and, “Using equipment, as childish as it is when the indicators look really cool, I was engaged.”

When asked whether they felt the learning objectives had been obtained through completion of this experiment however, the focus of the responses shifted drastically. Several students indicated that the majority of understanding gained was attained through completion of the post-experimental report rather than the process; this outcome is at odds with the intended learning experience to be delivered by a Guided Inquiry laboratory: “Learning objectives were only achieved upon conclusion of report. A lot of hours were needed to complete, not very effective use of time.” and, “Report takes far too much time to complete, particularly researching expected values, and formula to explain reactions. People who are likely to be struggling probably will not able to complete objectives before they give up. ”

Shifting the questioning towards how students perceived their learning gains in terms of their practical in-laboratory skills, the responses all agreed with one another, quoting the practice of previously learnt skills, titrations and standards preparation, being an important aspect of these laboratories. When asked their thoughts on the workload expected, once more the length of time required to complete the post-laboratory report was the focus. Several students...
quoted perhaps unrealistic time frames expected for completion, though this emphasises the pressures students felt at completing this:

"The report part took far too long, at least 24 hours, possibly 36 hours of full on time was devoted to completion of report. Researching expected values takes up a significant amount of this time, finding results that are similar and comparable. This was very painful."

and, "I was able to complete the experiment which is unusual but it feels as if you always have to rush. That takes away a lot of enjoyment and results in terrible findings. The full report takes far too long and its completion affects all other subjects. It has taken at least 24 hours to write and research and caused some stress. Also, if [practicals] were quicker to complete, some important questions could be answered before leaving the laboratory. Reflection."

One response drew particular attention to the Guided Inquiry nature specifically with respect to introduction of questions and points of interest throughout the procedure:

"It was unclear that some questions had to be completed before the lab (as usually questions strewn throughout I include in my discussion). We didn't have time to finish even though I thought we were working well and there were too many questions to include in discussion if you addressed all of them throughout the method."

A positive outcome was observed when asking students whether they would feel comfortable in repeating this experiment. Nearly all students responded that they felt that this experience had built upon and refined their previous skills and would therefore be easy to repeat. A
number of these students still quote hesitation in repeating the report component of this laboratory session. To consider the responses holistically, the feedback from the student cohort indicated that the two main points of interest for them lie in the specific hands-on skills being used and the workload requirements of completing a report post-laboratory. Little to no mention was seen with regards to the teaching approach other than occasional remarks on the in-laboratory experience being a positive one.

The Determination of Copper and Arsenic in Treated Wood by Atomic Absorption Spectroscopy experiment differed from both the Phosphate and EDTA experiments in that it required the use of a completely unfamiliar piece of instrumentation. This difference was observed quite rapidly with students quoting the learning of and use of the AAS being a key feature in making this an engaging experience:

"The fire in the AAS and the different flames from particular cathode bulbs. Having the AAS explained made using it far more interesting."

and,

"The fact that we had to look up the background information in the prelab gave us the opportunity to gain a better understanding of the new equipment that we would be using."

Students further expanded on this indicating that the use of previously known skills coupled with a new technique enhanced their learning of chemistry concepts:

"Some of the skills (dilutions, pipettes, etc) I had already developed but this format did enable me to feel much more comfortable using the AAS and helped me feel like I had a greater understanding of its concepts."
Despite this engagement with the use of a new instrumentation, when asked whether they would feel confident in repeating this experiment, many students expressed concern with being able to operate the AAS by themselves. Given that this is a single instance of utilising the instrument though, it is to be expected that the confidence may not be built quite yet.

Mirroring the results discussed previously for the Phosphate and EDTA experiments, many of the interesting or enjoyable components of this experiment as defined by students revolved around observable changes. One note of concern from students was the lack of real world context for this experiment. Despite the use of treated wood as a sample for analysis, students felt that the results being obtained were not placed in a context they could engage with and struggled to see the point of this activity.

The implementation of the Problem Solving versions of these experiments in Semester 2 of 2015 did not go to plan unfortunately. Whilst the laboratory procedures and methods had been closely moderated by the authors of this paper and academics teaching into this unit, the resulting laboratories were found to be near impossible for the students of this cohort. Whether due to an exception of that particular cohort or the methods developed for this study, the experiment caused such confusion and stress that a decision was made by the unit coordinator of this unit to provide the methods previously used to allow students to complete the experiment. Due to this, little to no data was obtained on the Problem Solving implementation. Some of the concerns provided by students listed the information in the laboratory manual as too vague and they had not realised that a method should have been prepared prior to attending the laboratory. This resulted in the majority of students spending laboratory time constructing a method and researching rather than completing the experiment.

Given these stumbling blocks, the avenue for moving forward would be the reconsideration of the methods previously developed looking towards re-implementation in future years.
7.2 KRA342: Catalysis and Reaction Processes

7.2.1 Unit Objectives
The KRA342 unit offered in third year chemistry focuses upon the application of contemporary organometallic chemistry and advanced computational chemistry to the study of catalysis and reaction processes (University of Tasmania, 2015d). In addition to the theory covered within these topics, emphasis upon the design and implementation of high-level chemistry techniques and laboratory skills is placed through the laboratory course.

7.2.2 Unit Operation
This unit is offered only within Semester 2 each year and consists of 3 hours of face-to-face contact through lectures throughout the semester and a 4-hour laboratory session weekly for 10 weeks. A number of experiments are completed throughout this laboratory course, the order being allocated to ensure an even dispersion of equipment and instruments amongst students. The length of each experiment varies depending on the ability of the student and the processes required ranging from one session through to potentially three.

7.2.3 Laboratory Experiment Details
Palladium Cross Coupling Reactions
The Palladium Cross Coupling Reactions experiment is a pseudo group mini-project completed over two weeks. This experiment is designed to replicate the processes that may be undertaken in a research laboratory. As such, the first week is focused upon a series of micro-scale syntheses to investigate the effectiveness of a number of potential reagents for a particular reaction. An adapted gas chromatography method is utilised to monitor the progress of each of these reactions after a set time period. Each individual student tests
several of these reactions with different substrates before collating these findings and determining the substrate that gave the highest conversion. The second week of this experiment requires students to develop a scaled-up version of their chosen experiment with an emphasis on optimising the conditions to obtain a pure compound in high yield. In the preparation of the scaled-up reaction, students were required to design the conditions for the reaction and the techniques for the isolation of their product. An abbreviated laboratory report is required upon completion of the experiment with discussion being made on the chemistry concepts within this experiment in addition to methodology, references, and appendices.

7.2.4 Results

The Palladium Cross Coupling Reactions experiment underwent multiple changes throughout this study resulting in a lack of consistent data for the comparison of the teaching approaches considered at this level. The first form of this experiment was implemented in 2013 and a need for modification was quickly recognised in the form of guiding students in their approach to the experiment. After considerable revision of the experiment, a plan to validate the experiment was developed. The primary author of this thesis and an academic involved in the teaching of this unit attended the 2014 Advancing Science by Enhancing Learning in the Laboratory (ASELL) National Workshop held in Perth, Australia. Each experiment presented at the ASELL National Workshop was presented to a mixture of peers and students. Using the feedback obtained from this experience, the experiment was once more adjusted and released to the students in 2014 with the intention to collect data from this cohort of students. Due to the low number of students, less than 20, undertaking this unit and a lack of interest by students in completing the survey instruments, no data was obtainable to quantify the
outcomes of this experiment's effectiveness. Observations of this experiment from both the primary author and the demonstrators teaching in the laboratory indicated students responded positively to the more authentic research experience, particularly recognizing the multi-stage approach taken in obtaining a product. One problem identified anecdotally was that students were not comfortable designing the experiment without some guidance and did not refer back to previous laboratories, lecture materials, or literature. Whilst the laboratory manual did not explicitly cite previous experiences as a resource, it is expected of third-year students to have initiative and autonomy when approaching experiments. Moving forward from this, future implementations will be monitored to continue the development of this experiment.

7.3 Final Thoughts

The investigation into the 2nd and 3rd year levels of chemistry teaching laboratories was undertaken as an expansion upon the main body of research, the foundation and first-year level laboratories. The decision to remove Expository as one of the teaching approaches considered in this study enabled the two remaining teaching approaches, Guided Inquiry and Problem Solving, to be examined in greater detail. Due to a number of unforeseen circumstances, this was a facet of the project that did not proceed as planned and therefore the intended outcomes evolved over time. Three experiments from the 2nd year unit KRA223, Chemical Analysis, were studied over two years to investigate the strengths of both Guided Inquiry and Problem Solving. Whilst the Guided Inquiry implementation appeared to provide insight into what the students felt was a positive laboratory experience, the recognition of the specific teaching approach was minimal in comparison to the results observed at the foundation and first-year levels. The Problem Solving implementation suffered from...
considerable setbacks and issues and effectively resulted in no data being collected. The key to improving upon this form of investigation would be generating interest and engagement from the students to participate. One potential approach to this would be to integrate a reflection and feedback into the laboratory reports students produce. The inclusion of this reflection and feedback section would guarantee an increase in responses and could be tied explicitly to facets of the experiment that were successful or unsuccessful.

One experiment from the 3rd year unit KRA342, Catalysis and Reaction Processes, was developed to represent a Problem Solving activity. When staff and students alike noted the potential of this experiment, it was decided to focus upon the refinement of this experiment as an exemplar of an authentic research Problem Solving activity.

The takeaway message drawn from this component of the study is the considerable potential for these experiences when developing these laboratories at a higher level. Undertaking these modifications or developments however, should be a primary focus of a separate study as the complexity of implementing alternative teaching approaches increases dramatically moving through to later years of study.
Chapter 8 – Conclusions

The process of learning and developing knowledge has been explained using a number of models through the years (Perkinson, 1984) before reaching the current model of choice, Constructivism (Savery & Duffy, 2001). Constructivism was chosen to underpin this study due to its philosophy that students are central within a classroom and their interaction with their surroundings enables the development of new knowledge. When applied within the chemistry teaching laboratory, this aligns particularly well with the rich environment available for customisation. Reviews by Domin (1999) and Garnett and Garnett (1995) highlight how various concerns with both the chemistry teaching laboratory and the research being conducted into this area of teaching.

The study completed within this dissertation intended to address these concerns through a cross-sectional case study (Cohen et al., 2011; Freebody, 2003; Yin, 2006) of alternative teaching approaches in the chemistry teaching laboratory. At the beginning of this dissertation a number of research questions were posed that drove the direction and intended outcomes for this study. These questions were guided by the outcomes of a systematic review completed as part of this doctorate study upon the 15 years of chemistry teaching laboratory research since Domin’s seminal review (1999). These questions were:

1. What are the advantages and disadvantages of implementing alternative teaching approaches within the chemistry teaching laboratory?
2. Do teaching approaches align differently with the type of experiments being undertaken (where type refers to the nature of that experiment being, for example, observational or interpretation based)?
3. Will a combination of teaching approaches be more effective than a single teaching approach in the development of a chemistry laboratory course?
Through the use of a mixed-methods approach (Cohen et al. 2011), these questions have been answered across a number of chemistry units offered at the University of Tasmania. Each of these research questions were answered in part:

1. The advantages of implementing alternative teaching approaches lay within the identification of teaching approaches where students were not only more engaged, but also better understood the content. By recognising these alternative teaching approaches we gradually improve the teaching quality within the chemistry teaching laboratory. The disadvantages of implementing these approaches are largely the negative impact that is possible for teaching approaches that are not compatible with experiments.

2. It was found that the Foundation Chemistry unit KRA001, and the First Year chemistry unit KRA113 had different outcomes to this question. KRA001 aligned with a gradual increase of the level of inquiry. Whereas, KRA113 had a correlation across the laboratory course and instead aligned specific teaching approaches to experiment types.

3. Without a doubt a combination of teaching approaches was more successful based on the results obtained from this study. Further implementation is required to measure consistency across cohorts however.

At their essence however, these research questions aim to identify which of the three teaching approaches (Expository, Guided Inquiry, and Problem Solving) is most appropriate within the chemistry teaching laboratory for a variety of experiments. This project intended to obtain an outcome not only applicable at the local scale but also to have global implications for other teaching institutions. By investigating the type of experiment being undertaken (for example hands-on, observational, interpretation-based) it was intended that the teaching approach...
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Most suitable for these experiment types would be more applicable than looking at the chemistry topics. In finding the most appropriate teaching approach it was intended to optimise the laboratory experience for students undertaking these laboratories in a number of areas including: engagement with both the experiment and the chemistry content, enjoyment of the laboratory experience, development of laboratory specific skills and chemistry knowledge, and improving the perception of chemistry for students.

Four research aims were chosen at the start of this study:

1. The development of an 'optimised' laboratory course at the University of Tasmania;
2. The development of a rigorous methodology for the investigation and validation of laboratory teaching practices;
3. To explore the advantages and disadvantages of alternative teaching approaches in comparison to one another; and
4. To investigate the relationship between teaching approaches and the types of experiments undertaken.

These research aims have been addressed through completion of this doctorate study. The results obtained from each experiment provide a recommendation for an 'optimised' laboratory course (Research Aim 1). Perhaps of most importance on a global scale is the approach taken to undertaking this study. The flaws discussed and the successful outcomes achieved can both be used to inform future studies within the University of Tasmania and the wider Chemistry Education research community (Research Aim 2). Finally, Research Aims 3 and 4 have been achieved and discussed with regards to the research questions.
This study can be summarised into two main components: the first and higher focus component centred upon the foundation and first year chemistry level where larger cohorts of students were available. The second investigated the effect of these teaching approaches at higher years of study with a smaller number of experiments and limited pool of students. Given the difference in sample sizes the foundation and first year chemistry investigation was primarily quantitative in nature, whilst the higher years of study collected qualitative information. A variety of experiments were selected from a number of units offered within chemistry at the University of Tasmania to represent a range of experiment types. Each pre-existing experiment chosen was then broken down to its core concepts and rebuilt to represent each of the teaching approaches considered, a process previously used by Pullen et al. (2014). Over the course of four years these experiments were then implemented with the student cohorts of each year to collect data on their perceptions, abilities, and perceptions within a laboratory environment.

The outcomes obtained varied in the degree to which they met the intended outcomes initially hoped for at the outset of this study. In particular, the implementation at the foundation and first year chemistry unit level appeared to be well received by students with insight into which teaching approaches were of most benefit. Some differences existed between the foundation and first year units however. The four experiments selected from the foundation chemistry unit spanned the laboratory course, totaling six experiments. The results suggested that the particular type of experiment seemed to be unrelated to the type of teaching approach used. Rather, the students indicated a far stronger trend towards having a gradual increase in the amount of student input for each experiment over the course of the unit. This is consistent with the position of Hmelo-Silver, Duncan and Chinn who posit the use of scaffolding to support outcomes in inquiry and problem-based learning (2007). Within the study completed...
for this thesis it can be seen in the initial experiments being undertaken as structured Expository experiences and moving forward with the laboratory course gradually shifting through deepening levels of inquiry until the final experiment would be undertaken as a Problem Solving activity. This differed substantially from the first year laboratory experiments considered where no gradual trend was observed. The results obtained for each first year experiment suggested that a particular teaching approach was suited to that experiment type. For example, the Organic Functional Groups experiment being observation centric was best as a Guided Inquiry activity whereas the Determination of the Freezing-Point Depression Constant for Cyclohexane as an interpretation experiment was preferred as an Expository experience. To consider the difference between foundation and first year, the first and most apparent difference lies within the demographics of the students undertaking each unit. Foundation chemistry students being mostly composed of students with no experience in laboratories or returning after a number of years could need that gradual incline to allow development of confidence in both laboratory skills and procedures. First year students however, mostly consist of those with recent laboratory experience and therefore either have or believe they have those skills necessary to function in a laboratory.

The second and third year component of this study underwent considerable setbacks through the implementation of each experiment. Whilst the second year experiments appeared to be well received as Guided Inquiry activities, the Problem Solving versions of these experiments failed to engage the students and were eventually abandoned during their implementation. The third year experiment utilised a different methodology to that of the other experiments considered when investigating alternative teaching approaches. The Palladium Cross-Coupling Reactions experiment was not a pre-existing experiment and was therefore developed from scratch with the intention that multiple versions would be developed. Upon implementation...
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However, it was noted that the potential in this experiment was well worth refining and developing as a single instance rather than as a comparison. Through multiple iterations and the use of evaluation from an external body, an exemplar of an authentic research laboratory experiment was developed.

Looking into the future with the findings from this study in mind a number of thoughts come to mind. To expand beyond the scope of this study, several approaches could be undertaken:

- Using the proposed versions of each experiment, continued collection of data would give insight into the sustainability of these experiment models.
- The second year experiments would require expansion into a greater number of experiments and a far more complex development phase to better investigate the benefits of alternative teaching approaches. Further this, it would be imperative to increase the response rate from students to bolster the sample size analysed.
- With the success observed in the third year experiment, further development into this is warranted.

With the recommendations for each laboratory provided to those academics coordinating the chemistry units at the University of Tasmania, it is hoped that continued implementation of these optimised experiments occurs in future years at the University of Tasmania.


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General References


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open-inquiry version of the same experiment.


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