Science and Mathematics Education Centre

An Exploration of Process Oriented Guided Inquiry Learning in Undergraduate Chemistry Classes

Venkat Rao Vishnumolakala

This thesis is presented for the Degree of
Doctor of Philosophy

of

Curtin University

October 2013

Declaration

The thesis contains no material which has been accepted for the award of any degree or diploma in any university. To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made.

Signature:

Date: 14.10.2013

Abstract

The main purpose of this research study was to explore students' understanding of stereochemistry and their perceptions of learning chemistry in first year undergraduate chemistry classes following a modified Process-Oriented Guided Inquiry Learning (POGIL) that included group work. POGIL, a student centered instructional strategy, is a blend of content knowledge and process skills. The research utilised an existing model of curriculum evaluation to ascertain that the goals of the curriculum are met. The model examined curricula under four headings - the intended curriculum, the implemented curriculum, the perceived curriculum, and the achieved curriculum.

A quasi-experimental mixed method research design was used to provide responses to the research questions. The researcher developed a 5-item two-tier stereochemistry concept diagnostic test (SCDT) that was administered to two student cohorts, Group 1 and Group 2, as a post-test and a delayed post-test format to explore their understanding of stereochemistry concepts. Both groups used POGIL worksheets; Group 1 received POGIL-style instruction and Group 2 students were taught using traditional lectures. Analysis of students' responses, administered to 218 students from Group 1 and Group 2 cohorts, revealed about ten misunderstandings. The delayed post-test performance was significantly higher than the post-test performance for Group 1 students, suggesting the positive impact of POGIL style instruction in first year chemistry classes. The results of independent samples t-test between the mean achievements of Group 1 and Group 2 students indicated that the POGIL instruction was more effective with regard to students' understanding compared to the traditional instruction in organic chemistry topics.

The investigation gauged the students' perception of POGIL learning using quantitative and qualitative methods. The primary imperative was the validation of the Student Assessment of their Learning Gains (SALG) instrument. The adapted SALG instrument was administered to 114 students in 2011. The exploratory factor analyses (EFA) of the data suggest that the factor SALG instrument has strong construct, convergent and discriminant validity. The validated 44 item 5-point Likert scale SALG instrument was subsequently administered to 154 students in 2012 for confirmatory factor analysis (CFA). The CFA of the 44 item 5-point Likert scale SALG instrument using SPSS v20 resulted in a slight variation from the factor structure obtained in EFA. Next, the CFA based Structural Equation Modelling (SEM) analysis was used to test the four factor model derived from the EFA and the results obtained with AMOS v20 met the adequacy criteria of goodness-of-fit. The Cronbach alpha internal reliability of the items of SALG after CFA was highly satisfactory. The results of the fit indices of the causal model of SEM provided a reliable and valid instrument that illustrated students' perceptions of improved learning gains with POGIL method of instruction.

This study has made distinctive contributions to POGIL and undergraduate chemistry education, being the first attempt to investigate students' understanding of stereochemistry concepts in POGIL classes with a two-tier diagnostic test (SCDT) and establishing construct and convergent validity to the SALG instrument. The SCDT and the four factor SALG instrument could be valuable to science educators interested in measurement of students' conceptual understanding and perceptions of their learning.

Acknowledgements

My research journey through chemical education at the Science and Mathematics Education Centre has been a most humbling experience. I wish to express my sincere gratitude to my research supervisor, Professor David Treagust for accepting me into the POGIL research project. I will be forever indebted to him for all the exceptional guidance, prompt feedback and response. I also wish to thank my other supervisors, Associate Professor Mauro Mocerino and Senior Lecturer Dr. Daniel Southam for their intellectual contributions and directions that enriched my research work. The active involvement, guidance and support of the supervisors had helped me present my research findings at various international conferences.

I extend my sincere thanks to Professor Barry Fraser, Dr. Arulsingam Chandrasegaran, the staff at the Science and Mathematics Education Centre, especially Ms Petrina Beeton and Mrs Rosalie Wood, the Department of Chemistry, doctoral students and undergraduate chemistry students for their assistance and cooperation during my doctoral study. I also wish to thank Curtin University for the financial support in the form of Australian Postgraduate Award.

This work is dedicated to my parents, my wife Bharathi Vishnumolakala, and my son Sravan for their love and unconditional support.

Table of Contents

Abstract iii

Acknowledgements v

Chapter 1 1

Introduction 1

1.1 Introduction 1

1.2 Background 1

1.3 Objective 3

1.4 Significance 3

1.5 Definitions and Terminology 4

1.5.1 General Definitions 4

1.5.2 Chemistry Terminology 5

1.6 The Organisation of the Thesis 6

Chapter 2 8

Review of the Literature 8

2.1 Introduction 8

2.2 Curriculum Framework 8

2.3 POGIL 11

2.3.1 Theoretical Framework 11

2.3.2 Constructivism 12

2.3.3 Learning Cycle 15

2.3.4 Characteristics of POGIL materials 16

2.3.5 Process Skills 20

2.4 Student Conceptions 22

2.4.1 Origin of Alternative Conceptions 22

2.4.2 Studies on Students' Alternative Conceptions in Chemistry 25

2.4.3 Organic Chemistry 25

2.5 Methodologies for Investigating Conceptions 27

2.5.1 Interviews 28

2.5.2 Two-Tier Multiple Choice Tests 29

2.6 Implementation of POGIL 31

2.7 Effectiveness of POGIL 32

2.8 Students' Perceptions 35

2.9 POGIL in Australia 36

2.10 Summary 37

Chapter 3 39
Methodology 39
3.1 Introduction 39
3.2 Research Paradigm 39
3.3 Research Design 39
3.4 Research Questions 42
3.5 Participants 42
3.6 Instructors 43
3.7 Ethical Procedures 43
3.8 Data Collection and Analysis Procedures to respond to each Research Question 43
3.9 Data Collection and Analysis Procedures to respond to Research Question 1 44
3.10 Data Collection and Analysis Procedures to respond the Research Question 2 45
3.11 Data Collection and Analysis Procedures to respond to Research Question 3 .. 45
3.11.1 Stereochemistry Concept Diagnostic Test (SCDT) 46
3.12 Data Collection and Analysis Procedures to respond to Research Question 4 .. 52
3.12.1 Student Assessment of Their Learning Gains (SALG) 52
3.13 Qualitative Data Analysis 54
3.14 Methods used for Data reliability and validity 55
3.14.1 Triangulation 55
3.14.2 Reliability of the instruments 56
3.14.3 Validity of the Instruments 56
3.15 Summary 58
Chapter 4 59
The Intended and Implemented Curricula 59
4.1 Introduction 59
4.2 The Intended Curriculum 60
4.2.1 Course Units 60
4.2.2 Learning Outcomes 62
4.3 Graduate Attributes 64
4.4 POGIL Process skills 65
4.5 The Implemented Curriculum 70
4.6 Activity Materials 71
4.7 Researcher’s Observations 71
4.8 Process Skills 74
4.9 Summary 77

Chapter 5 78
The Achieved Curriculum 78
5.1 Introduction 78
5.2. Statistical Analysis of Student Responses to the Stereochemistry Concept Diagnostic Test (SCDT) 79
5.3. Group 1: Chem102, Semester 2, 2011 79
5.3.1 Stereocentres *(Item 1)* 80
5.3.2 Enantiomers *(Item 2)* 81
5.3.3 Chirality *(Item 3)* 83
5.3.4 Stereoisomers *(Item 4)* 85
5.3.5 Molecular Visualisation *(Item 5)* 87
5.4 Group 1 (Chem102) Students' Overall Performance in the SCDT 89
5.5 Group 2: Chem121, Semester 1, 2012 92
5.5.1 Stereocentres *(Item 1)* 92
5.5.2 Enantiomers *(Item 2)* 93
5.5.3 Chirality *(Item 3)* 94
5.5.4 Stereoisomers *(Item 4)* 94
5.5.5 Molecular Visualisation *(Item 5)* 95
5.6 Group 2 (Chem121) Students' Overall Performance in the SCDT 96
5.7 Stereochemistry Learning Gains: Group 1 and Group 2 97
5.8 Summary 100
Chapter 6 104
The Perceived Curriculum 104
6.1 Introduction 104
6.2 Perceived Curriculum 104
6.3 Students' Assessment of Their Learning Gains (SALG) 105
6.3.1 Stages 1 and 2 105
6.3.2 Stages 3 and 4 106
6.4 Exploratory Factor Analysis (EFA) of SALG Instrument 108
6.5 Confirmatory Factor Analysis 112
6.6 The Hypothesised Model 115
6.7 Qualitative Data Analysis 123
6.7.1 The Profile of the Interviewees 124
6.7.2 Approach to the Interview Analysis 124
6.7.3 Students' Perception of their Learning Gains in POGIL Classes 125
6.8 Summary 137

Chapter 7 ... 139
Discussion and Conclusions ... 139
7.1 Introduction ... 139
7.2 Summary of the Thesis ... 139
7.3 Major Findings ... 141
7.3.1 Research Question 1 ... 141
7.3.2 Research Question 2 ... 141
7.3.3 Research Question 3 ... 142
7.3.4 Research Question 4 ... 144
7.4 Limitations of the Study ... 146
7.4.1 The Sample ... 147
7.4.2 Instruments, Data Analysis and Interpretation ... 147
7.5 Recommendations Relating to this Study ... 147
7.5.1 Improving the Validity of the Instruments ... 147
7.5.2 Further Research on Diagnostic Tests Suitable to POGIL ... 148
7.5.3 Future Research on Trans-national Study of POGIL Implementation ... 148
7.5.4 Future Research on Australian POGIL Implementations ... 148
7.6 Summary ... 148
References ... 150
Appendices ... 177
Appendix A ... 177
Appendix B ... 179
Appendix C ... 184
Appendix D ... 188
Appendix E ... 192
Appendix F ... 206
Appendix G ... 208
Appendix H ... 221
Appendix I ... 229
Appendix J ... 232
Appendix K ... 236

List of Tables

Table 3. 1: Relationship between research questions and data collection tools: RQ1 and RQ2 44
Table 3. 2: Relationship between research questions and data collection tools: RQ3 and RQ4 44
Table 3. 3: Summary of the final sample of first year chemistry cohort 46
Table 3. 4: Propositional content knowledge statements 49
Table 3. 5: Specification grid of propositional content knowledge statement 50

Table 4. 1: List of topics covered in Chemistry units 101 and 102 61
Table 4. 2: Extract from the programme calendar for chemistry 101 and 102 62
Table 4. 3: Learning outcomes and targeted graduate attributes – extracts from course units Chemistry 101 & 102 63
Table 4. 4: POGIL process skills 66
Table 4. 5: Alignment of graduate attributes and POGIL process skills as evidenced from POGIL class observations 68

Table 5. 1: Percentage of Group 1 (Chem102, Sem 2, 2011) student response pattern to Item 1 80
Table 5. 2: Percentage of Group 1 (Chem102, Sem 2, 2011) student response pattern to Item 2 82
Table 5. 3: Percentage of Group 1 (Chem102, Sem 2, 2011) student response pattern to Item 3 85
Table 5. 4: Percentage of Group 1 (Chem102, Sem 2, 2011) student response pattern to Item 4 86
Table 5. 5: Percentage of Group 1 (Chem102, Sem 2, 2011) student response pattern to Item 5 88
Table 5. 6: Percentage of students (Chem102, Semester 2, 2011) who correctly answered the first part and both parts of the items in the diagnostic test (Post-Test and Delayed Post-Test) 90
Table 5. 7: Comparison of students' misunderstanding of stereochemistry concepts at the end of post-test of SCDT 91
Table 5. 8: Percentage of Group 2 (Chem121, Sem 1, 2012) student response pattern to Item 1 93
Table 5. 9: Percentage of Group 2 (Chem121, Sem 1, 2012) student response pattern to Item 2 93
Table 5. 10: Percentage of Group 2 (Chem121, Sem 1, 2012) student response pattern to Item 3 94
Table 5. 11: Percentage of Group 2 (Chem121, Sem 1, 2012) student response pattern to Item 4 95

Table 5. 12: Percentage of Group 2 (Chem121, Sem 1, 2012) student response pattern to Item 5 96
Table 5. 13: Percentage of students (Chem121, Semester 1, 2012) who correctly answered the first part and both parts of the items in the diagnostic test (Post-Test and Delayed Post-Test) 96
Table 5. 14: Descriptive statistics for students' achievement in SCDT........99

Table 6. 1: Factor loading, eigenvalue and percentage of variance for SALG (Chem102, 2011) (n = 114)........109
Table 6. 2: Scale development of SALG 110
Table 6. 3: Internal consistency reliability (Cronbach's alpha) for the SALG scales 111
Table 6. 4: Inter construct correlations and square roots of average variance extracted for the SALG scales 111
Table 6. 5: Factor loading after CFA for SALG – Chem102, 2012........113
Table 6. 6: Factor loadings of four-factor SEM and Squared Multiple Correlations (SMC)........118
Table 6. 7: Internal consistency reliability of SALG scales after CFA 119
Table 6. 8: Standardized regression weights........119
Table 6. 9: Squared multiple correlations 121
Table 6. 10: Student assessment of their learning gains (SALG) mean scores Chem102, 2012 122
Table 6. 11: Pearson correlation coefficient values of four factors of the SALG instrument........123
Table 6. 12: Demographics profile of the interviewees (N= 10) 124
Table 6. 13: The six categories that emerged out of the coding of student qualitative data 125

List of Figures

Figure: 2. 1. Curriculum Evaluation Model 9
Figure: 2. 2. POGIL facilitation plan 14
Figure: 2. 3. Learning cycle approach 15
Figure: 2. 4. An illustration of how a POGIL session is organised 19
Figure: 2. 5. A model for summarising the main components of working memory (proposed by Baddeley and Hitch (1974)) 23
Figure: 2. 6. Johnston's Information Processing Model 24

Figure: 3. 1. An outline of the research design 41
Figure: 3. 2. Items 4 & 5 from the Stereochemistry Concept Diagnostic Test (SCDT) 48
Figure: 3. 3. Item 1 from Student Assessment of Their Learning Gains questionnaire 53
Figure: 3. 4. Framework for construct validity (Trochim & Donnelly, 2006) 57

Figure: 4. 1. Curtin graduate attributes 65
Figure: 4. 2. Students' responses to a clicker question 72

Figure: 5. 1. The percentages of Chem102 students who provided the correct response to both tiers of the 5 items in the Stereochemistry concept diagnostic test. 90
Figure: 5. 2. The percentages of Chem121 students who provided the correct response to both tiers of the 5 items in the Stereochemistry concept diagnostic test. 97

Figure: 6. 1. An outline showing the administration and data analysis of SALG.... 107
Figure: 6. 2. The measurement and structural models of SEM: with three latent factors. 114
Figure: 6. 3. Confirmatory factor model obtained with SALG data from Chem102, Semester 2, 2012 117
Figure: 6. 4. Structural model showing relationship between the latent constructs. 120

Chapter 1
Introduction

1.1 Introduction

Section 1.2 provides some background to the genesis of the research and the nature and scope of the study. Section 1.3 outlines the key research questions upon which the research has focused. Section 1.4 includes insights on the significance of the research study. At the end of the chapter, Section 1.5 lists key terms used in this thesis and their definitions; in Section 1.6 the general outline of the organisation of the thesis is given.

1.2 Background

Pedagogical approaches in chemistry at the tertiary level are changing from a knowledge-transmitting teacher-focused lecture method to concept-developing student-centered active learning (Anderson, 2002; Bedgood Jr., 2008; Bowen, 1994; Day & Houk, 1970; Trigwell & Prosser, 1996). The trend is not an exception in Australian universities as evidenced from the literature (Cawley, 2008; Hager, Sleet, Logan, & Hooper, 2003; Lawrie, 2010; O'Toole, 2010; Watters & Watters, 2007; Zeegers & Martin, 2001). Contemporary research into cognitive understanding of post-secondary students is providing exciting challenges for teachers to improve chemical education.

First year tertiary science educators in Australian universities, through grant funding groups from the Committee for University Teaching and Staff Development (CUSD), Australian Universities Teaching Committee (AUTC) and the Australian Learning and Teaching Council (ALTC) have been practicing various innovative teaching approaches both in the classroom and in the laboratory. These innovative approaches are designed to accommodate class size, diversity, students' incoming skills, knowledge bases, and expectations (Rice et al., 2009).

Indeed, studies reveal that traditional didactic methods are no longer meeting students' educational needs. Typically, the first year cohort of science students taking chemistry as one of the science courses, vary widely in students' background, interest and ability levels. The abstract nature of chemistry topics may create difficulties for students to appy knowledge to solve text-book, examination and real-world problems (Frost, 2010). According to Apple (2004), students in the lecture setting gain little experience in teamwork and associated skills needed for the workplace. All these considerations may have led to chemistry education reform initiatives that include changing the curriculum and course content, including digital technology-assisted instruction, and incorporating student-focused active learning.

A general notion of university chemistry educators is that active student engagement and social interaction are now recognised as being essential for most students to gain a scientific understanding and long-term retention. Marshall (2010) argues for an established need for introductory chemistry courses to offer interactive learning environments for all types of students in order to advance their scientific reasoning and problem solving skills. Many such research-based instructional strategies which involve small groups of students (Anderson, 2002; Felder, 1996; Kovac, 1999) have been proposed and implemented in first year science courses (Basu-Dutt, Slappey, & Bartley, 2010; Ruiz-Primo, 2011).

These research-based teaching practices are often termed reciprocally as *cooperative learning, collaborative learning, small-group learning,* and *team-based learning* by university academics but pedagogical researchers find distinctions among these terms (Cooper, 2005). However, when these innovative instructional strategies were used optimally, the educational experience of students in terms of satisfaction and retention was shown to have improved significantly (Francisco, 1998; Gosser, Kampmeier, & Varma-Nelson, 2010; Lewis, 2006; Lyon & Lagowski, 2008).

Process Oriented Guided Inquiry Learning (POGIL Project) is one such student-centered instructional approach where students work in small groups with the instructor acting as a facilitator. In a POGIL classroom, students work in learning teams using specially designed activities that promote mastery of the discipline content and the development of skills necessary for scientific inquiry.

The POGIL method of instruction effectively combines processing skills and the small-group learning environment and POGIL-influenced instruction has shown substantial improvement in student attitudes, retention and performance in general chemistry classes (Farrell, Moog, & Spencer, 1999; Hanson & Wolfskill, 2000).

1.3 Objective

The purpose of this research was to study the effectiveness of POGIL instruction in undergraduate chemistry classes. The research objectives for this study were generated from the literature regarding small group active learning like POGIL in chemistry classes.

1. Identify the skills needed for the development and practice of skills in POGIL classrooms.
2. Investigate how the POGIL was implemented in classrooms.
3. Investigate students' conceptual understanding in POGIL classrooms.
4. Investigate students' perception of their learning in POGIL classrooms.

The following research questions were addressed.

1. How do the skills that students learn in POGIL classroom align with university graduate attributes?
2. How are these learning requirements implemented through POGIL-based curriculum?
3. How effectively do students achieve the intended learning outcomes using a POGIL approach?
4. In what ways do students perceive their learning while engaged in POGIL classes?

1.4 Significance

The use of guided inquiry and cooperative learning has been very limited at university level. However, the POGIL method has shown to be effective in chemistry major courses at several institutions in the United States. More recently, in Australia, Active Learning in University Science (ALIUS), a collaborative project of six Australian universities, uses POGIL as a model of teaching innovation to engage students in large first year chemistry classes. In a recent report submitted to ALTC (Australian Learning and Teaching Council), Bedgood Jr et al. (2012) highlighted the successful journey of POGIL implementation and discussed significant challenges faced by Australian chemistry educators while adopting active learning strategies at ALIUS member institutions. Bedgood et al. state that student performance is maintained or improved by changing to an active learning strategy.

The study reported in this thesis measures the effectiveness of POGIL as a pedagogy to reduce students' non-scientific conceptions involved in stereochemistry. In this study, the use of POGIL allowed students to discover for themselves the principal features of chirality in organic molecules. Engagement of students' conceptions and their misconceptions is important during instruction for the achievement of deeper and a scientifically correct understanding (Ozmen & Ayas, 2003; Sreenivasulu & Subramaniam, 2012; Tan, Taber, Goh, & Chia, 2005; Treagust, 1988). The results of an exploratory research study of organic chemistry educators (Duis, 2011) on students' understanding of organic chemistry concepts recommended the need to design new assessments to elicit students' explanations of their different conceptions in organic chemistry.

This research is significant in several ways. Firstly, the study is designed to show that a change of existing teaching practice is possible and that improved learning outcomes may be achieved. Secondly, the study is designed to gain an understanding of Australian students' perceptions of the philosophy behind POGIL. Thirdly, the research findings may help Australian educators to extend POGIL methodology to other learning areas of Science and Engineering, besides Chemistry. Furthermore, the research outcome may help innovative secondary school science teachers explore the possibilities of implementing POGIL methods in senior secondary science subjects.

1.5 Definitions and Terminology

Several terms have been used in this thesis to convey specific meanings and to avoid any misunderstandings.

1.5.1 General Definitions

Collaborative learning – a small group of students working together towards a common goal using well-structured learning materials that help guide the group toward a particular learning outcome (Shibley & Zimmaro, 2002).

Constructivism – a philosophy of learning in which knowledge is built up from within by a thinking person (Staver, 1998).

Cooperative learning – small-group based student interaction to support each group member to improve their learning (Joliffe, 2007).

Learning cycle – a theory that states that students' learning occurs in three stages: exploration, concept invention, and application (REF, Karplus and Thier?).

Metacognition – being aware of one's conscious and deliberate thoughts.

Misconceptions – the ideas that provide incorrect understanding of ideas, objects, or events that, typically, are constructed based on a person's experience (Ameyaw & Sarpong, 2011).

Pencast – a digitalised interactive, portable document containing student's and/or teacher's notes and their captured audio (Murray, 2012).

Process Oriented Guided Inquiry Learning: POGIL – a student centered teaching philosophy in which students as self-managed small groups are engaged in a learning cycle of focused guided inquiry activities that are intended to develop content mastery and process skills (Moog & Spencer, 2008).

Process skills – a set of skills that POGIL students are expected to gain in order to promote their maturity in communication, written expression and problem solving (Hein, 2012).

1.5.2 Chemistry Terminology

A chemistry book authored by Blackman, Bottle, Schmid, Mocerino and Wille (2008) was consulted for the following chemistry related terminology.

Achiral molecules – molecules that are superimposable on their mirror images.

Chiral molecules – molecules that can form non-superimposable mirror images.

Conformations – the different positions into which a molecule can twist.

Configuration – a matter of right handedness and or left handedness.

Diastereomers – stereoisomers that are not mirror images of each other.

Enantiomers – a pair of stereoisomers that are mirror images of each other.

Isomers – compounds with the same formula and different structures.

Organic chemistry – the chemistry of carbon-containing compounds

Stereoisomers – isomers in which the atoms are connected in the same way, but differ in how the atoms are arranged in space

Stereocenter or stereogenic atom – A stereocenter is an atom for which the interchange of two groups converts one stereoisomer into another

1.6 The Organisation of the Thesis

The thesis is organised into various chapters based on the research objectives. After the first chapter, the thesis consists of a further 6 chapters:

Chapter 2, Literature Review, describes studies pertaining to the POGIL approach; the curriculum evaluation framework adopted for the research study, students' conceptions of the particulate nature of matter and organic chemistry, and an evaluation of POGIL implementations.

Chapter 3, Research Methodology, describes the research methods used in the study, which begins with a general description of research design and includes data collection, data analysis, and details of instruments with their validity and reliability.

Chapters 4, 5, and 6 contain the results of the research. Chapter 4, Intended and Implemented Curriculum, addresses the first and second objectives of the research concerning the skills needed for first year undergraduate chemistry students for successful learning in POGIL class. Relevant information relating to the intended and implemented curriculum of the first year chemistry courses, Chem101 and Chem102 is presented. The second research objective addressed was, how the learning requirements were implemented as part of the curriculum. The researchers' observations of the POGIL interactions were included in this chapter.

Chapters 5 and 6 address the third and fourth objectives of exploring the students' conceptual understanding and their perceptions of learning in a POGIL class.

Chapter 5, Achieved Curriculum, the results of the data analysis pertaining to students' understanding of stereochemistry concepts are presented.

Chapter 6, Perceived Curriculum, addresses exploratory and confirmatory studies relating to the validation of SALG questionnaire. The results of students' general perception of their learning gains were also reported.

Chapter 7, Discussions, Conclusion, and Implications for Future Research, the final chapter, summarises and compiles the findings of the research. The implications of the results and limitations of the research are discussed along with suggestions for future research.

Chapter 2
Review of the Literature

2.1 Introduction

This review focuses on literature relevant to this study of an intervention that used Process Oriented Guided Inquiry Learning, POGIL, as a way to improve students' understanding of chemistry in first year undergraduate classes.

Section 2.2 reviews literature related to the curriculum evaluation framework adopted for the study. Further to an introduction to POGIL, Section 2.3 reviews the theoretical framework, research on the use of POGIL for the development of students' process skills, logical thinking, characteristics of POGIL materials and the use of technology in POGIL classes.

Section 2.4 reviews literature relating to research on student conceptions, their origin and several studies related to students' alternative concepts in chemistry, especially, organic chemistry. Section 2.5 features the literature related to methods used in investigating students' conceptions and their implications for teaching and learning. Literature pertaining to the implementation and effectiveness of POGIL is reviewed in Sections 2.6 and 2.7. Section 2.8 highlights the research related to students' perceptions of POGIL implementation in undergraduate classes and identifies the need for a reliable instrument to gauge students' perception of their learning in POGIL classes. Finally, Section 2.9 reviews literature related to POGIL implementation in Australia.

2.2 Curriculum Framework

The ideas of education in practice are expressed as curriculum, defined concisely by Taba (1962, p. 529) as a "plan for learning" and elaborated further by Walker (1990, p. 133) as "the content and purpose of an educational programme together with their organisation". The framework, as shown in Figure 2.1, for the evaluation of the POGIL course used in this research, was developed by Keeves (1995), originating from the studies of the International Association of Evaluation of Educational Achievement (IEA) and modified or developed further by Van den Akker (1988) and Treagust (1993).

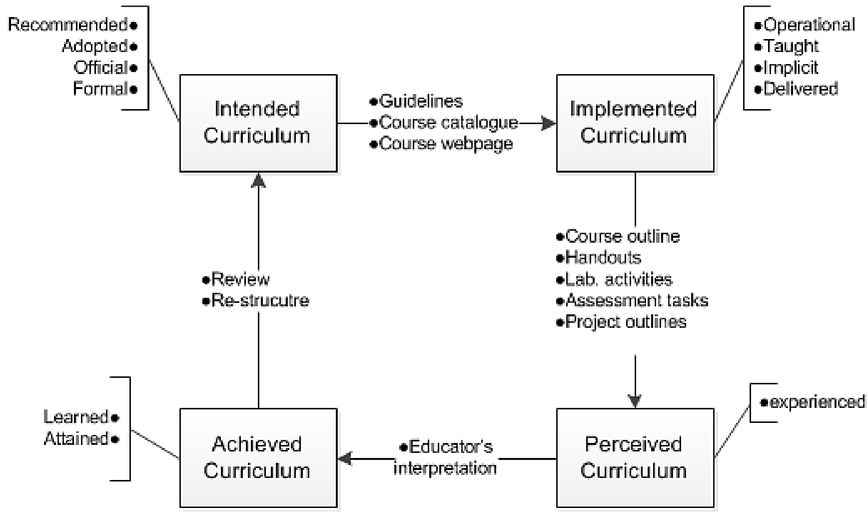


Figure: 2. 1. Curriculum Evaluation Model

Summarising information on the science curricula of 23 countries, Rosier and Keeves (1991) suggested that the science curriculum could be viewed in terms of:

> *"three sequential stages, which related to three groups of agents involved in science education, namely the curriculum planners, the classroom teachers and the students. The stages are (1) the intended curriculum, (2) the implemented curriculum, (3) the achieved curriculum"*.

The implemented curriculum is dependent on the intended curriculum and the achieved curriculum depends on the curriculum implemented in the classroom. Treagust (1986b) added an additional stage to the framework, that is the perceived curriculum. These four aspects were used as a lens though which this study viewed the implementation of POGIL in first year chemistry classes. Subsequently, the effectiveness of the POGIL was evaluated in terms:

(i) the *intended curriculum* - the way chemistry during first and second semesters of a year-long course is to be presented based on the course outline and instructional materials;

(ii) the *implemented curriculum* - the manner in which POGIL is blended into first year chemistry instruction;

(iii) the *perceived curriculum* - the actual learning experiences as perceived by the students

(iv) the *achieved curriculum* - the resulting learning outcomes of the students.

The intended curriculum, which may also be labelled as recommended, adopted, formal, explicit or the ideal curriculum (Cuban, 1993), consists of the aims objectives, syllabus, course materials, and textbook content and indicates the learning programme to be achieved through teaching science or chemistry (Menis, 1994). According to Van den Akker (1988), the intended curriculum comprises the fundamental philosophy or the vision of the curriculum and written curriculum documents or materials that outline these intentions. Course outlines, practical activities, handouts, assessment tasks, and in-class worksheets reflect the teachers' interpretation of the intended curriculum. The intended curriculum, according to (Treagust, 1986b), is described in terms of the syllabus, the textbooks, 'teaching foci', and the nature of course-work as illustrated by the teaching academics.

The implemented curriculum, also termed the taught, implicit, operational or delivered curriculum (Cuban, 1993), represents the opportunity that is offered formally or informally to students to learn and is more visible than the intended curriculum. Eggen, Pelgrum and Plomp (1987) described the implemented curriculum as the teaching-learning process within the classroom in terms of the methods used and the applied teaching approaches. According to Treagust (1986b), the implemented curriculum can be examined by the qualitative and quantitative data related to the teacher's class organisation, class management, the teacher's handling of students of different ability levels, student motivation and the nature of academic work.

The perceived curriculum, according to Treagust (1986b), is the curriculum actually experienced by the students. Van den Akker (1998, pp. 421-447) referred to the students' perspective of their learning experiences as the experiential curriculum which consists of "those things that a student chooses to emphasise, elaborate on, ignore, or omit as he or she recounts learning from a science class or a field trip – learners personal meanings".

The achieved curriculum also referred to as the learned or attained curriculum (Cuban, 1993; Van den Akker, 1988; 1998, pp. 421-447), portrays learning outcomes achieved by the students as recorded in their results of assessment.

2.3 POGIL

POGIL is a student-centered instructional strategy that provides opportunities simultaneously to teach both content and key process skills. The genesis of POGIL is deeply rooted in Spencer's (1999) student-focused active learning (SFAL) that offered students opportunities to become involved in their learning though social interaction. In his article, Spencer commended the need to change the conventional roles of teachers and students for the successful implementation of SFAL in the chemistry classroom and laboratory. According to Spencer, students become active learners when they reach their own conclusions rather than just verifying the information or concept. Similarly, POGIL aims to develop learning and process skills while guiding the students to a conceptual understanding.

According to the Moog, Creegan, Hanson, Spencer, Straumanis, and Bunce (2009), the structure of POGIL is based on philosophical foundations of teaching that provide a pedagogical basis for structuring the learning environment. Identifying POGIL as a succinct model of effective learning, Moog et al. state that:

> *(POGIL Project) learning is an interactive process of thinking carefully, discussing ideas, refining understanding, practicing skills, reflecting on progress, and assessing performance. (p. 90)*

In a POGIL paradigm, instructors facilitate learning rather than serve as a source of information while students work in small self-managed groups on activities to explore concepts by examining the data or information (Spencer & Moog, 2008). Furthermore, Moog et al. (2009) highlight the incorporation of five key ideas into research-based pedagogies like POGIL: adoption of a *constructivist* model for learning; use of the *learning cycle* as a paradigm for the construction and design of classroom and laboratory activities; in-class activity sheets containing models and representations that help students *make connections* and *visualise the material*; incorporation of peer to peer teaching through *cooperative learning* groups; and teaching *metacognitive* skills in an explicit manner.

2.3.1 Theoretical Framework

The research-based chemical education approaches have utilised and/or modified learning theories in order to develop curriculum materials and instructional strategies. According to Abraham (2008), the theoretical framework helps the researcher identify the appropriate research procedures to assess the developed curriculum materials and instructional strategies. The following is a review of the theory-base to which the POGIL approach and the characteristics of POGIL activity materials were deeply related.

2.3.2 Constructivism

The theory of constructivism emphasises knowledge construction rather than knowledge transmission. Knowledge is personal and is constructed in the minds of the learners when they actively analyse information or data. It is not acquired through direct transmission from the instructor or a resource (Bodner, 1986; Sewell, 2002). Students' constructive learning of new information widely depends on their misconceptions, beliefs, likes and dislikes (Karplus & Butts, 1977) and their prior knowledge influences what new or modified knowledge they will construct as a result of their learning experience in the classroom (Sewell, 2002). Explaining students' knowledge construction in chemistry courses, Cracolice (2005) stated that the constructivist model of science learning serves as a pragmatic theoretical base for designing an effective curriculum that allows students to learn concepts effectively. Cracolice infers that the constructivist theory of knowledge development is the most applicable in the chemistry classroom.

Providing a more focussed theoretical framework, Cole, Becker, Towns, Sweeney, Wawro, and Rasmussen (2012) identify theoretical foundations for small group active learning pedagogy like POGIL as emerging from Vygotsky's social constructivism which views the origin of knowledge construction as being the social interaction of people, interactions that involve sharing, comparing and debating among learners. Vygotsky's (1978) sociocultural theory of learning accentuates the supportive guidance of peers, mentors for the development of higher order functions, and independent competence. Accordingly, Wertsch (1985) viewed 'teaching by engaging' as a way of transforming social interaction into individual tools of thinking and problem solving. The interactive social milieu of learning is central to the POGIL classroom, where learners identify the concept and refine its meaning by critically exploring the information.

In a POGIL class, students work in groups of three or four with a flexible membership. The assignment of group membership varies with the size of the class (Straumanis, 2010). In a smaller class, the instructor may assign the group membership based on the skills and personality, whereas in large classes, the instructor may assign in a random manner. The instructors allow students to switch groups at the start of the semester and this switching becomes less frequent as the semester progresses. Students are assigned roles which can often be changed. Typical POGIL roles (Bailey, Minderhout, & Loertscher, 2012; Libby, 2008; Vacek, 2011) are: Manager, Recorder, Presenter or Spokesperson and Reflector or Strategy Analyst. Additional roles such as Technician, Encourager and Significant Figure Checker are made available depending on the nature of the POGIL activity.

- The *manager* ensures that members are fulfilling their roles while participating in the activities and understanding the concepts.
- The *recorder* maintains a log of important concepts that the group has learnt and records important aspects of group discussions, observations, insights, etc.
- The *presenter* concisely reports the group discussion to the whole class within the set time limit.
- The *reflector* or *strategy analyst* observes and comments on group dynamics and behaviour with respect to the learning process.
- The *technician* performs all technical operations for the group, sourcing information, and using resources like a computer or calculator.
- The *encourager* acknowledges good ideas and insights of group members.
- The *significant figure checker* ensures an orderly role out of events/ideas.

Formal roles are considered essential to generate equal participation among group members in terms of achieving the content and process goals (Straumanis, 2010). In other words, without participation or contribution, a student may not have an opportunity to develop content knowledge or process skills. Structured roles in collaborative learning groups foster connections between students (Caulfield & Persell, 2006) and develop teamwork skills that add value at the workplace (Dickinson, 2000). Interpersonal dynamics in a POGIL classroom are important to positively shape student learning. When a POGIL class has student groups with unassigned roles, the instructor may direct the question to a less active student or invite a group of students to present their information to the whole class (Cole et al., 2012). In an ideal POGIL setting, the instructor advises the students to rotate their roles.

In a POGIL class, the role of a teacher is like a facilitator rather than an information transmitter, guiding students to develop their process skills and conceptual understanding. Here, the role of a facilitator is to encourage full participation, promote mutual understanding, and cultivate shared responsibility (Doyle, 2011). Effective facilitation involves an expert teacher utilising his or her expertise to enable learners to gain a deeper self-understanding of concepts or content. However, facilitation is more than a set of technical skills that are applied to promote discussion in a student-centered learning environment (Regmi, 2012). Minderhout and Loertscher (2008) outlined a profile for a quality POGIL facilitator that included a set of skills ranging from preparation to the closure of POGIL-style interaction. Skills of listening and rephrasing, asking critical questions and recognising emotions are considered extremely useful in learner-centered classrooms. Minderhout and Loertscher modelled a facilitation plan, as shown in Figure 2.2 that aimed to guide successful teaching performance before, during and after active learning.

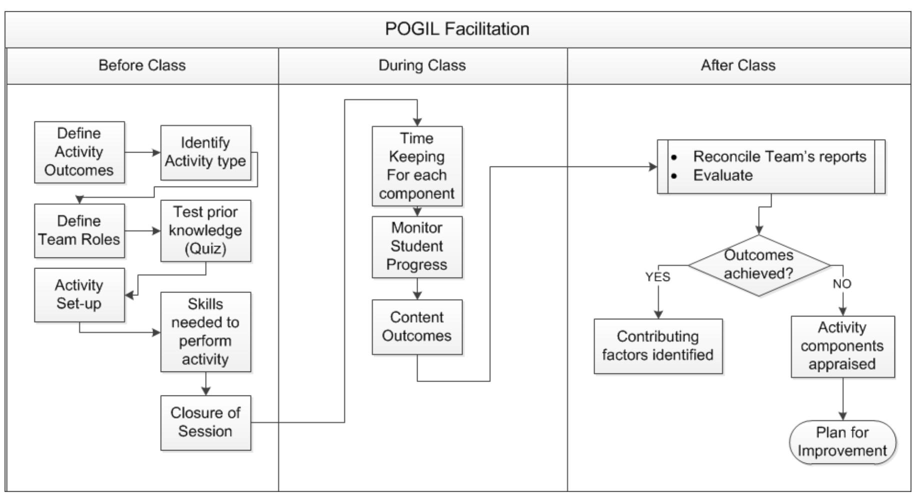


Figure: 2. 2. POGIL facilitation plan

2.3.3 Learning Cycle

Karplus and Butts (1977) proposed the learning cycle as a structured, mediated form of learning and, according to them, the three phases of a learning cycle are *exploration*, *concept introduction*, and *concept application*. During the exploration phase, students explore new materials and new ideas with minimal teacher guidance. During the concept introduction phase, students try to define the concept or idea or principle, applying a new pattern of reasoning to their experiences. During the last concept application phase, students apply their conceptual understanding or reasoning to a new learning situation. The learning cycle approach has been accepted by many science educators as a teaching method (Abraham & John, 1986; Goh & Chia, 1989), as a source for curriculum construction (Renner, Abraham, & Birnie, 1985), and as an inquiry model offering students the opportunity for meaningful and efficient self-evaluation and self-regulation (Halloun, 2006).

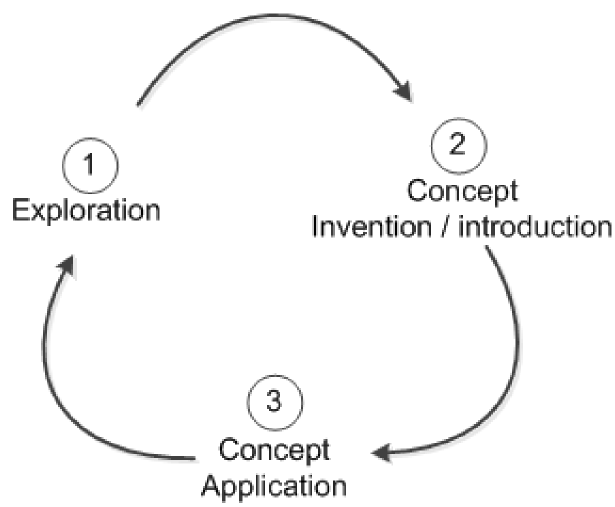


Figure: 2. 3. Learning cycle approach

The learning cycle approach has been reported as being superior to traditional approaches with regards to reflection of scientific inquiry processes in the laboratory (Pavelich & Abraham, 1979), content achievement (Purser, 1983), intellectual development gains (Killian & Warrick, 1980; Purser, 1983; Schneider, 1980), and retention of gains of content achievement (Killian & Warrick, 1980; Schneider, 1980). Abraham (2005) identified the learning cycle approach as a student-oriented inquiry-based instructional strategy with strong connections to constructivist ideas of nature of the science (Bodner, 1986) and the developmental theory of Piaget (1963).

Inquiry-based teaching methods modelled on the learning cycle are widely believed to be the best methods for helping students develop an understanding of the nature of science (Lawson, 2003). Further, Lamba (2008) inferred that learning cycle-based, hands-on and minds-on strategies encourage scientific thinking and yield better student outcomes. Student discussions from learning cycle structured activities can lead to the discovery of concepts. One of the important features of the POGIL approach is assigning special attention to the use of the learning cycle as the primary structure for the development of content knowledge. In a POGIL class, students work in self-managed groups and explore the information to construct their own understanding of concepts or ideas with a guidance of the teacher.

The learning cycle activities of POGIL have a sequence of questions that are intended to help students progress steadily, to help them derive appropriate conclusions and to develop process skills such as problem solving, deductive reasoning, communication and self-assessment (Eberlein, 2008). Libby (2008) proposed the use of learning cycle activities without class groups as a way to move from lecturing to active learning.

Research supports the learning cycle as an effective way to help students enjoy science, understand content, and apply scientific processes and concepts to authentic situations (Lawson, Abraham, & Renner, 1989). The learning cycle approach is effective for learners exploring new science concepts. Further, teachers can use the learning cycle approach to diagnose and challenge students' conceptions about scientific principles (Colburn & Clough, 1997).

2.3.4 Characteristics of POGIL materials

POGIL pedagogy uses specially designed activities/materials:

- for usage in self-managed team learning where the instructor becomes a facilitator
- that help students construct their understanding of concepts
- facilitate the development of higher level thinking skills and ability to apply the learnt knowledge in new situations

The POGIL activities contain a number of models that the students explore to answer critical thinking questions (P. J. P. Brown, 2010). The models may include text, equations, diagrams, tables, graphs, and figures related to the chosen concepts. Writers of POGIL activities (Luxford, Crowder, & Bretz, 2011; Spencer & Moog, 2008) usually focus on the development of one to three concepts. The students are asked to answer some key questions, usually, sentence completion items, manipulation of physical objects, and filling in tables through which they are guided to the desired concepts. The critical thinking questions of the activity sheets test the ability of the students to apply their conceptual knowledge in new learning situations. Interpretation of graphs and written communications are ideally considered the key process skills. The POGIL activities which are designed for upper level university courses emphasise the exercise of a set of process skills for insightful conceptual understanding. According to Geiger (2010), the structured POGIL activities lead students to higher levels of Bloom's taxonomy, particularly at Level 2 (concept development) and Level 3 (application of knowledge to new contexts).

The POGIL activities are broadly of two categories based on the learning cycle approach: concept invention activity, and concept formation activity. Concept invention (Spencer, 1999) activities typically follow the learning cycle approach of exploration, concept invention/introduction and application. In situations where the learning cycle structure is not applicable, the learning content provides opportunities for the development of process skills (Cole & Bauer, 2008). In concept formation activities, the concept or concepts to be understood are presented in the model as a graph or table at the start of the activity. For concept formation activities, the learning cycle approach starts with concept introduction/concept invention stage, followed by exploration and application stages. The critical thinking questions affirm understanding of concepts presented and develop process skills. Content learning objectives are in the form of statements of what students will be able to 'gain' as a result of completing the POGIL task (Cole & Bauer, 2008 pp. 566-569). In an article on their implementation of lecture-free biochemistry using POGIL, Minderhout and Loertscher (2007) listed four expected learning outcomes of a POGIL activity on enzyme catalysis. The structure of the POGIL activities included a pre-activity assignment, a classroom activity, and a post-activity skill exercise. In another study, Luxford, Crowder and Bretz (2011) reported that POGIL activity on symmetry elements and symmetry operations allowed students to explore and understand the concepts and helped them create definitions of common symmetry terms. The activities consisted of two models where critical thinking and exercise questions were included. During their POGIL implementation at an urban university, Ruder and Hunnicutt (2008) used POGIL class activities containing many short models with three to ten critical thinking questions each to enable the large class stay on task and for easy intervention.

The POGIL materials and the classroom facilitation support the development of both cognitive inquiry skills and group process skills (POGIL Project, 2008b). A hierarchical rating scheme in the form of rubrics (Stevens & Levi, 2005) was proposed by Bauer and Cole (2012) to provide guidance for the development of new materials for POGIL. The POGIL rubric, according to Bauer and Cole, guides authors of POGIL activities on the intended structure to reflect the simultaneous development of inquiry and process skills.

Several POGIL practitioners (Geiger, 2010; Luxford et al., 2011; Schroeder & Greenbowe, 2008; Straumanis, 2010; Yezierski & Birk, 2006) have established examples of POGIL implementation strategies in small and large enrolment chemistry classes. The organisation of a POGIL session in large enrolment classes or workshops is illustrated in Figure 2.4.

In a typical POGIL class, the students organise themselves into small groups of three to four. The instructors offer a structured or flexible group membership. As the students arrive the class, the instructor projects the day's intended learning objectives and the first model of the POGIL activity. The introduction lasts a very short time, maybe a minute or two. The students are asked to explore the model and answer the questions given in the activity sheet. As the students work in groups, the instructor walks around observing the students' progress and provides direction, if sought by any student groups, without divulging any answers.

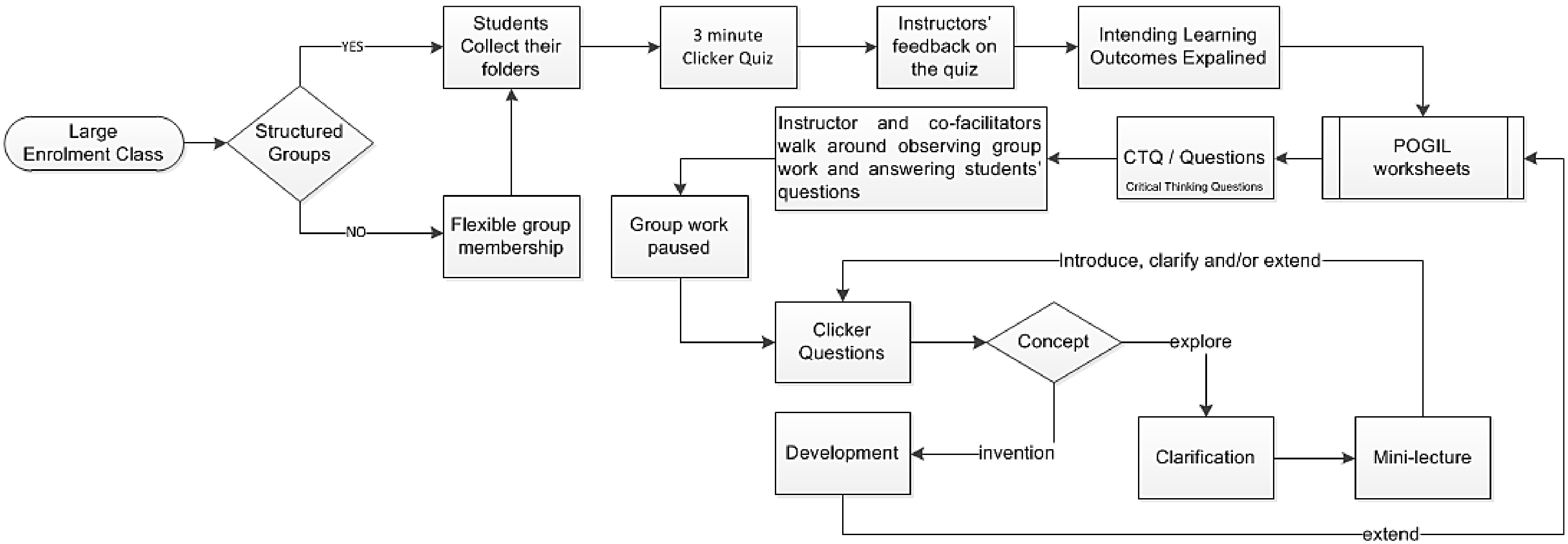


Figure: 2. 4. An illustration of how a POGIL session is organised

This learning cycle approach of POGIL activities helps the students to identify the concepts themselves and to construct their own understanding of the concepts. The instructor projects a series of multiple-choice clicker questions at key intervals to help groups progress towards completion and to check their understanding of the material. The students then answer the questions using a physical clicker device in about 30 seconds. Based on the results, the instructor may give a mini-lecture or a whole-class discussion to resolve any students' misunderstandings of the concepts.

This instructional method motivates students to stay engaged in their group work. In some POGIL classes, the honours students act as teaching assistants and they report back to the lecturer on any difficulties faced by the students and their progress on a particular activity. In practice, these POGIL sessions last for about 45 to 50 minutes. The class ends with a wrap-up of concepts, either with a mini-lecture or with clicker questions. Further, the students are expected to complete the exercises and/or problems as homework or complete assignments during the tutorial sessions.

Drossman et al. (2011) assessed the mentoring programme in a first year atmospheric science class wherein four mentors developed and tested the effectiveness of a POGIL-based curriculum and reported that the use of POGIL assignments promoted graduate students' understanding of cognitive and social constructivist principles. In their qualitative studies, the mentors acknowledged the use of teamwork and student collaboration in POGIL lessons as tools to develop problem-solving skills and connecting classroom topics with the real life experiences. The study also reported an improved understanding of the concepts of atmospheric physics by the students with the use of well-structured POGIL assignments.

2.3.5 Process Skills

Process skills are defined as the "methods of collecting, analysing, and acting upon information used in problem solving" (Molitor & George, 1976, p. 405). Hanson and Wolfskill (1998) highlighted the importance of process skills for chemistry students and introduced workshops aimed to impart skills that employers expect from their prospective newly graduated employees. Hanson and Overton (2010) reported the need for the development of generic skills like time management, organisation, oral presentation and team working than chemical knowledge skills amongst the graduates. The 2012 Graduate Outlook Survey report (Arnott & Carroll, 2013) published by Graduate Careers Australia found that the top skills sought by employers from the job-ready graduates were: learning, teamwork, communication, problem-solving, initiative and enterprise, planning and organising, self-management, technical skills from the course. Innovative teaching practices focus on connecting academic and employability skills. When instructors focus on how students learn, they guide students to use the process skills to learn the information.

The POGIL philosophy, according to Moog and Spencer (2008), emphasises the classroom implementation of process skills development that help students enhance their mastery of the course content and the institution's goals. In a typical POGIL class, students use both cognitive and affective processes to acquire, interpret and apply knowledge. These process skills include: teamwork, oral and written communication, management, problem solving, information processing, self-assessment and critical thinking.

POGIL activities guide the students to use and practice a set of all these process goals based on the nature of the learning task. In a study on the effectiveness of process workshops in chemistry, Hanson and Wolfskill (2000) reported a significant increase in the number of students scoring 50% and above in the examinations, a 15% increase in enrolment for second year organic chemistry course, and a 70% increase in attendance at the recitation (or tutorial) sessions.

Denson (1986) documented the effectiveness of investigative instructional methods in promoting the acquisition of process skills and inferred that laboratory methods and instructional methods are equally effective in improving students' knowledge of chemistry and process skills. More recently, Bailey, Minderhout and Loertscher (2012) have evaluated the implementation of POGIL in their biochemistry classes and have reported the benefits in both teaching and learning. In addition to students' practice of process skills like critical thinking, teamwork, problem-solving, their incorrect pronunciation of biochemistry vocabulary was reduced by 57% in the POGIL class, a key process skill in this context. Micari, Streitwieser, and Light (2005) investigated the experiences of undergraduate science students in a large peer-learning programme, and reported improved personal growth in the form of communication skills of the participating students that included confident speaking, audience understanding, and self-expression.

2.4 Student Conceptions

Learning is conceptualised when there is a connection between existing and new knowledge. Pedagogical research in science over the past few decades (Gilbert & Watts, 1983; Taber, 2006; Taber & Watts, 1997) has focussed on students' general understanding of scientific phenomena. The research community, including science teachers, have reported an array of findings identifying and analysing reasons for the students' erroneous understanding of concepts (Lawson, Baker, Didonato, Verdi, & Johnson, 1993; Schmidt, 1997; Treagust & Chiu, 2011). Though not unusual in the learning process, these illogical understandings are often termed misconceptions or alternative conceptions. In other words, concepts that are different from scientifically acceptable notions have been variously labelled as 'misconceptions', 'alternate conceptions', 'preconceptions', 'alternate frameworks', and 'children's science' (Treagust, 1988). Misconceptions are ideas held by students that do not align with reality. Preconcepts are the ideas that are often self-developed by students without any prior knowledge of the subject. The conceptions that differ significantly from those which are socially agreed by the scientific community constitute alternative conceptions (Gilbert & Watts, 1983). Duit and Treagust (1995) defined conceptions as "the individual's idiosyncratic mental representations" while concepts are "something firmly defined or widely accepted" (p. 47). In a study that examined undergraduate students' preconceptions of university research experience, Adedokun and Burgess (2011) acknowledged that the impact of students' preconceptions on their learning outcomes should neither be ignored nor overemphasised.

2.4.1 Origin of Alternative Conceptions

Alternative conceptions may arise from a variety of experiences and many students hold alternative conceptions or misconceptions which are densely embedded in their long term memory (Gabel, 2005). Baddeley and Hitch (1974) proposed the working memory model to depict the mechanism of information processing for complex cognitive activities. According to Baddeley (2003), the temporary working memory supports human thought processes by providing an interface between perception, long term memory and action. The model of working memory system (Baddeley & Hitch, 1974), as shown in Figure 2.5, involves the central executive, phonological/verbal state, visuo-spatial storage, and the episodic buffer.

The central executive is responsible for orchestrating storage, transformation, and retrieval of information and modality-specific storage buffers like phonological and visuo-spatial storage are responsible for holding different types of information whereas, the episodic component combines visual and verbal components and links them to multidimensional representations in long term memory. Any disorders in this storage system may have implications for complex cognitive activities like comprehension, learning and reasoning.

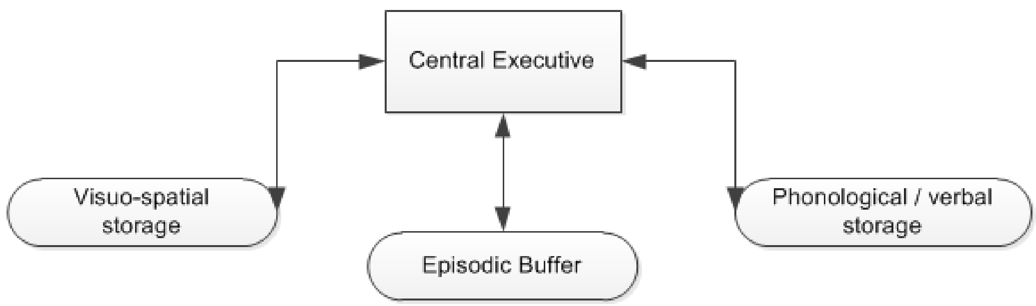


Figure: 2. 5. A model for summarising the main components of working memory (proposed by Baddeley and Hitch (1974))

Further, based on Baddeley and Hitch (1974) work, Johnstone (1997) proposed an information processing model, as shown in Figure 2.6, to describe the complexities associated with teaching and learning. In this model, the sensory information passes through a perception filter (controlled by prior knowledge) into the limited space in short-term/working memory where it is prepared for storage in long-term memory, as branched networks or fragments.

Alternative conceptions adhere to these networks when learners are taught with incorrect information or when they inaccurately interpret information. Consequently, these misconceptions or alternative conceptions become robust when embedded in long-term memory.

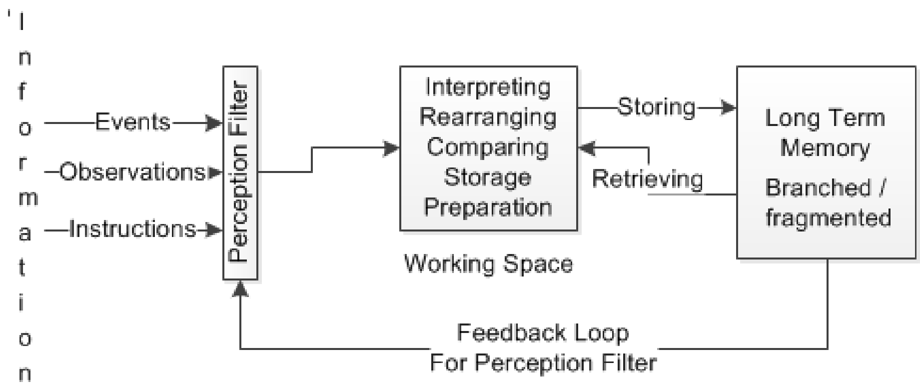


Figure: 2. 6. Johnston's Information Processing Model

The succeeding nature or the continuity of alternative conceptions, if not diagnosed and addressed in learning (Sreenivasulu & Subramaniam, 2012) make them highly resistant to change (Garnett, Garnett, & Hackling, 1995) and interfere in the process of acquiring new knowledge (Kendeou & van den Broek, 2005). According to Gilbert et al. (1982), some of the misconceptions or alternative conceptions arise due to "perplexed interpretation of common language with specific scientific language" (p. 625). Garnett et al. (1995) considered that some of the conceptions result from pedagogical practices and inferred that any conscious knowledge of these should help inform teachers in the selection and organisation of the taught curriculum and in the scientifically valid construction of conceptions by students.

For educators, it is imperative to identify alternative conceptions before any pedagogical practice (Wandersee, 1994); if not, these alternative conceptions become integrated into their cognitive structure and can interfere with their subsequent learning (Treagust & Chandrasegaran, 2007). As a result, students' understanding of new concepts may be inappropriate and the integration of new information into their process of thinking may be very challenging. The knowledge of how students perceive, process, and apply their experiences in ways that lead to inaccurate way of understanding the world can be useful to instructors in tailoring their teaching to address these alternative conceptions (Rushton, Hardy, Gwaltney, & Lewis, 2008) .

2.4.2 Studies on Students' Alternative Conceptions in Chemistry

Appropriate understanding of chemistry concepts may happen when students are able to understand the fundamental chemistry concepts from macroscopic, sub-microscopic, and symbolic perspectives (Orgill & Sutherland, 2008; Treagust, Chittleborough, & Mamiala, 2003) and integrate these concepts into their new learning.

A broad range of chemical education research focuses studies on student understanding and misconceptions in the conceptual areas of particulate nature of matter (Ben-Zvi, Eylon, & Silberstein, 1986; Garnett et al., 1995; Griffiths, 1992; Nakhleh, 1992; Novick, 1981), chemical equations (Ben-Zvi, Eylon, & Silberstein, 1987; Hesse III & Anderson, 1992; Kelly, 2010; Naah, 2012; Niaz & Lawson, 1985; Nurrenburg, 1987; Savoy, 1988; Staver & Jacks, 1988a, 1988b; Yarroch, 1985), chemical equilibrium (Banerjee, 1991; Bergquist, 1990; Johnstone, MacDonald, & Webb, 1977; Tyson, Treagust, & Bucat, 1999; Van Driel & Graber, 2002; Wheeler, 1978), acids and bases (Cartrette, 2011; Epstein, 1998; Kelly, 2010; Sisovic, 2000; Smith, 1996), oxidation-reduction (BouJaoude, 1991; Tan et al., 2007) and electrochemistry (Boulabiar, Bouraoui, Chastrette, & Abderrabba, 2004; Garnett & Treagust, 1990), physical and chemical change, and thermodynamics (Garnett et al., 1995; Ozmen, 2004; Palmer & Treagust, 1996).

A minor and yet a steadily increasing number of studies has been taking place on students' understanding of concepts in organic chemistry (McClary & Bretz, 2012; Rushton et al., 2008; Villafañe, Bailey, Loertscher, Minderhout, & Lewis, 2011). These and other studies have demonstrated that pedagogical methods which systematically address common student misunderstandings or misconceptions do produce significant gains in students' conceptual learning. The following is the summary of research related to students' understanding of organic chemistry (Section 2.4.4) from where the aims of the present research study have emerged.

2.4.3 Organic Chemistry

Organic chemistry is the study of the properties, preparation, identification and modification of compounds involving carbon. In his introductory activity of a textbook on organic chemistry, Straumanis (2009a) considered that the study of organic chemistry was a potential field for sharpening analytical and problem-solving skills. Analogising the study of organic chemistry to a long story, Klein (2012) stated that organic chemistry "is not about memorization, but making sense of the plot, the scenes, and the individual concepts that make up the story" (p.iv). The research study in this thesis explored students' understanding of stereochemistry concepts in a POGIL-influenced class.

Stereochemistry is an important aspect of organic chemistry that primarily includes the study of relative spatial arrangement of atoms within molecules and the study of stereochemical requirements and outcomes of chemical reactions. Furio and Calatayud (1996) analysed the knowledge levels of grade 12 and university students concerning the geometry and polarity of molecules. They reported students' difficulty with molecular geometry, specifically three-dimensional visualization which was observed to be due to students' lack of spatial ability. Earlier, Schmidt (1992) investigated pre-university students' conceptual difficulties associated with isomerism and reported restricted conceptions of isomers held by the students. The study focused on alcohols and ethers. When identical molecular formulas for two alcohols and one ether were given, students classified only two alcohols as isomers. The acquisition of stereochemical knowledge is difficult and confusing to students (Boukhechem, Dumon, & Zouikri, 2011; Kurbanoglu, Taskesenligil, & Sozbilir, 2006; Lujan-Upton, 2001). Nevertheless, the integration of conceptual knowledge and visuo-spatial skills are considered essential while studying stereochemistry (Barnea, 2000; Boukhechem et al., 2011; Habraken, 2004)

Commenting on freshmen difficulties in chemistry, Zoller (1990) highlighted examples from organic chemistry that are very easily prone to learning difficulties, often leading to misunderstandings or misconceptions. These identified difficulties were: relative chemical reactivity of alkenes and alkynes, identifying molecules as chiral/achiral based on their steric structure, and comparing nucleophilicity or leaving groups. Further, Zoller inferred that the students' conceptual misunderstanding was due to the very abstract or non-intuitive nature of the concepts that are not logically interrelated.

According to another investigation by Rushton, Hardy, Gwaltney and Lewis (2008), fourth year chemistry students exhibited persistent alternative conceptions of organic chemistry topics. For example, students incorrectly recognised a resonance stabilized, non-aromatic molecule as having aromaticity and a six carbon arene as a cyclohexane or an alkene. Their view may be due to a persistent alternative conception, that is, the identification of hexagons in bond-line formulas as one category, all aromatic or non-aromatic. Further, some of the near-to-graduation fourth year chemistry students chose most stable species as the most reactive, due to their unclear understanding of the relationship between relative energies and reactivity of molecules.

Taagepera and Noori (2000) studied the results of a test administered through the application of knowledge space theory, a procedure used to display the students' cognitive organisation of knowledge, and found that organic chemistry students in a three-course sequence exhibited alternative conceptions about bond polarity, boiling vs. burning, and hydrogen bonding. The students had difficulty in recognising reaction types like nucleophilic addition to carbonyl compounds. In a recent study, McClary and Bretz (2012) identified alternative conceptions held by undergraduate organic chemistry students related to acid strength, their frequency of appearance, and their intensity of existence in the students' mental models. Conspicuously, 30% of the students held two alternative conceptions: *functional group determines acid strength* and *stability determines acid strength*, the mean confidence of these was greater than 50%.

2.5 Methodologies for Investigating Conceptions

The prerequisite for first year chemistry course enrolment in Australia is successful completion of Year 12 chemistry or its equivalent. For, international students and non-traditional school leavers, bridging units or foundation programmes offer an alternative entry into a first year undergraduate chemistry course. Hence most students' prior knowledge and assumptions about chemistry were learned prior to starting their first semester chemistry course, and students access these ideas for further constructing their knowledge in chemistry. For any science curriculum, the essential constituents are its quality and scope of students' understanding of scientific concepts or phenomena. Access to suitable assessment tools which can effectively measure the effectiveness of instruction is highly desired (Treagust, 2006). In an introduction to a special issue on diagnostic assessment in chemistry, Treagust and Chiu (2011) stated that "globally there is increasing interest in the need to provide formative diagnostic assessment as a means to assist learners in their efforts to develop a more comprehensive understanding of the chemical concepts in the implemented curriculum" (p. 119).

For the assessment of students' conceptions, researchers use a variety of methods, such as interviews, think-aloud protocols, open-ended questions, free writing, conceptual surveys, pencil-and-paper diagnostic instruments based on multiple choice items, two-tier multiple choice tests, prediction–observation–explanation, drawings and word associations (Adadan & Savasci, 2011; Peterson, Treagust, & Garnett, 1989; Schmidt, 1997). Amongst these, interviews and two-tier multiple choice tests are more research-driven and widely validated (Ozmen, 2004). Bell and Cowie (2001) had argued that these assessments of students' thinking need to be integrated into teaching. For the study of students' understanding of stereochemistry concepts in a POGIL classroom, this researcher used interviews and multiple choice tests.

2.5.1 Interviews

Interviews can help teachers recognise, represent, and evaluate students understanding. Osborne and Gilbert (1980) used the interview-about instances technique, a method meant to explore students' understanding of a single concept, by means of a voice capturing device. To elicit students' understanding of a concept, Osborne and Gilbert showed students a number of cards containing line diagrams. Some of the cards depicted an instance or occurrence of the concept and others did not. The students were asked to identify with reason, whether the card contained the instance of the concept or not. Further to the interview-about instances method, Osborne (1980) used the interview-about events technique which he considered a more direct way of eliciting students' descriptions of the physical events.

The think-aloud strategy (Ericsson & Simon, 1998) allows students to verbalise their thoughts while completing the task without any disruption. Described as a popular strategy, the think-aloud protocol has helped uncover students' alternative conceptions in chemistry problem solving (Gabel, Sherwood, & Enochs, 1984; Rushton et al., 2008). Nyachwaya, Mohamed, Roehrig, Wood, Kern, and Schneider (2011) have developed an open-ended drawing tool as a qualitative approach to assess students' understanding of the particulate nature of matter. In this study, students described their answers vividly through particulate drawings in an effort to provide insight into particulate thinking. The study helped confirm past findings as well as uncovering new findings on students' misconceptions or misunderstandings which were not reported in the earlier literature.

2.5.2 Two-Tier Multiple Choice Tests

Two-tier multiple choice tests have been developed and used by several science education researchers since the outcome of Treagust's (1988) seminal article on diagnostic testing in science for the purpose of identifying students' alternative conceptions. Considered easy to administer, the paper and pencil test contain two-tier multiple choice diagnostic items. The first tier of the each item consists of a content question with two or four choices. The second tier of each item contains a set of four possible reasons for the chosen answer in the first part. The reasons contain the best possible correct answer and other identified students' alternative conceptions.

Two-tier multiple choice tests when administered and the analysis of results have led to the identification of many alternative conceptions held by the students are secondary and tertiary levels in various science topics, *viz.* chemical bonding (Jacobs, Kawanaka, & Stigler, 1999), covalent bonding (Birk & Kurtz, 1999), covalent bonding and structure (Peterson et al., 1989), qualitative analysis (Tan, Treagust, Goh, & Chia, 2002), chemical equilibrium (Tyson et al., 1999), multiple representations (Chandrasegaran, Treagust, & Mocerino, 2005), ionisation energies of elements (Tan et al., 2005), acids and bases, states of matter (Chiu, Chiu, & Ho, 2002) and chemistry of solutions (Adadan & Savasci, 2011).

Birk and Kurtz (1999) administered Peterson et al.'s two-tier diagnostic test to assess first year and advanced college chemistry students' understanding of molecular structure and bonding. Besides reporting several misconceptions, this US study also had revealed first year chemistry students' lack of understanding of concepts of molecular structure from their inconsistent responses to the same questions. Later, Yezierski and Birk (2006) developed a 20-item Particulate Nature of Matter Assessment Version 2 diagnostic test to identify the students' alternative conceptions about particulate nature of matter and determined the role of computer animations in challenging and changing the alternative conceptions.

The two-tier diagnostic tests proved to be convenient for students to answer, and valuable for teachers to use in terms of their capability for large-scale administration, easy marking, reducing students' guessing of answers, and more importantly offering insights into students' reasoning (Adadan & Savasci, 2011; Liu, 2010; Othman, Treagust, & Chandrasegaran, 2008). Griffard and Wandersee (2001) acknowledged the ability of the validated diagnostic instruments in statistically predicting the prevalence of students' alternative conceptions and further argued that experienced teachers are able to successfully uncover and address their students' alternative conceptions. Griffard and Wandersee studied college biology students' pattern of completing several tasks from the two-tier diagnostic test aimed to detect high school students' understanding of photosynthesis. They argued that the diagnostic test measured students' test taking skills rather than their actual knowledge because some students did not logically follow their response to the first tier question while answering the second tier question. Moreover, Griffard and Wandersee stressed the need for diagnosing the students' unconnected knowledge gaps in their conceptual framework and that subsequent bridging could prevent the development of the non-scientifically acceptable concepts.

Garnett et al. (1995) had postulated several factors contributing to students' lack of understanding of PNM, chemical bonding and chemical equilibrium. These factors included scientific contextual usage of daily language, over-simplification of concepts, use of un-qualified generalised statements, multiple definitions and models, lack of prerequisite knowledge and overlap of concepts of similar nature.

The use of diagnostic instruments does benefit instructional staff to identify the type of knowledge that students depend on during problem solving and their non-scientifically acceptable conceptions. Awareness of this knowledge could aid planning of lesson sequences. Treagust (2006) suggested that the administration of diagnostic tests at pre and post levels of instruction may help instructors understand clearly the nature of students' understanding and the presence of any alternative conceptions related to the particular topic of their studies. Further, Adadan and Savasci (2011) hoped that the of Nature of Solutions and Solubility – Diagnostic Instrument may help teachers explore the extent and nature of students' conceptions and also provide information on the effectiveness of their own instruction.

Analysis of two-tier diagnostic test results and qualitative data obtained from semi-structured interviewing of students helped Tsui and Treagust (2010) to make evidence-based assertions about students' scientific reasoning in genetics. Diagnostic testing helped to identify students at risk who primarily rely on rote learning of concepts without understanding the underlying reasons (Kilic & Saglam, 2009).

2.6 Implementation of POGIL

With no specified/required approach for its implementation, POGIL can be implemented in various ways; no two POGIL settings are alike at any institution or in any course. Every implementation of POGIL is unique because every instructor and institutional setting is unique (POGIL Project, 2008a). However, the most common features of any POGIL classroom implementation includes a daily quiz to encourage students to prepare for and attend every class, graded home-work, time investment in structuring and emphasising group work, encouraging students to adhere to the group roles, use of facilitation strategies to promote group members' interaction, and mini-lectures. However, the uniqueness of POGIL implementations is characterised by small groups of students working collaboratively on learning cycle-oriented POGIL worksheets facilitated by instructors in a non-lecturing learning environment.

POGIL implementations may span over a few semesters (Drossman et al., 2011; Johnson, 2011; Schroeder & Greenbowe, 2008; Vacek, 2011) or alternatively during a semester as partial implementation (Cole et al., 2012; Criasia, Lees, Mongelli, Shin, & Stokes-Huby, 2009; Mitchell & Hiatt, 2010; Murphy, Picione, & Holme, 2010; Rajan & Marcus, 2009). In sharing their knowledge and experience of POGIL implementation and assessment, Cole and Bauer (2008) call for the inclusion of a feedback loop that comprises self-analyses, student assessments and peer assessments from other instructors to identify the strengths and areas of improvement in the POGIL implementation.

2.7 Effectiveness of POGIL

Farrell, Moog and Spencer (1999) first reported successful implementation of process-oriented guided inquiry learning in their general chemistry course. Later, POGIL was reported to have been successfully implemented in organic chemistry (Hein, 2012; Schroeder & Greenbowe, 2008; Straumanis & Simons, 2008), physical chemistry (Spencer & Moog, 2008), general chemistry (Criasia et al., 2009; Garoutte, 2008; Murphy et al., 2010; Rajan & Marcus, 2009), biochemistry (Bailey et al., 2012; Minderhout & Loertscher, 2007), medicinal chemistry (S. D. Brown, 2010), and high school chemistry (Barthlow, 2011). Beyond chemistry, POGIL had been implemented with positive results in anatomy and physiology (P. J. P. Brown, 2010), mathematics (Rasmussen & Kwon, 2007), information technology (Kussmaul, 2011a, 2011b; Myers, Monypenny, & Trevathan, 2012), environmental health (Jin & Bierma, 2011), atmospheric science (Drossman et al., 2011), information literacy (Mitchell & Hiatt, 2010), marketing education (Hale & Mullen, 2009), environmental engineering (Thompson, Ngambeki, Troch, Sivapalan, & Evangelou, 2012) and foreign language education (Johnson, 2011).

Referring to the specifics of POGIL in chemistry classes, a number of studies are now discussed. Lewis and Lewis (2005) investigated the effect of replacing one of the three general chemistry lectures each week with peer-led small group learning sessions using POGIL worksheets. They reported that the students who attended the group learning sessions achieved a higher average score on the common examination.

Bailey et al. (2012) assessed student understanding of general chemistry and biology concepts in a POGIL class using a diagnostic test. The 24-item multiple choice diagnostic test addressed concepts related to bond energy, pH/pK_a, hydrogen bonding, free energy changes, London dispersion forces, protein alpha helix structure, and the impact of mutation on protein function. This test was developed and validated by Villafañe et al. (2011) to identify incorrect ideas held by biochemistry students and investigate students' learning gains. Bailey et al. have reported a statistically significant increase of mean scores from 9.1 to 12.5 out of a possible 21 in a pre and post-test format.

Nyachwaya et al. (2011) investigated the ability of first year general chemistry students in balancing chemical equations and drawing particulate representations related to those reactions while they were taught in an environment using POGIL activities, clickers and think-pair-share discussions. The study aimed at diagnosing students' underlying conceptions of the particulate nature of matter related to chemical equations for reactions involving covalent compounds and/or ionic compounds. When students' answers to three drawing task questions from the previously administered mid/end of semester examinations were coded and analysed, the data showed that the students had difficulty in drawing conceptual diagrams of chemical equations, especially with ionic compounds. Besides revealing several students' alternative conceptions pertaining to PNM, the study reported students' representational errors related to the behaviour of polyatomic ions in aqueous solution. The diagnostic assessment study of Nyachwaya et al. in a POGIL influenced course, created opportunity to further investigate how POGIL influences students' understanding of the particulate nature of matter.

Hein (2012) studied student's final examination scores to evaluate the effectiveness of POGIL on students' concept retention and their cumulative knowledge in organic chemistry. The data included the ACS final examination scores from the POGIL and the traditional lecture instruction, taught by the same instructor over a period of three years. The assessment criteria used throughout the study were similar such as class schedule, online and written homework, laboratory reports, mid-semester and the ACS final examinations. When the average percentile rankings for ACS examination results were compared between traditional and POGIL groups, 72% of POGIL students' achieved higher than the median percentile achieved by the students in the traditional lecture group. The number of students ranking in the 25th percentile and below decreased over each year the POGIL method was used and the median national percentile ranking for the POGIL group was 36% compared to 20% for the traditional lecture group. Data on attrition levels for both of traditional lecture and POGIL instruction indicated that the teaching methods were independent of the students' drop-out rate.

In another study, where one year traditional lecture was followed by a two year POGIL practice, Ruder and Hunnicutt (2008) reported successful implementation of POGIL in a large organic chemistry class in terms of test scores and knowledge retention. When three examination scores from each course semester were compared, a slight difference in first examination scores between traditional and POGIL groups was hypothesised to be due to students' transitional adjustment into small group learning. In the second examination, the POGIL group outperformed the traditional lecture group, whereas in the third examination, more POGIL students were in in the grade distribution range of A and B than the traditional lecture group which had more students in the grade range of D and F.

An action research study by Murphy, Picione and Holme (2010) investigated the implementation of POGIL in a preparatory college chemistry with 180 students in three lecture sections per semester for two years. Three one-hour examinations were given to students throughout the spring and fall semesters where students had used clickers to record their feedback. The initial experimental design which included a typical control i.e. lecture group, a partial POGIL and a full POGIL group, did not yield any statistically significant data in support of the POGIL methodology, due to students' resistance to the new teaching methodology. Subsequent modifications to the POGIL approach in the form of integrated concept mapping, mini-lectures, and exclusion of reading material were implemented leading to a positive effect on student performance. This significant institutional modification of POGIL was further evidenced by Geiger (2010) who stated that the "institutional environment has a significant impact on the implementation of POGIL and process oriented learning; what works at one institution may need significant modification to be successful someplace else" (p 30).

Schroeder and Greenbowe (2008) investigated student performance on nucleophilic substitution reaction mechanisms and reported improved performance by POGIL students on nucleophilic substitution and elimination examination questions compared to traditionally taught students from the previous year. For comparing the traditional and POGIL groups, Schroeder and Greenbowe included two examination questions similar to the previous year. For the first question where students needed to draw the correct structure of the product, 95% of the POGIL students drew a correct structure which was comparable to the traditionally taught students. For the second question, where students needed to draw major and minor elimination products, 47% of POGIL students represented the major and minor products correctly. The mechanism of nucleophilic substitution and elimination reaction was represented correctly by 34% of POGIL students whereas only 6% of the traditionally taught students were able to answer this question correctly in the previous year.

2.8 Students' Perceptions

Further to the reporting of improved learning outcomes via POGIL, researchers had published their results of student engagement, their perceptions of the value of small group learning and the perceived growth in process skills. In an end-of-course survey of chemistry for non-science majors that comprised POGIL and project-based learning methodologies, 80% of the respondents were enthusiastic and comfortable with guided inquiry learning (Lees, 2008). Contrary to this, Douglas (2009) reported a minimal benefit due to students' expectations of instructors providing them with answers to all POGIL activity questions despite their positive reflections about small group work. However, Brown's (2010) study showed little difference in students' perceptions about the course between traditional lecture group and POGIL group on specific criteria such as delivery of course material, relevance to real-life situations, and its communication, with an exception to group work. Jin and Bierma (2011), from the limited available data, indicated that their environmental health students enjoyed the POGIL activities which helped them in deep understanding of the concepts.

The Student Assessment of Their Learning Gains – SALG, an instrument developed by Seymour, Wiese, Hunter, and Daffinrud (2000), is used to gauge students' perceptions of skills, understanding, and attitudes towards teaching or laboratory courses. Carroll (2010) inferred that a combination of SALG and student achievement tests could offer curriculum practitioners a powerful triangulation on measures and causes of student learning. Straumanis and Simons (2008) used SALG as an indicator of growth of students' process skills in POGIL organic chemistry classes and reported that POGIL responses were higher than those in the lecture group. When compared to the traditional lecture group, the POGIL students perceived greater value for course elements and a higher growth was shown in their process skills.

Descriptive statistical analysis and response frequencies are widely used to interpret students' responses (Douglas, 2009; Heady, 2002; Johnson, Corazzini, & Shaw, 2011; Keeney-Kennicutt, Gunersel, & Simpson, 2008; Keeves, 1995; van Rooij, 2009) to each or a set of the Likert scale questions in an effort to provide a glimpse of students' perception of course implementation. Heady (2002) administered the SALG survey successively to two student cohorts over two years in introductory biology classes to find out what helps students to learn. The study compared the mean values for all of the student responses to the items of SALG. In an another study on the effectiveness of project management methodology in a psychology class, van Rooij (2009) administered a 20-item SALG survey and presented a comparative mean scores of students' SALG responses in project management methodology and traditional project scaffolding. Keeney-Kennicutt et al. (2008) used SALG instrument to investigate the general chemistry students' perception of an educational web-based tool called, calibrated peer review. The results of the time-series analysis included the percentage values of students' responses to the 5-item SALG survey. Validity and reliability of SALG was established by comparing student responses with their interview data and by means of correlational study of SALG results, mainly mean values and other measures of learning. According to Seymour (2000), the flexibility of adapting SALG in between multi-disciplinary sciences is dependent on the extent of cohesiveness of various course elements such as goals of class or laboratory activities, curriculum, resources used and tested. At present, there is no study on establishing construct validity for any modified SALG being used in assessing POGIL implementations. Construct validity answers whether or not the instrument actually measures the construct under question.

2.9 POGIL in Australia

In a report submitted to the Australian Learning and Teaching Council, Bedgood et al. (2012) narrated the Australian experience of implementing POGIL in first year chemistry classes. Member institutions of the Active Learning in University Science (ALIUS) have been implementing POGIL in chemistry, veterinary chemistry, statistics, botany dentistry and nutrition. Despite their geographical isolation, pedagogically, the POGIL practitioners in the US and Australia collaborate periodically to effectively implement POGIL in first year undergraduate courses. Leaders of ALIUS and POGIL practitioners from the US have been conducting POGIL workshops in Australia to train and support faculty members interested in teaching innovations.

During the early implementation of POGIL in 2009 at their member institution, the instructors used POGIL worksheets as homework and the students discussed these during tutorial sessions. Following the initial ‘mixed’ feedback from the students, the instructors implemented a modified POGIL by integrating group-work questions into the lecture which was well received by the students who claiming that they liked the blended mode of lecture method and POGIL. The students’ achievement in quizzes was compared with another student cohort to whom the same instructor taught at a different institution. The results indicated that there was no change in average and median grades, but an increase in the proportion of high-distinction grades due to students’ enhanced learning by means of POGIL and increase in fail grades due to various factors including instructor’s inexperience with POGIL activities. Later in semester 1, 2010, the quiz scores in another first year chemistry module were again compared between students in POGIL and traditional classes. The results showed a significant increase in the proportion of high-distinction, distinction, credit grades and a drop in fail grades in support of blended POGIL approach. According to Bedgood et al. (2012) the students’ positive comments on the POGIL activities revealed that they are better prepared for examinations, their lecture notes became shorter, and they have been guided through in solving problems and clicker questions that followed POGIL activities, made the lectures more interesting and interactive.

2.10 Summary

This review of literature focused several areas of research-salient features of Process Oriented Guided Inquiry Learning, POGIL, curriculum model for the evaluation of implementation of POGIL and a theoretical framework for this study was presented. A considerable amount of chemistry education research was conducted in the area of student centered learning pedagogies. A summary of the findings of the literature include:

- The curriculum evaluation framework used to investigate the effectiveness of instructional strategies included four aspects of the curriculum.
- Social constructivism forms the theoretical basis for research-based pedagogies in chemistry education.
- Numerous researchers support the need of inquiry approach for the development of process skills and logical thinking ability besides mastery of content.
- Student interviews and 2-tier diagnostic tests were widely used to explore students' understanding of science concepts.
- Numerous studies reported students' difficulties in organic chemistry, a very few included alternative conceptions regarding stereochemistry.
- Successful POGIL implementation studies utilised examination scores as a measure of effectiveness.
- POGIL is modified in accordance with the institutions' learning environment.
- A gap exists for establishing construct validity of Student Assessment of Their Learning Gains, SALG instrument to make it relevant to investigate student perceptions of POGIL implementation.

The effectiveness of POGIL in first year chemistry classes in the United States is evident in the literature, but the effectiveness of POGIL in Australia has not been researched extensively. The research study addressed:

- Students' acquisition of POGIL process skills and their alignment with the graduate attributes of the university.
- Implementation of learning requirements via POGIL based curriculum.
- Students' understanding of stereochemistry concepts in first year chemistry classes.
- Students' perception of their learning while engaged in a POGIL class.

Chapter 3
Methodology

3.1 Introduction

This chapter describes, in detail, the research methods used in the present study. The Section 3.2 outlines the research paradigm used in this research. The research design presented in Section 3.3 was based on the literature reviewed in Chapter 2. The research questions outlined in Section 3.4 emerged from the research paradigm described in Section 3.2. Sections, 3.5, 3.6 and 3.7 feature the details of participants, instructors and the ethical procedures implied in this study. Sections 3.8, 3.9, 3.10, 3.11, and 3.12 provide details of instruments, data collection and analysis procedures used to answer the research questions. Section 3.13 elucidates the qualitative data analysis procedures. Section 3.14 details the triangulation methods, reliability and the procedures for the validation of the instruments.

3.2 Research Paradigm

Willis (2007, p.1936) defined a paradigm as "a comprehensive belief system, world view or framework that guides research and practice in a field". Post-positivism was considered appropriate for this study as it offered the researcher an impersonal position to make context-dependent generalisations (Cooper, 1997) using methods that minimise the susceptibility of participants, reducing the effect of bias by means of structured interactions with students. Post-positivism is considered as an emergent alternative to positivism. The post-positivists assert that all reality is mentally constructed and can never be completely known, there are no general or universal laws that can be counted on in every situation (Guba, 1985). Post-positivist research is commonly aligned with quantitative methods of data collection and analysis. Similarly, in this study, quantitative data were obtained from the Stereochemistry Concept Tests and the Student Assessment of Their Learning Gains (SALG) instrument.

3.3 Research Design

The theoretical framework for this study was based on social constructivism (Vygotsky, 1978) and the learning cycle approach (Farrell et al., 1999). The focus of this research is to create an understanding of the measurable and observable aspects of students’ understanding of concepts and their perceptions of POGIL-influenced learning in a chemistry course.

A variety of data gathering techniques were employed in this study: class observations, diagnostic testing of their understanding of chemistry concepts, survey of students’ perceptions of their learning in a POGIL class, and student interviews.

Towns (2007) argued that mixed method designs offer a greater research landscape for explaining and expanding the investigating phenomenon composed of a single research strategy. Tashakkorri and Teddlie (1998) regarded mixed methods design as a philosophical framework that influences the entire research process. Similarly, Abraham (2008) argued that the integration of quantitative and qualitative methods bring in greater power to theory-based research designs. Most common mixed methods designs are – triangulation, explanatory and exploratory designs (Creswell, 2005; Creswell & Plano-Clark, 2007). The sequential explanatory design (Creswell, 2003), a mixed method strategy that prioritises quantitative data over qualitative data, is widely used by chemistry education researchers (Staver & Lumpe, 1995) to gain insights into the students’ misconceptions and the functional nature of students’ knowledge. Essentially, the qualitative results help in the elaboration and extension of findings of the primary quantitative study (Dinah, 2008).

The layout of the research design is presented in Figure 3.1. As shown in the figure, the four research questions that originated from the research framework take the appropriate approach for the exploration of the process-oriented guided inquiry learning in chemistry classes. The accurate description of the sub-processes is presented in the corresponding chapters. For example, the method of validation of the SALG instrument is represented in Figure 6.1.

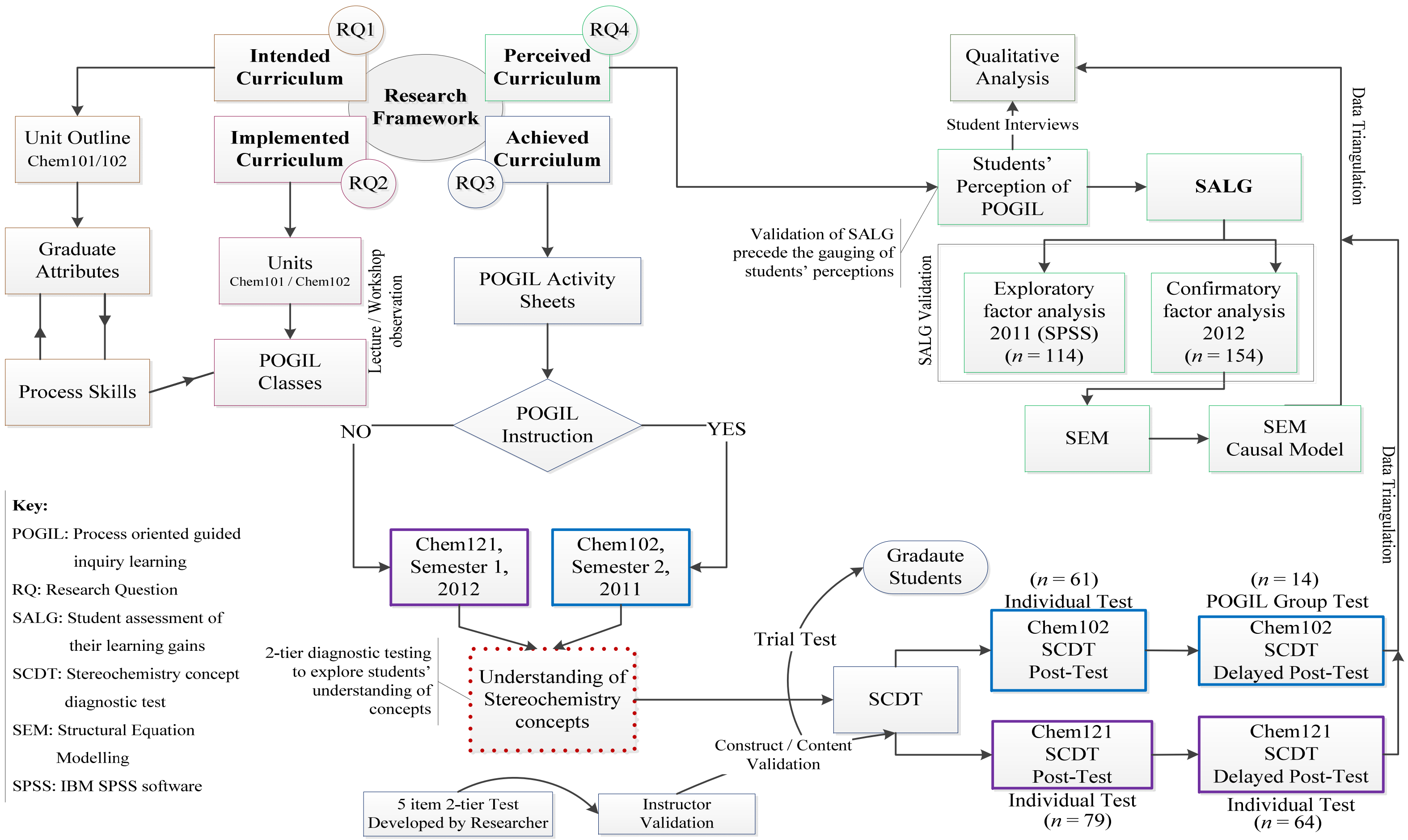


Figure: 3. 1. An outline of the research design

3.4 Research Questions

This study investigated the effects of using student-centered process oriented guided inquiry learning (POGIL Project) on first year chemistry students' learning. The research questions to be answered are:

1. How do the skills that students learn in POGIL classroom align with university graduate attributes?
2. How can these learning requirements be implemented through POGIL based curriculum?
3. How effectively do students achieve the intended learning outcomes using a POGIL approach?
4. In what ways do students perceive their learning while engaged in POGIL classes?

The study focuses students' understanding of stereochemistry concepts in a POGIL class. The research hypothesis is that students misunderstanding of stereochemistry concepts will be reduced by the use of Process Oriented Guided Inquiry Learning lessons.

3.5 Participants

The population studied comprised a cohort of first year chemistry students enrolled during 2011 at Curtin University, Bentley campus in Western Australia. Most of the students were Engineering and Science first year students opting to study chemistry during the first and second semesters. The majority of the students (domestic and international) were school leavers, however, non-traditional students such as mature age learners and students with vocational qualifications comprised a minority of the population. The student cohort had varying degrees of background knowledge in high school chemistry.

Of the 320 students enrolled in chemistry at the start of semester 1 in 2011, the number of students participating in the research studies varied according to the changes in the enrolment and requirement of chemistry as a subject of studies during the following semester in 2011. The research study involved students enrolled in general chemistry units, Chem102 and Chem121. The students enrolled in Engineering and Science studied Chem102 whereas, the students enrolled in

Pharmaceutical Science studied Chem121. Both cohorts studied topics outlined in Appendix (E). The details of the course unit were provided in Chapter 4.

3.6 Instructors

The Department of Chemistry at Curtin University, Bentley campus has been actively implementing active learning strategies into its core teaching practices. The core teaching faculty of first year chemistry are pioneers of the reform-oriented Active Learning in University Science (ALIUS) project and have been teaching first year chemistry units for several years.

The entire course is not taught the POGIL way; the instructor selects topics (see chapter 4) where POGIL is considered the best fit for effective learning.

3.7 Ethical Procedures

The research proposal and plan for data collection were presented to the Graduate Studies Committee, Human Research Ethics Committee and the first year coordinators of the Department of Chemistry at Curtin University. The proposal explained the aims of the study, type of data that would be collected, and the plan for handling data to protect confidentiality. Upon receiving the formal permission to proceed, the schedule for class observation, administration of tests and questionnaire was worked out in conjunction with the first year chemistry coordinators. A memorandum approving the research proposal by the Human Research Ethics Committee of the university is included in Appendix (A). The students were issued with the information sheet highlighting the purpose and objectives of the research and were made aware that their voluntary participation in the research would not generate any extra grade or credit.

3.8 Data Collection and Analysis Procedures to respond to each Research Question

The data were collected mostly during the tutorial sessions which are of 60 minutes duration. In these sessions students seek help from tutors to complete their assignments or activity sheets every week during the semester. A scheme was worked out that would only allow the export of coded data (without name, student identification numbers, or other data that could directly identify individual students) to ensure that data remained confidential. The relationship between the four research questions and their respective data collection tools is shown in Tables 3.1 and 3.2.

Table 3. 1: Relationship between research questions and data collection tools: RQ1 and RQ2

Research Question	Data Source
Research Question 1	
POGIL process skills and graduate attributes	Curriculum documents POGIL activity materials
Research Question 2	
POGIL implementation	Researcher's observation of lectures, tutorials/workshops Student interviews / Open ended SALG statements

Table 3. 2: Relationship between research questions and data collection tools: RQ3 and RQ4

Research Question	Instrument	Item Numbers	Form of Data
Research Question 3 Students' achievement in POGIL class	SCDT	5 items	2 Tier Response and Reason *(except for Item 1)*
Research Question 4			
Student learning and their perceptions in POGIL class	SALG	44 items 10 items	Likert Open ended

A semi-structured interview format was used to obtain students' feedback on their gains in POGIL-influenced learning. Students were interviewed using a Livescribe smartpen (Hannon, 2008; Hastings, 2008; Schmidt, Hernandez, & Ruocco, 2012) during the end of the semester.

3.9 Data Collection and Analysis Procedures to respond to Research Question 1

To answer the Research Question 1, the researcher analysed the course outline of the chemistry units for the first year undergraduate programme to see how the learning outcomes were articulated with respect to an active learning pedagogy like POGIL in terms of process skills and graduate attributes. The curriculum documents and POGIL activity materials were analysed to identify the relevant graduate attributes and POGIL process skills that the instructors aimed to target during the implementation process.

3.10 Data Collection and Analysis Procedures to respond the Research Question 2

To answer the Research Question 2, the researcher observed the actual implementation of modified-POGIL in lecture and tutorial sessions. Qualitative data were obtained from semi-structured student interviews and students' responses to the open ended items of SALG.

3.11 Data Collection and Analysis Procedures to respond to Research Question 3

One instrument was used to gather data for the quantitative analyses of this study. The Stereochemistry Concept Diagnostic Test (SCDT) measured students' understanding of stereochemistry concepts. An outline showing the administration of the SCDT was illustrated in Figure 3.1. The SCDT was administered in semester 2 for Chem102 students in 2011. For Chem121 students, the SCDT was administered in semester 1, 2012.

Only 14 students participated in the delayed post-test of SCDT as it was administered just before the commencement of the examination preparation week. Pharmacy students study chemistry 121 during their first year and the module was taught by the same instructor who taught the organic chemistry part of chemistry 102. The fundamental difference between Chem102 and Chem121, (see Figure 3.1) is that, the instructor delivered Chem102 modules (Chapter 4) using POGIL interaction and the Chem121 modules (Chapter 4) were delivered via lecture mode. However, both cohorts used POGIL style worksheets. A summary of the final sample of students who participated in the study is presented in Table 3.3.

Table 3. 3: Summary of the final sample of first year chemistry cohort

Course	Semester	Number of participants		
		SALG	SCDT	
			Post-Test	Delayed Post-Test
Chem102	Sem 2, 2011	114	61	14
Chem121	Sem 1, 2012		79	64
Chem102	Sem 2, 2012	154		

3.11.1 Stereochemistry Concept Diagnostic Test (SCDT)

To identify students' understanding of stereochemistry concepts, a diagnostic test was developed by the researcher. The test consisted of 5 two-tier item questions. The questions on the test were adopted from organic chemistry text books (Straumanis, 2012a, 2012b) and are moderated by the chemistry instructor who has been teaching the course for several years and is also a co-author of first year general chemistry book (Blackman et al., 2008).

Limited availability of literature on studies relating to students' conceptions in stereochemistry and non-availability of a validated two tier diagnostic instrument which can effectively elicit students' misconceptions has motivated the researcher to prepare the stereochemistry concept diagnostic test (SCDT).

The researcher used Treagust's (1988) guidelines to develop the SCDT; namely to:

- examine the literature for possible difficulties in conceptual understanding of a particular topic
- conduct informal interviews to attain a broad outlook of students' understanding
- develop 2-tier diagnostic test items, where the first part has content specific statements and the second part has reason specific items that primarily project students' understandings, misunderstandings or misconceptions.
- refine the developed assessment

To ensure the development of representational competence among the students, the instructor initially gave the students worksheets that featured practice questions (not SCDT items) on nomenclature of organic compounds, and structural representations of organic molecules during the workshops.

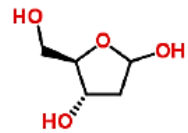
Post-Test: In the second semester of 2011, a week after the occurrence of POGIL lecture on aromatic chemistry that included principles of stereochemistry and chirality, the SCDT was administered to Chem102 students. The students were made aware of the purpose of the testing and they knew that their performance on the test had no effect on their semester result. The results of the test have never been shared with the students. The participants who volunteered were invited to take the test individually during the workshop session. A 20 minute time had been assigned and the test was held in a typical examination pattern where the students recorded their responses in the given answer sheet.

Delayed Post-Test: Two weeks later, the students were again invited to take the test as POGIL groups where they had an opportunity to collectively identify their best response and reason. For Chem121, the students had individually answered the delayed post-test without any POGIL interaction. The POGIL group roles were assigned and the students actively discussed the items before agreeing on their response-reason combinations. From a randomly chosen POGIL group, the student's discussion while answering the questions was captured using a Livescribe smartpen (Hannon, 2008). The researcher in a non-confronting way had the opportunity to interview the students to gain an insight into their actual understanding of the concepts that underpin the questions.

The two-week period between the post-test and delayed post-test did not involve any exclusive/follow-up teaching activity relating to stereochemistry. The instructors continued their routine lecturing and workshop schedule. The items of the stereochemistry concept diagnostic test attempt to identify how well students' understand the concepts of chirality, stereocenters, and stereoisomers. More information on these concepts is presented in chapter 5.

Examples of the SCDT are shown in Figure 3.2. The complete SCDT is available in Appendix B

Question 4
The 2-deoxyribose, a five carbon sugar component of DNA (deoxyribonucleic acid) which alternates with phosphate groups to form the backbone of DNA polymer has the following structure:



How many stereosiomers are possible for 2-deoxyribose?
a. 8 b. 6 c. 4 d.0

Reason
1. presence of 4 asymmetric carbons
2. presence of 3 stereocentric carbons
3. presence of 2 asymmetric carbons
4. 2^n rule is valid only to acyclic molecules

Question 5
What is the best way to describe the relationship between these two molecules

a. they are enantiomers
b. they are constitutional isomers
c. they are diastereomers
d. they are identical

Reason
1. they are non-super imposable, they are also mirror images
2. the molecules are not non- superimposable and also are not mirror images
3. these molecules have same molecular formula and different connectivities
4. they are superimposable and are not mirror images

Figure: 3. 2. Items 4 & 5 from the Stereochemistry Concept Diagnostic Test (SCDT)

Development of Stereochemistry Concept Diagnostic Test

For the development of SCDT, the researcher adopted the model for identifying students' conceptions in science, suggested by Treagust (1995), wherein the content for this study, stereochemistry concepts, was first explored to identify the propositional content knowledge statements followed by content validation of the items of SCDT against the propositional content knowledge.

The five questions of SCDT were chosen from the textbooks and other resources that the teaching staff use (Blackman et al., 2008) and they were content validated by the instructor who teaches organic chemistry, also, an ALIUS leader and co-author of the popular and prescribed reference book that most of the first year chemistry students either refer to or own a copy.

Propositional content knowledge statements

The required knowledge to conceptualise the principles of setereochemistry are stated as propositional content knowledge statements. The SCDT addressed 14 propositional content knowledge statements which are tabulated in Table 3.4.

Table 3. 4: Propositional content knowledge statements

SC1	Stereogenic atoms are also called chiral centers
SC2	Stereogenic carbon has four different groups around it
SC3	A molecule with an internal mirror plane is not chiral
SC4	A molecule with no internal mirror plane is chiral
SC5	Chiral molecule is not identical to its mirror image
SC6	Achiral molecule is identical to its mirror image
SC7	Enantiomer is a mirror image of a chiral molecule
SC8	Enantiomers are a pair of non-identical molecules that are mirror images of each other
SC9	Diastereomers are any two molecules that are not enantiomers
SC10	A meso compound always has two or more chiral centers and an internal mirror plane
SC11	Configurational stereoisomers have the same atom connectivity, but are not identical
SC12	Stereoisomers are molecules with same connectivity but different arrangement in space
SC13	The number of stereocenters in a molecule determines the maximum possible number of stereoisomers for that molecule
SC14	The formula $X = 2^n$ (n = number of stereocenters) is used to find the maximum number of possible stereoisomers

A test specification grid was developed (see Table 3.5) to ensure that the SCDT covered the propositional content knowledge statements. There are some SCDT items where the propositional statements remain implicit.

Table 3. 5: Specification grid of propositional content knowledge statement

Item	Propositional content knowledge statement
1	SC1, SC2, SC12
2	SC1, SC2, SC3, SC4
3	SC5, SC6
4	SC13, SC14, SC10
5	SC2, SC11, SC9, SC7, SC8

The SCDT included the associated aspects of stereochemistry like chirality, stereocenter, stereoisomer, molecular orientation at stereo-carbons, and ability to identify a chiral molecule on the basis of plane of symmetry, non-superimposable mirror image formation, and ability to estimate the possible number of stereoisomers from a stereocenter of the molecule. As described in chapters 3 and 4, due to varying degrees of background chemistry knowledge of the students, the researcher chose to administer the SCDT a week after the lecture on introduction to isomerism as a post-test, with an assumption that students will have had a learning opportunity to be familiar with the content.

The students will have answered the questions individually during the tutorial session. One point was awarded if both the response and reason were correct, no point was awarded if the student had chosen a correct response and an incorrect reason or vice versa. A total of 5 points are possible for the entire 5 itemed 2 tier SCDT.

Three honours students had volunteered to complete the stereochemistry diagnostic test as a trial test. Following the notification of a mutually agreed time, all these three students participated in the simultaneous individual trial testing. Of these three students, two were Forensic Science major students and another majored in nanotechnology; they all have studied chemistry for at least two years at undergraduate level. They all agreed to the correct answers to each questions and their positive feedback lead the researcher to re-confirm that the test items were precise and clear.

For the delayed post-test of SCDT, the selected POGIL groups also used the Livescribe smartpen to record their discussions and/or arguments as a think-aloud strategy. The Livescribe smartpen records audio digitally and connects it to the handwritten notes. The device allowed the group members to interact naturally without any distraction. The smartpen allowed the researcher to capture all diagrams or problems that were recorded by the POGIL group members and also what is being said while working on the diagrams or problems.

The following are the some of the questions chosen for the follow-up interview of SCDT: (see Appendix D for the complete transcript)

B) Group work; concept test and group problems

   2) "Tell me what it was like to work in groups on the Stereochemistry concept diagnostic test."

   3) "How did the answering of questions like this as a group affect your understanding of the chemical concepts being studied?"

C) In-class activity sheets, critical thinking questions and tests

   4) "Here is an example of an activity-sheet you have already taken in chemistry 102. What reasons would you use for deciding to answer this question?"

   5) "What reasons would you use for deciding not to answer this critical thinking question?"

Items in B are aimed at capturing students' feedback on the benefits of POGIL based small group learning. Items in C attempt to follow students' participation in POGIL related activity.

The following are some of the questions chosen for semi-structured individual interviewing of students: (see Appendix D for the complete transcript)

1.5 Do you think that the in-class small group activities are challenging?

1.6 Do you think the in-class group activities have helped you develop your critical/logical thinking? (making decisions based on information, analysing, comparing, synthesizing, and reasoning?)

1.7 Do you think that in-class group activities and argumentative discussions have provided opportunities to improve your written and oral skills in this course?

1.8 Are these small group discussions / in-class activities stressful and frustrating?

3.12 Data Collection and Analysis Procedures to respond to Research Question 4

A modified version of Student Assessment of Their Learning Gains (SALG) evaluated students reporting of their learning gains. The student assessment of their gains (SALG) instrument was administered to Chem102 students during semester 2 in 2011 and 2012.

3.12.1 Student Assessment of Their Learning Gains (SALG)

Designed by Seymour et al. (2000), the SALG instrument allows students to self-assess their learning in science classrooms particularly at the tertiary level. The customizable items in the SALG instrument have a 5-point Likert scale, giving students the opportunity to evaluate the elements of lecture and/or laboratory in terms of their own learning. According to Seymour et al. (2000), SALG provides average scores and standard deviations for responses to each statement and requests that students include verbal explanations for their responses to each main question.

The SALG was chosen because, when compared to other student evaluation instruments, Seymour et al. (2000) consider that the information gathered using the SALG instrument is more reliable and useful in negotiating changes in teaching methods with colleagues and it offers flexibility of inter-faculty use. The SALG instrument helps in eliciting the elements of the course that best support student learning and those that needs improvement. The SALG instrument helps instructors in obtaining students' anonymous responses on class content, teaching strategies, activities, assessment, materials, resources, organization and pacing.

The SALG instrument has 72 items; of these 62 items have a 5-point Likert scale for quantitative rating and for the remaining 10 items students given their feedback as a written statement.

Students completed the SALG immediately before the course final examination to provide their opinion on learning chemistry 102 in a POGIL environment and their perception of learning gains made by the small group process oriented guided inquiry learning. Student responses in each five categories were studied and written comments were analysed. Item 1 from the SALG is shown in Figure 3.3. The complete SALG is available in Appendix C.

Instructions:
Please fill in one box only for the following statements corresponding to the scale indicated by completely filling the circle ● with a blue or black ballpoint pen.

		no help	A little help	Moderate help	Much help	Great help
1	**HOW MUCH did the following aspects of the class HELP YOUR LEARNING?**					
1.1	Attending class	1	2	3	4	5
1.2	The pace of the class	1	2	3	4	5
1.3	Working with peers during class	1	2	3	4	5
1.4	Working with peers outside of class	1	2	3	4	5
1.5	Explanation of how the class activities, reading and assignments related to each other	1	2	3	4	5
1.6	Explanation given by instructor on why the class was organised into groups	1	2	3	4	5
1.7	Explanation of why the class focused on the topics presented	1	2	3	4	5
1.8	Connecting key class ideas with other knowledge	1	2	3	4	5
1.9	Small Group Activities in this class help my learning	1	2	3	4	5
1.10	Participating in discussions during class	1	2	3	4	5
1.11	Listening to discussions during class	1	2	3	4	5
1.12	Participating in group work during class	1	2	3	4	5
1.13	The number and spacing of tests	1	2	3	4	5
1.14	The way the grading system helped me understand what I needed to work on	1	2	3	4	5
1.15	The feedback on my work received during and after tutorials	1	2	3	4	5

1.16 Please comment on HOW the INFORMATION YOU RECEIVED about the class helped your learning.

1.17 Please comment on HOW OFTEN YOU PARTICIPATED in class discussions and HOW THE ATMOSPHERE IN THE CLASSROOM ENCOURAGED OR DISCOURAGED your participation

Figure: 3. 3. Item 1 from Student Assessment of Their Learning Gains questionnaire

Students were asked to evaluate their gains in learning on a scale from 1 to 5. (1 indicates no help, 2 indicates a little help, 3 indicates moderate help, 4 indicates much help and five indicates great help)

The study used Structural Equation Modelling (SEM) to investigate the student perception of their learning in a POGIL class. Described as "a hybrid of factor analysis and path analysis" (Watson & Gore, 2006, p. 720), SEM allows the researcher to design, test and confirm models of complex relationships (Gallagher, Ting, & Palmer, 2008). The "measurement model" of SEM allows the researcher to assess how well the variables represent the unobservable (latent) construct, whereas in the "structural model" the researcher estimates the strength of the relationships amongst these unobservable constructs. Researchers describe these relationships among latent variables as covariances, direct effects, or indirect (mediated) effects. In other words, SEM helps in testing causal relationships for the validation of instruments (Gefen, Straub, & Boudreau, 2000).

Analysis of Moment Structures (AMOS) software was used for the confirmatory factor analysis of SALG survey as it has an easy user interface and is bundled to the SPSS package which was readily available to the researcher. AMOS produces statistical details that describe the fit of the measurement model and the significance of parameter estimates obtained from the structural model.

3.13 Qualitative Data Analysis

For chemical educators, qualitative research is inductive, that is the data were used to develop a theory based on the patterns of observed phenomena (Phelps, 1994). For qualitative researchers who study meaning, their obligation lies not only on eliciting the meanings that the individuals hold but also experiences and feelings they ascribe to such constructions of meaning. Successful qualitative research primarily depends on the authentic representation of participants' perspectives in the research process and the interpretations from the gathered information and the coherence of the findings (Fossey, Harvey, McDermott, & Davidson, 2002).

The study used qualitative analysis approaches suggested by researchers (Bretz, 2008; Ezzy, 2002; Hsieh & Shannon, 2005; Pope, Ziebland, & Mays, 2000; Sandelowski, 1995; Tesch, 1990) to analyse, interpret and understand the meaning of qualitative data. A combination of inductive and deductive approaches such as content analysis and thematic coding were utilised to generate patterns and categories from the data for the purpose of responding to research questions (Bruck, Towns, & Bretz, 2010; Fereday & Muir-Cochrane, 2008; Selepe, 2011). Content analysis begins with predefined categories whereas thematic analysis allows categories to from the data.

Themes are abstract constructs that investigators identify before, during, and after data collection. Coding in thematic or content analysis refers to identification of themes or concepts that are in the data from where the relevant theory emerges. The success of content analysis greatly depends on the coding process because the researcher uses predetermined themes and categories and it restricts the researcher in the analysis of other themes and categories that emerge from the data that could add value to the study. Concurrent use of content and thematic analysis allows the emergence of new categories from the data inductively. In this study, the issues of interest for analysis were the students' perceptions on learning chemistry in a small group POGIL format.

Qualitative data obtained from this study were mainly used to triangulate, confirm or contrast results and findings from the quantitative data. The predetermined themes used for categorising students' responses were similar to the scales of SALG.

All qualitative data from the students' written responses in SALG questionnaire and students' interview transcripts were analysed using QSR NVivo version 9. The qualitative research software, NVivo was designed and developed by QSR International to explore patterns, identify themes and develop meaningful conclusions (NVivo, 2012). To start with, the transcribed interview data were transferred into NVvio document files. Then, textual information storing 'nodes' were generated by both a priori coding (deductive and predetermined) and generative coding (inductive and stemming from data) from the data (Georgiou & Sharma, 2012). The Nodes contain themes that enable the investigator to answer the research questions. Themes were systematically reduced and analysed in an effort to organise the data specific to the research goal (Ozkan, 2004).

3.14 Methods used for Data reliability and validity

3.14.1 Triangulation

Used as data analysis technique in multi-method research designs, triangulation is regarded as a combination of more than one data sources. Duffy (1987) defined triangulation as multiple methodological study of a phenomenon. According to Thummond (2001), triangulation varies according to the nature of the source of data such as investigators' triangulation, theoretical triangulation, analytical triangulation and methodological triangulation and further inferred the use of quantitative and qualitative strategies in the same studies as a means of triangulation to obtain complimentary research results.

Investigators' triangulation features the comparison of findings of several investigators originating from a particular study. Duffy viewed that the use of more than one investigator not only eliminated the potential bias but also ensured greater reliability. Theoretical triangulation involves the analysis of the same data set to test several theories or hypotheses. Analytical triangulation attempts the data exploration using a set of statistical techniques for validation.

The multi-method triangulation that determines data convergence in support of a phenomenon increases the validity of research findings (Janice, 1999), thus providing analysis opportunities not available through the use of a single method.

3.14.2 Reliability of the instruments

Reliability refers to the extent to which the results or observations of assessments are consistent. Carmines and Zeller (1979) described the stability with which the instrument items are answered or the individual's scores remain relatively the same in repeated measurements as reliability. A higher degree of stability indicates a higher degree of reliability, establishing the repeatability of the results. The reliability of SALG instrument was estimated by computing the Cronbach's alpha value. Mamo, Kettler, Husmann, and McCallister (2004) have reported an acceptable Cronbach's alpha value of .97 from their reliability studies of SALG in introductory soil science class.

3.14.3 Validity of the Instruments

This study has attempted to establish construct validity for the Student Assessment of Their Learning Gains, SALG, survey following the framework of Trochim and Donnelly (2006), who emphasised translation and criterion-related validity requirements.

An instrument is said to be valid when it truly measures what it is intended to measure. Construct validity is the extent to which the test provides accurate information about the concept of theory being assessed. The Figure 3. 4 represents a framework proposed by Trochim and Donnelly.

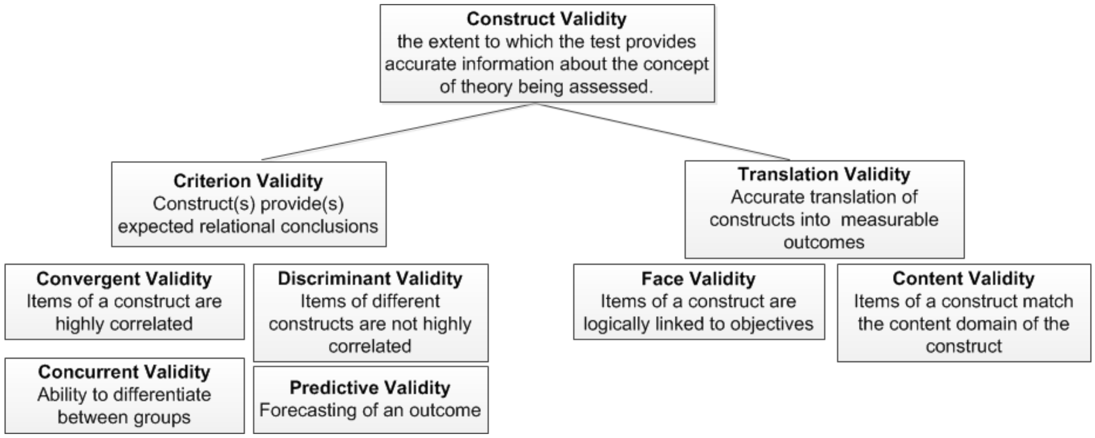


Figure: 3. 4. Framework for construct validity (Trochim & Donnelly, 2006)

According to Trochim and Donnelly (2006) an instrument is said to possess high construct validity if it can establish *content* (assessment of the items with respect to the extent of coverage of the construct), *face* (assures that each question or item on the scale have a logical link with an objective), *convergent* (high correlation of items of a particular construct), *discriminant* (items from different constructs are not correlated), *concurrent* (how well an instrument compares with a second assessment) and *predictive validity* (extent to which the instrument can forecast an outcome).

The Cronbach alpha coefficient was measured for each factor to estimate the internal consistency reliability. The criterion validation of SALG survey was established using factor analysis. Factor analysis helps to identify related survey items, expecting to produce similar answer patterns. Factor loadings indicated how strongly each item was related to a particular factor, the relative importance of each factor was indicated by eigenvalues, retaining of sufficient number of factors was based on the cumulative variance (Muijs, 2011). The factor loadings and internal consistency reliability revealed convergent validity of SALG survey.

Attempts to establish validity of the Stereochemistry Concept Diagnostic Test, SCDT, were centered on its content validity using expert opinion and checking the items with propositional knowledge statements to ensure that the internal items are consistent. For construct validity group differences were studied including the difficulty index.

3.15 Summary

This chapter described the research questions, research design, research paradigm, participants, and data collection methods. An overview of the three types of data collection instruments, their sample items, and how they were developed was described. Methods of quantitative and qualitative data analysis were also discussed. The results of the data collected from the data sources described in this chapter were analysed, interpreted and presented in the following chapters.

Chapter 4
The Intended and Implemented Curricula

4.1 Introduction

Section 4.2 answers the first research question (RQ1): How do the skills that students learn in POGIL classroom align with university graduate attributes, by describing the intended curriculum of chemistry from the course outline and providing documentary evidence of the intended learning outcomes and the targeted graduate attributes. Section 4.3 presents an introduction to the graduate attributes and the university's policy statement on graduate attributes. Section 4.4 describes the process skills that instructors intend to target in a POGIL class and their relevance to the graduate attributes that were outlined in the intended curriculum.

Sections 4.5, 4.6, 4.7 and 4.8 answer the second research question (RQ2): In what ways do students perceive their learning while engaged in POGIL classes, by describing the implementation of curriculum via the POGIL approach. Section 4.6 describes the features of POGIL activity sheets used in the observed lectures. Section 4.7 presents the details of the researcher's observation of the two lectures and tutorials that were focused on the POGIL method. Section 4.8 describes the students' acquaintance of the process skills in a POGIL class.

Higher education institutions are autonomous in designing, implementing and assessing the outcomes of their programmes (Henard, 2010). In other words, universities have their own approved curriculum framework containing faculty approved course descriptions (Mills, 2002). In Australia, the Tertiary Education Quality and Standards Agency (TEQSA) is the regulatory body for the higher education standards framework, including teaching and learning standards. Many universities in Australia consistently review and redesign curricula that reflect the objects of the TEQSA act (Reedman, 2011).

This research focused on the first year undergraduate chemistry course designed and implemented by the Department of Chemistry at Curtin University in the years 2011 and 2012 in an attempt to answer the first two research questions in the study discussed above. To answer the first research question, the researcher analysed the course outline of the chemistry units for the first year undergraduate programme to determine how the learning outcomes were articulated with respect to an active learning pedagogy like POGIL in terms of process skills and graduate attributes (see Section 4.2 to 4.4). To answer the second research question, the researcher observed the actual implementation of modified-POGIL in lecture and tutorial sessions (see Section 4.5 to 4.8).

4.2 The Intended Curriculum

4.2.1 Course Units

The first year chemistry course comprised two units, Chemistry 101 in semester 1 and Chemistry 102 in semester 2. The course unit coordinators and unit delivering teaching staff of the department collectively designed the content of the course unit. After an approval process from the respective department and the university academic board, the approved unit outline is distributed to the students at the start of the semester. The unit outline document (Appendix: E) contains information on topics to be covered, unit learning outcomes, graduate attributes, pedagogical interventions used, essential and recommended textbooks and other reading, assessment schedule, grading details, assessment policies and the programme calendar for the semester (Curtin University, 2011c). For some students, Chem101 and Chem102 provide the chemistry required by their major area of study, such as engineering. For other students, Chem101 and Chem102 provide review and preparation for subsequent Chemistry classes during their second and third year undergraduate programmes.

The topics of principles of quantitative analysis, sub-atomic structure, quantum numbers, spectroscopy and nuclear chemistry, thermodynamics, bonding theories, molecular and ionic equilibria and coordination chemistry are covered in chemistry 101 (Curtin University, 2011a). In chemistry 102 (Curtin University, 2011b), during the second semester, the students learn topics in instrumental analytical chemistry, intermolecular forces, redox reactions, hydrocarbons, chemical kinetics, substitution reactions, carbonyl compounds and biologically important molecules. The textbook titled 'Chemistry', authored by Blackman et al. (2008) was prescribed to students as a learning resource. Students who have completed Year 12 chemistry or equivalent are eligible to study the units; however, students without the required level of chemistry knowledge are expected to complete a foundation level course in chemistry. The topics for the course are listed in the Table 4.1.

Table 4. 1: List of topics covered in Chemistry units 101 and 102

Chemistry 101 **Semester 1**		**Chemistry 102** **Semester 2**
Module D: Principles of analytical chemistry *Module E:* Thermodynamics *Module F:* Equilibria	**Traditional**	*Module B:* Intermolecular forces *Module C:* Redox reactions *Module E:* Kinetics
Module A: Atomic theory and nuclear chemistry *Module B:* Bonding *Module C:* Coordination chemistry	**Active learning**	*Module A:* Instrumental analytical chemistry *Module D:* Hydrocarbons *Module F:* Substitution and elimination reactions *Module G:* Carbonyl compounds and biologically important molecules

Some of the content was delivered via traditional lectures whereas some modules (as listed in the Table 4.1) were delivered by a modified POGIL approach that mixed lecture presentations with small group activities in the lecture theatre and tutorial sessions. A programme calendar handed out to the students was included in the Appendix F, and an extract of the same is presented in Table 4.2.

Table 4. 2: Extract from the programme calendar for chemistry 101 and 102

Week	Lecture 1	Lectures 2/3	Tutorial	Other
Chemistry 101				
2 (7 Mar)	Module D: Principles of analysis	Module A: Atomic theory	Tutorial 1 (Module D)	
3 (14 Mar)	Module A: Atomic theory	Module E: Thermodynamics	Tutorial 2 (Module A)	Quiz 1 (A/D)
4 (21 Mar)	Module E: Atomic theory	Module A: Atomic theory	Tutorial 3 (Module A)	
Chemistry 102				
2 (25 Jul)	Module B: Intermolecular forces (3 lectures)		Tutorial 1 (Module A)	
3 (1 Aug)	Module C: Redox (3 lectures)		Tutorial 2 (Module B)	
4 (8 Aug)	Module B: Intermolecular forces (3 lectures)		Tutorial 3 (Module C)	Mid-semester
5 (15 Aug)	Module D: Hydrocarbons (9 lectures)		Tutorial 4 (Module B)	Test1 (Modules A, B, C)

4.2.2 Learning Outcomes

The learning outcomes at university level provide the details of knowledge, skills and abilities that students will develop during their chosen course of study. The learning outcomes that were provided to the students in the unit study package for Chemistry 101 and 102 units are presented in Table 4.3 (refer Appendix E).

The learning outcomes are linked to the graduate attributes, which are contextualised, embedded and assessed in every unit and course. However, according to Barrie (2004), the curricular approach of the academic staff varies with their understanding of graduate attributes.

Table 4. 3: Learning outcomes and targeted graduate attributes – extracts from course units Chemistry 101 & 102

Learning Outcomes	Graduate Attributes addressed:
Chemistry 101 (Semester 1)	
1. Critically evaluate atomic theories and apply them to predict bonding within and properties of matter.	
2. Calculate the physical reactivity and energetics of matter	
3. Employ the principles of quantitation to determine uncertainty in measurement.	
4. Apply molecular-centric logical skills to discipline-specific problem solving	
5. Employ experimental and analytical skills in the correct and safe use of laboratory equipment, individually and within a group.	
Chemistry 102 (Semester 2)	
1. Apply the basic principles of kinetics to solve problems in theoretical and practical contexts.	
2. Identify common functional groups and describe their principle reactions, their mechanistic pathway and predict the products of such reactions.	
3. Predict physiochemical properties of matter from their intermolecular forces.	
4. Use of internationally recognised conventions in the communication of chemistry, including nomenclature, graphical and symbolic representation of molecules.	
5. Efficiently and safely perform a range of laboratory procedures, including analysis, synthesis, isolation and purification.	

Note: The graduate attribute icons were taken from the web page of Curtin Teaching and Learning

4.3 Graduate Attributes

In the Encyclopedia of Sciences of Learning, the *graduate attributes* or *university learning goals*, are described as:

> *'generic outcomes that all graduates are supposed to have learned as a result of their education. Such attributes include lifelong learning, creativity, critical thinking, professional knowledge and skills, intellectual autonomy, and independent problem solving as appropriate to a student's area of specialization'.* (Steel, 2012, p. 1383)

The generic skills, often called graduate attributes at university level, refer to thinking skills such as logical and analytical reasoning, problem solving and, intellectual curiosity, communication skills, teamwork skills, information processing skills, personal qualities like imagination, creativity and values of ethical practice (Hager & Holland, 2006). With the advent of the technological and knowledge economy, the employers and organisations, nowadays, are emphasising the possession of such skills of employability amongst the new graduates.

The expectations and development of student skills were introduced into the guidelines of the university (Curtin Teaching and Learning, 2010). The graduate attributes policy stated that: "*all graduates will have developed during their course in order to equip them for the future. Student achievement of the graduate attributes is accomplished through implementation of outcomes-focused education".* Curtin's policy statement on graduate attributes is illustrated in Figure 4.1.

The graduate attribute statements reveal the status of the institution's position in influencing the values and attitudes of its students (Shephard, 2008). Policy statements listing graduate attributes ideally reflect a layered or staged development of such attributes (Barrie, Jain, & Carew, 2003).

Apply discipline knowledge: Understanding theoretical underpinnings and ways of thinking; extend the boundaries of knowledge through research.

Communication skills: Communicate in ways appropriate to the discipline, audience and purpose.

International perspective: Think globally and consider issues from a variety of perspectives; apply international standards and practices within a discipline or professional area.

Thinking skills: Apply logical and rational processes to analyse the components of an issue; think creatively to generate innovative solutions.

Technology skills: Use appropriate technologies recognising their advantage and limitations.

Cultural understanding: Respect individual human rights; recognising the importance of cultural diversity particularly the perspective of Indigenous Australians; value diversity of language.

Information skills: Decide what information is needed and where it might be found using appropriate technologies; make valid judgements and synthesise information from a range of sources.

Learning how to learn: use a range of learning strategies; take responsibility for one's own learning and development; sustain intellectual curiosity; know how to continue to learn as a graduate.

Professional skills: Work independently and in teams; demonstrate leadership, professional behaviour and ethical practices.

Figure: 4. 1. Curtin graduate attributes

4.4 POGIL Process skills

POGIL lessons and activity sheets are designed to target the development of specific process skills, namely, *cognitive process skills* - information processing skills, critical thinking and problem solving; *group process skills* – management, communication and teamwork (Bauer & Cole, 2012). The intended and identifiable student actions aimed at the development of process skills during any POGIL activity are listed in Table 4.4 (POGIL Project, 2008b).

Table 4. 4: POGIL process skills

Process skill	Identifiable Student Actions
Communication	articulating an idea, rephrasing, reporting and writing with technical skills
Teamwork	collaborating, keeping group members at same pace, responsibility for group concept development, group decision making, building consensus, sharing ideas
Problem solving	accepting challenge, applying prior knowledge, imagining, identification of problem, key issues, assumptions
Critical thinking	making decisions based on information, analysing, comparing, synthesising, and reasoning
Management	self-managing and group managing, time consciousness, asking questions on behalf of group
Information processing	using information to think, interpretation of graphs and diagrams, assessing the perception of correct information
Assessment	self-assessment and assessment of other's responses

As outlined in chapter 2, the philosophy of POGIL and the ongoing POGIL research indicate that the process skills developed from the small group active learning strategies like POGIL may academically be aligned to graduate attributes at any institution. A model to illustrate the alignment of graduate attributes and POGIL process skills in the Chem101 and Chem102 units as evidenced from the observations of POGIL classroom is presented in Table 4. 5.

The fit between graduate attributes and the POGIL process skills was closely examined by following the classroom proceedings and especially observing students' interactions within the groups. Both graduate attributes and the POGIL process skills focus on students' ability to effectively communicate within the discipline. The reporter's role is very effective in collating the outcome of the group discussions and presenting then to the entire class. The following excerpts from the open-ended statements of SALG indicate that students considered the importance of the skill of communication in POGIL interactions:

better communication, learning to tackle problems, communication, logical questioning and more independent thinking, communication skills among peers, interpersonal skills, a lot of improvement there.

The fit between graduate attributes and the POGIL process skills in terms of collaboration, teamwork and group discussion is coherent as indicated from the classroom observations and students' feedback. The icebreaker strategy implemented by the instructor not only inculcated the aspect of collaboration through teamwork instantly but also worked as a very powerful move to bring students together. The frequent rotation of group roles among the students provided an opportunity for every student to experience and develop professional skills. The following excerpt from the students' interviews provides evidence to the fit between graduate attributes and POGIL skills:

I am comfortable with all that kind of thing. Absolutely, I mean, it is not just a little about learning, it is also about the socialisation part.

A similar trend was observed for thinking and information skills from the information presented in the Table 4. 5.

Table 4. 5: Alignment of graduate attributes and POGIL process skills as evidenced from POGIL class observations

	Graduate Attributes	Process Skills	Observations from POGIL classes
Communication	Communicate in ways appropriate to the discipline, audience and purpose	Articulating ideas, reporting and rephrasing	At the end of the allocated time for the completion of a POGIL activity model, the reporter from each POGIL group was invited to answer a specific critical thinking question (if it involved an organic structure / reaction, students were advised to draw its representation on the whiteboard) and the instructor randomly asked other reporters to comment on how they had answered that particular question / model. Depending on the outcome of the discussion, the instructor may either choose to explain the concept further or direct the POGIL groups to move to the next model. The reporters appeared to be actively listening to the other members of their group while preparing their own answers to the expected questions.
Professional Skills	Professional skills, collaboration, teamwork, and safe use of laboratory equipment	Collaborating, keep group members at same pace, group discussion, building consensus, sharing ideas	For every group, at the start of the POGIL session, the instructor recruited a manager by posing some motivating questions like *"a person who went to the school close to the university" or "a person whose month of birth is lower will be the manager today"*. The strategy worked as an icebreaker. The manager ensured that the group members stayed on task and encouraged the members to arrive at a consensus, in case of any argumentative discussion. In practice, some inter-group conversations also took place mainly to compare their work and confirm their answers before the instructor called the reporters to present their findings. The laboratory work also offered POGIL groups the opportunities for teamwork and collaboration in the form of setting up of the equipment, recording observations, cleaning of the equipment, and discussions to complete the laboratory report. The excerpts from student interviews (*CS3*, *CS4*, and *CS7*) presented in 4.8 support the views of the students on the importance of the professional skills

(Table 4.5 continues)

(Table 4.5 continued)

Thinking Skills	Application of content- specific logical skills to discipline specific problem solving	Critical thinking skills: making decisions based on information, analysing, comparing, synthesising, and reasoning	The characteristic feature of POGIL materials is that they are highly structured and organised as models containing several critical thinking questions (CTQs). The students were guided through these CTQs using clickers to solicit their responses in identifying, developing and applying the concepts. As shown in Appendix G, the CTQs presented in 3.1 and 3.2 provide the students an opportunity to explore the models and identify and revise the essential concepts like the central atom valence electron (CAVE) method to determine the number of electron domains in covalent compounds and valence shell electron-pair repulsion (VSEPR) to predict molecular geometry. This sequential way of reviewing the pre-requisite knowledge helped the students to overcome any perceptive difficulties (arrangement of electron pairs and molecular shape) that they may have encountered. Responding to a question on the importance of CTQs and discussion in the class, CS6 said: *The diagrammatical representations. I see. So in the activity sheets, there are many graphs, charts and tables given. I think they are helpful in identifying the trends. So if one is going the wrong way, so you could get hold of him or her, saying that (hey) this is true. You are thinking side-ways. This is the conceptual basis for that. (CS6)*
Information Skills	Deciding on the nature and scope of the presented information, making valid judgements and synthesising information from a range of sources	Information processing: Using information to think, interpretation of graphs, assessing the perception of correct information	POGIL materials are usually written following the learning cycle paradigm that consciously develops particular learning skills in students. As shown in Appendix H, the students are expected to understand and predict the chemical reactions/mechanisms from the given information. The skill of information processing is not exclusively taught in POGIL classes, but the students make use of the given data or information to identify the concepts. The model 3 in the Appendix is one such example where the students understand the concept of nucleophilic substitution and recognise S_N1 and S_N2 reactions by carefully examining the given data.

The practice of process skills, according to Straumanis (2010), helps students learn the content and create new transferable chemistry knowledge. Simonson and Shadle (2013) viewed that the task of writing POGIL activities and the synchronisation of the learning objectives with the targeted process skills is a challenging and labour-intensive activity until they are refined. Further, Anderson and Rogan (2011) argued that there is a greater responsibility for the teaching staff when they seek innovative pedagogies, select appropriate curriculum components and achieve successful implementation. Coleman and Lang (2012) proposed *collaboration across curriculum*, emphasising a curriculum-wide approach to develop collaboration skills. Further, Coleman and Lang suggested the development of the intended collaboration skills as an integral part of the natural progression of students' course work. Burke, Lawrence, El-Sayed, and Apple (2009) viewed process-oriented education as:

> *Integration of the tenets of constructivism with personal development, performance measures, and assessment in order to produce learner growth, promote critical thinking, and nurture continuous improvement. (p.37)*

The alignment of process skills and the graduate attributes could be evidenced from the nature of the POGIL activities. As shown in the Appendices G and H, the POGIL materials are highly scripted and provide opportunities for the development of specific process skills at various levels during the lectures and workshops. These POGIL materials were carefully structured by the instructors who had rich experience in implementing POGIL. Another significant contribution that ensured the cohesiveness of graduate attributes and process skills was that both instructors had the independent responsibility to design the unit modules.

4.5 The Implemented Curriculum

The Department of Chemistry at Curtin University are leaders in implementing active learning strategies in first year chemistry course units. The teaching staff had developed and adopted POGIL (Moog & Farrell, 2011) activities for use in the first year units. The programme calendar outlined in the Appendix F showed that the each semester is approximately 14 weeks long with two tuition free weeks happening at week 9 and week 14. Students attend two lectures, one tutorial/workshop, and a three hour laboratory session per week. Students were expected to take a mid-semester examination during weeks 6 and 7, and end of semester examinations during weeks 15 and 16. The preliminary lecture was intended to develop an understanding of the unit structure, information on the nature of the pedagogies used, followed by an introduction to the small group active learning strategies that the teaching staff intended to utilise for selected sections of the unit. There were no distinct POGIL and non-POGIL classes.

The main source of data for answering the second research question, RQ2: How can the learning requirements be implemented through a POGIL based curriculum, came from the researcher's observation of lectures, tutorial sessions and interviews with selected students. Of the several lectures observed, two lectures were chosen to explore the implementation of POGIL aspects. Lecture 1 focused molecular geometry and shape and the lecture 2 focused curved-arrow processes. Both these lectures were presented by different POGIL practitioners.

4.6 Activity Materials

The POGIL activity materials included a short introduction to the theme/topic, learning objectives and the details of study resources. Activity 3 (Appendix G) used in lecture 1 on molecular geometry and shape has three models, each targeting a learning objective that the staff member intended to develop. The three learning objectives included were model 3.1 – calculating the number of electron domains, model 3.2 – determining geometry and shape, and model 3.3 – bond angle and electron domains. Each model has several critical thinking questions. For example, activity 3 included 30 critical thinking questions and five homework problems. The time required to complete the activity was 60 minutes in the class and 60 minutes outside the class, for homework. The Chem102 Activity – F3 (Appendix H) used in lecture 2 has 5 models. The content that covered these models broadly were classification of curved-arrow processes and nucleophilic substitution reactions.

4.7 Researcher's Observations

Lecture 1

A typical lecture session began with the academic member making announcements and introducing the topic and handing out activity sheet 3 (Appendix G) on molecular geometry and shape to the students who were seated in groups of 3 or 4.

The instructor sequentially refreshed the students' background knowledge using a mini-lecture on electronegativity, its definition, and the periodic trends of electronegativity, the relationship between electronegativity and bonding, definitions of ionic bonding, covalent bonding, bond length, and bond energy. Before directing the students to activity 3, the instructor once gain quickly presented the lecture slides containing the information on the method of determining electron domains, identifying the central atom in covalent compounds and multiple bonds, and method of estimating the total electron domains.

The students were then asked to look at model 3.1 of activity 3 and, as a group, answer the critical thinking questions 1 to 3. While the students answered the questions, at each stage, the academic staff member posed a clicker question to verify their understanding of the concepts. Students were expected to tender their chosen response within 20 seconds using the clicker device. A sample clicker question containing the results of students' response is shown in Figure 4.2. After the allocated time had passed, following the students' responses to the clicker question, the academic member led a whole class discussion of critical thinking questions. At the request of the instructor, the designated reporter from each group shared the groups' reasoning to the critical thinking question. The instructor provided a mini-lecture to explain the concept of using Central Atom Valence Electron (CAVE) method of determining the number of electron domains when 18% of the students gave an incorrect answer.

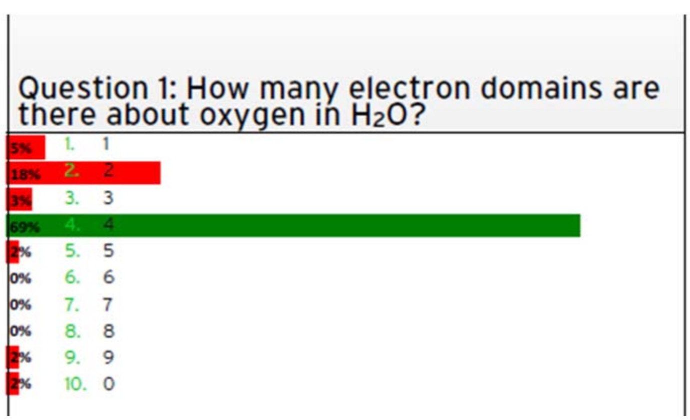


Figure: 4. 2. Students' responses to a clicker question

At this stage, the instructor directed the students to answer the remaining critical thinking questions of the model 1 in small groups, thus continuing the cycle of student discussion, clicker questioning, and mini-lecture. The academic member walked around the lecture hall offering advisory help to the students while they actively discussed and answered the remaining questions.

Lecture 2

An activity (Appendix H) on curved-arrow processes was used to describe the mechanistic concepts like bond breaking and bond making processes and their application in understanding the nucleophilic substitution reactions. Model 1 of the activity provided some examples of how chemists use curved arrows. The students were advised to discuss the mechanism as a POGIL group and answer the questions given under model 1. The instructor used clicker questions to provide an opportunity for students to defend their answers. The instructor preferred the students to struggle first, if they had not understood the question, then he gave an explanation via a mini-lecture. The students' acquaintance of the language from the introductory activity on the arrow pushing mechanism guided them to apply their knowledge to solve problems in other modules that focussed the reactions of alkenes, alkyl halides, alcohols, aldehydes and ketones. In other words, the activity may have helped the students increase their understanding of curved-arrow processes and their proficiency of using this knowledge to solve other problems related to the nucleophilic substitution reactions. The instructor used the clickers to generate opportunities for discussions and the activity was further continued as a tutorial task where the students were supposed to hand in for grading.

Tutorial

About 25 to 30 students attended the tutorials/workshops once every week during the semester. The seating plan was more organised as compared to the large lecture theatre wherein four students work as a small group, organised by two facilitators. At the start of the tutorial the facilitators invited the reporters from every group to identify any question/item with which their group needed help. Then the instructor individually facilitated each group's completion of the activity. At the end of the tutorial/workshop, the instructor collected the students' answer scripts for marking and further individual feedback. The following excerpt illustrates a student reflecting on the merit of working in a small group for construction of knowledge.

> *In the tutorials it was really helpful, because if you don't know how to do it, then you can speak to your group, and if somebody does know how to do it then they can explain what they think, but it is not necessarily right (it could be wrong), so at least you've got your tutors as well that you can all double check if nobody's sure about anything. So ultimately it worked in a sort of hierarchy, I guess. (CS5)*

> *If the question is different to what we have been thinking of, the tutor or facilitator is capable of directing us to the right conceptual thinking, which in turn leading to a feeling of success that we are heading towards the right answer. (CS4)*

Based on the observations from POGIL classes listed in Table 4.5 and the proceedings of the POGIL sessions mentioned in Section 4.7, it is proposed that a modified POGIL approach in the form of embedded mini-lectures, small group POGIL discussions, followed by clicker questions appeared to be an appropriate way of implementing the intended process skills along with chemistry content knowledge.

4.8 Process Skills

The development and acquisition of process skills were implemented within the curriculum. There was no specific incident or assessment that was linked to the process skills because most of the graduate attributes were described in the curriculum outline as targeted throughout the course. However, the development of learning requirements from the implemented curriculum was illustrated by various comments from the student interviews.

> *POGIL style interaction reinforces the use of information processing skills like interpretation of data from graphs etc. though the skills were gained in the engineering stream. (CS2)*

Integrated with the development of information processing skills was the development of communication and teamwork skills that was illustrated by several students in response to the open-ended statements of the SALG instrument, for example:

> *The skills like teamwork, problem-solving, connecting ideas, communication, logical questioning are transferable beyond the coursework and prepares students for work-related tasks. (CS3)*
> *This class let me gained the skills which I can connect some knowledge to others what we had learnt before. (CS7)*
> *Small group discussions help me pick-up the concepts quickly and the ability to walk in the lecture room help us share ideas and develop problem solving skills. (CS4)*

These examples indicated that students collaborated with the members of their POGIL groups as well as sharing ideas and discussions across other groups. The skills of management and critical thinking are considered necessary for successful learning in a POGIL class. The structured or semi-structured small groups offered tasks for the group members to efficiently manage the dynamics within the group. The instructors at the start of the tutorial/workshop swap the roles of the students for every session in order to give every student an opportunity to perform the various POGIL group roles. The following excerpts from student interviews gave an indication of the use and development of the skill of group management and critical thinking in the POGIL class.

> *The activities are more enjoyable when every group member puts an effort to achieve the most out of it. The benefit of working in an intelligent group is that you do not need to put in any effort. You could know how to do it but learning from them by looking at what they do. I generally feel more comfortable learning from friends. When we answer the questions as a group, generally one person who knows most of the topic leads the group hence there would not be any disagreement. (CS7)*

Well the critical thinking questions, they do help me understand the content, because they do make you think… well what is annoying is that you don't really get, like, answers to it, so you don't know if you're right or wrong. I think it has helped me quite a bit, because chemistry is quite an organised unit, I think it makes you answer the questions and forces you to think. (CS6)

Students' ability to self-assess their own and others' responses is another critical skill required for successful learning in POGIL class. To enforce the practice of the skill, the instructor in a lecture often used clicker questions to initiate a whole-class discussion amidst POGIL activity or in workshops, the tutor/facilitator visited every POGIL group assessing the students' grasp of the material. Several students illustrated the development of this skill through the use of clicker questions in the class.

Yes, it is good, because you know which question you have answered, and then you get feedback as well if you got the questions right. (CS6)

I love clickers. Nowadays, like in the activity, that we have questions, challenging questions. So that means that you can make mistakes and clickers can help you revise stuff during the study and understanding. (CS4)

Yes. I think so. I mean the fact that general arguing doesn't occur within the group, or even across groups, and one group thinks one thing, another group thinks the other, then we kind of work out the answer between ourselves. That is where the clicker questions come in to help us, because they kind of reinforce that knowledge. (CS2)

When you get stuck on something, you can ask someone and say, oh, what did you get for this one? Can you give me a hand with this, sort of thing, and I think there were more things like group related self-assessment perhaps, help you prepare for the examinations…. (CS8)

Hence, the researcher's observations of the lecture, tutorial/workshop and the student interview data add further evidence to that of the intended curriculum, with respect to student development of the process skills necessary for a POGIL class to be implemented. As will be shown in Chapter 6, a Pearson correlation value of 0.79, significant at the 0.01 level (2- tailed), between the students' mean scores for the scales of process skills and active learning on the SALG instrument indicated that the implementation of POGIL strategy may have helped the students' development of process skills.

4.9 Summary

The study investigated the intended and implemented curriculum by examining the data obtained in the form of course outlines observation of the POGIL classes, and interviewing the students.

Initially for the first research question, the study had identified the skills that were considered essential in first year chemistry from the intended curriculum. The subsequent analysis of curriculum documents and POGIL activity materials and they were found to be in line with the process skills proposed by the POGIL practitioners.

The second research question focused the actual implementation of modified POGIL in lectures and tutorial/workshops to explore students' acquisition of process skills. The existence of a good fit between the graduate attributes and process skills in POGIL classes was evident from the nature of POGIL materials, students' interactions and instructors' rich experience in POGIL facilitation. The examination and triangulation of several data sources demonstrated that the skills required for POGIL learning were implemented and the POGIL approach may help in the development of process skills amongst the first year chemistry students.

Chapter 5
The Achieved Curriculum

5.1 Introduction

This chapter describes the researcher's approach to answer the third research question of this investigation, 'How effectively do students achieve the intended learning outcomes using a POGIL approach?'

The following ancillary research questions are answered in determining the effectiveness of POGIL in first year chemistry classes.

- RQ 3.1. What understandings of stereochemistry are held by first year chemistry students following POGIL instruction in the post-test and in the delayed post-test? (Group 1: Chem102, Sem 2, 2011)
- RQ 3.2. What understandings of stereochemistry are held by first year chemistry students following lectures in the post-test and in the delayed post-test? (Group 2: Chem121, Sem 1, 2012)
- RQ 3.3. Are there any statistical differences between learning gains for Group 1 and Group 2?

Section 5.2 outlines the layout of the statistical analysis of student responses. Section 5.3 presents Chem102 students' (Group 1) post-test and delayed post-test results of the SCDT in an attempt to answer the first ancillary research question 3.1. The overall SCDT performance of Group 1 students is presented in Section 5.4. The second ancillary research question 3.2 is answered in Section 5.5 that included Chem121 students' (Group 2) post-test and delayed post-test results and in Section 5.6 the overall performance of Group 2 students in the SCDT is presented. Section 5.7 attempts to answer the third ancillary research question 3.3 by presenting information on the differences in the learning gains of the concepts of stereochemistry between Group 1 and Group 2 students. The two-fold study to address students' misunderstanding of stereochemistry concepts included (i) developing the Stereochemistry Concept Diagnostic Test - SCDT (as outlined in Chapter 3) and (ii) identifying the extent and features of students' understanding of stereochemistry concepts in the POGIL class. The study differed from other previous research studies in identifying students' understanding of stereochemistry concepts using multiple-choice stereochemistry tests (Krylova, 1997; Kurbanoglu et al., 2006; Staver & Halsted, 1984; Tuckey & Selvaratnam, 1993) because it used a 2-tier, 5 item multiple-choice test.

5.2. Statistical Analysis of Student Responses to the Stereochemistry Concept Diagnostic Test (SCDT)

The students' responses to the SCDT were analysed using SPSS v20. The test scores of the students who participated in both post-test and delayed post-test were only considered and the students were de-identified. The analyses for the five items in the post-test and delayed post-test are summarised in two categories: Group 1 (Chem102, Semester 2, 2011) and Group 2 (Chem121, Semester 1, 2012). For Group 1, the SCDT results are presented in Tables 5.1, 5.2, 5.3, 5.4, and 5.5; and for Group 2 the SCDT results are presented in Tables 5.8, 5.9, 5.10, 5.11, and 5.12. Item 1 of the SCDT contained an error in the reasons and has been treated as a one-tier question. Consequently, the analysis is based only on the students' response to the question, without considering their reason choices. The remaining four items were two tier questions, where for every content choice made by the students in the first tier of an item, the analysis provided the corresponding number who selected each of the reason choices from the second tier. The percentage of students selecting each content-reason choice is depicted in parentheses. The most appropriate content choice and reason choice for each item are displayed with an asterisk (*). The total percentages are presented as whole numbers.

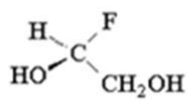
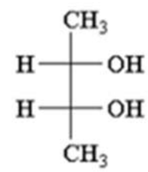
The students' misunderstanding of stereochemistry concepts was identified when students incorrectly responded to either content part or reason part or both (Peterson et al., 1989). The study considered any incorrect response as misunderstanding if more than 10% of students have selected it (McClary & Bretz, 2012; Othman et al., 2008; Tan et al., 2007).

5.3. Group 1: Chem102, Semester 2, 2011

The results included in the sections 5.3.1 to 5.3.4 are in response to the Research Question 3.1: What understandings of stereochemistry are held by first year chemistry students following POGIL instruction in the post-test and in the delayed post-test? (Group 1: Chem102, Sem2, 2011). Details are provided in relation to all of the two-tier items on stereochemistry concept diagnostic test.

5.3.1 Stereocentres *(Item 1)*

Determine which of the compounds have stereogenic carbon atoms (chiral centres)?

A. 
B. 
C. 
D. All of them

To answer this item correctly, the students are expected to apply their understanding of what makes a tetrahedral carbon a chiral centre or stereocentre. Molecules ‘A’, ‘B’ and ‘C’ in item 1 have at least one tetrahedral carbon atom which is attached to four different groups of atoms making them stereogenic (Straumanis, 2012a). Therefore the correct answer to this question is ‘D’ as all the molecules ‘A’, ‘B’ and ‘C’ contain stereogenic centres. The response patterns of Group 1 students (Chem102) in the post-test and delayed post-test of the SCDT are displayed in the Table 5.1.

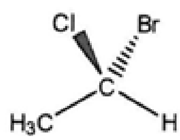
Table 5. 1: Percentage of Group 1 (Chem102, Sem 2, 2011) student response pattern to Item 1

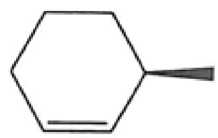
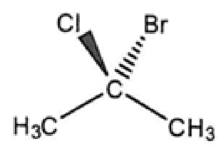
		Content Choice			
Group 1		A	B	C	D
Chem102, Sem2, 2011	**Post-Test**	6 (9.84)	15 (24.59)	12 (19.67)	*28 (45.90)
	Delayed	A	B	C	D
	Post-Test	0	2 (14.29)	3 (21.43)	*9 (64.29)

More than one third (45.90%) of Chem102 students have correctly answered this question. Interestingly, about 19.67% of Chem102 students who chose ‘C’ appeared to have misunderstood chirality and stereogenic centres. Compound ‘C’ contains two stereogenic centres but is not chiral because it has a plane of symmetry. The percentage of Group 1 students who gave the desired response for the question has increased from 45.90% in the post-test to 64.29% in the delayed post-test, whereas the remaining students (35.71%) were unable to identify the stereogenic carbons in the molecules. This indicated that POGIL interaction may have helped some students to recognise that stereogenic carbon atoms are bonded to four different groups of atoms. Interestingly, very few students recognised ‘A’ as having stereocentres. This may be because they misinterpreted the term ‘four different groups’ to be limited to the atoms bonded directly to the carbon and did not consider what was next along the ring.

5.3.2 Enantiomers *(Item 2)*

Which of the following doesn’t have an enantiomer (is not an enantiomer)

A. 

B. 
C. 

Reason

1. It has a chiral center
2. doesn’t have a plane of symmetry
3. It is achiral
4. it’s a chiral molecule with no chiral centre

According to Blackman et al. (2008), enantiomers are chiral molecules that can form non-superimposable mirror images. Item 2 of the SCDT was aimed at assessing students’ application of their knowledge of chirality in recognising the possibility of a molecule existing as enantiomers. Molecule ‘C’ is achiral and does not have a non-superimposable mirror image; in other words, it does not exhibit enantiomerism, due to the fact that the carbon to which the Cl, Br and two CH_3 groups are attached is not stereogenic.

The data shown in the Table 5.2 indicate that a relatively smaller number of Chem102 students (14.75%) have given a correct response and reason (C3) to this item. More than one third (39.34%) of those students have chosen molecule ‘B’ (incorrect molecule) with a third of these selecting ‘B3’ (13.11%) being the incorrect molecule with a correct reason. Molecule B possesses chirality and exhibits enantiomerism. More than one tenth (11.48%) of the students have chosen A1 indicating their misunderstanding of chirality with respect to enantiomerism.

Surprisingly, 18.03% of the students, though they chose the correct response, were unable to recognise the inability of C to form enantiomers.

For this item in the delayed post-test, 42.86% of Group 1 students have chosen the desired answer-reason combination compared to their post-test answer (14.75%) indicating an overall significant improvement in their understanding of the principle of enantiomerism, which may have resulted due to POGIL interaction during the delayed post-test. From the results shown in Table 5.2, 43% of this student group has developed a new misunderstanding that a chiral molecule without a chiral centre is not an enantiomer, which could have been due to their argumentative discussion or lack of a consensus on the selection of the answer during the POGIL discussion. About 14% of the students still continued to hold a misunderstanding that chiral compounds do not have an enantiomer (C2).

Table 5. 2: Percentage of Group 1 (Chem102, Sem 2, 2011) student response pattern to Item 2

Cohort	Content Choice	Reason Choice 1	2	3	4	Total (%)[a]
	Post-test (*n* = 61)					
	A	7 (11.48)	1 (1.64)	1 (1.64)	1 (1.64)	16
Group 1:	B	8 (13.11)	4 (6.56)	8 (13.11)	4 (6.56)	39
Chem102	C	11 (18.03)	2 (3.28)	*9 (14.75)	4 (6.56)	43
Semester 2, 2011	**Delayed Post-test** (*n* = 14)					
	A	0	0	0	0	0
	B	0	0	0	6 (42.86)	43
	C	0	2 (14.29)	*6 (42.86)	0	57

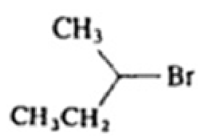
[a] The total percentages have been reduced to the nearest one per cent.

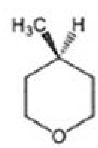
As outlined in Chapter 3, Section 3.11.1, a semi-structured interview format was used to record students' discussions and/or arguments during the delayed post-test. The following is the conversation between two students 'S1', 'S2' and the researcher 'R'. A full transcript can be found in Appendix I.

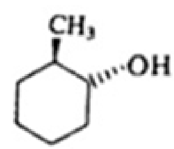
S1: which of the following doesn't have an enantiomer?
S2: laughs…
R: OK
S1: actually, I do not know what an enantiomer is ….
R: it is not an enantiomer, if you know what makes a molecule super-imposable and non-superimposable, you can answer this?
(Smartphone screen is mimicked as a mirror) look at the molecule…. (directs the student to view the image of the molecule on the screen of the smartphone) are these same or different?
S1: they are different; an enantiomer is a different ….. thing.
S2: points towards, molecule C, does this one have?
S1: yes, because… carbon, hydrogen … that is different…… the carbon doesn't have four different groups (recognises that it is not chiral)
S2: yes
S1: one, two … three, (searches for different groups of atoms around carbon) doesn't have, so, that would?
S2: yes
R: think about it; think about it…, does it have four different groups attached to the carbon?
S2: No
R: so, does this mean, it is the feature you are after
S2: did you get that (questions ' S1')
S1: yes
R: (prompting to view the mirror images through smartphone screen) Do you think the image of molecule C is super-imposable or non-superimposable? Imagine, would the mirror image completely overlay the molecule C?

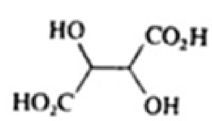
5.3.3 Chirality *(Item 3)*

Identify the achiral molecules

A. 

B. 

C. 

D. 

E. they are all chiral

Reason

1. The molecule has no internal plane of symmetry, hence it is not chiral
2. The mirror images are non-identical
3. The stereocentric carbon is bonded to four different groups
4. The mirror image is identical to the original, hence the molecule is not chiral

Any achiral molecule has at least one plane of symmetry (Straumanis, 2009b). Also known as *mirror plane*, a plane of symmetry refers to an imaginary plane passing through an object, dividing it equally so that one half of it is the true reflection of the other. The students are generally expected to assess each molecule based on its plane of symmetry. Any misjudgement may lead to a misunderstanding of the concept of chirality. For this item, the correct response and reason combination is 'B4', because molecule 'B' has an internal plane of symmetry and its mirror image is identical to the original, hence it is achiral molecule.

The results of response patterns of students are shown in Table 5.3. More than a third (37.70%) of the students incorrectly identified molecules A and D as achiral and reasoned out that these do not have an internal plane of symmetry (A1, D1). Students were unable to recognise the salient features of an achiral molecule, namely having a plane of symmetry and identical mirror image formation. The data indicate that the most commonly observed students' misunderstanding about achiral molecules is that achiral molecules have no internal plane of symmetry and chiral molecules have an internal plane of symmetry. Only 16.39% of the students provided the correct answer.

The data pertaining to the delayed post-test, as shown in Table 5.3, indicate that 50% of the Chem102 students were able to display a correct understanding that achiral molecules are superimposable on their mirror images as compared to their post-test performance of 16.39% (B4). The misunderstanding of an achiral molecule not having a plane of symmetry that emerged at the end of the post-test in Chem102 students appeared to be resolved during their delayed post-test POGIL discussion and in return it may have led to the emergence of a new misunderstanding – that an achiral molecule has a tetrahedral carbon with four different groups of atoms connected to it.

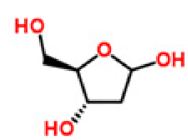
Table 5. 3: Percentage of Group 1 (Chem102, Sem 2, 2011) student response pattern to Item 3

Cohort	Content Choice	Reason Choice				Total (%)[a]
		1	2	3	4	
		Post-test (*n* = 61)				
	A	8 (13.11)	0	1 (1.64)	1 (1.64)	16
	B	9 (14.75)	2 (3.28)	1 (1.64)	*10 (16.39)	36
	C	3 (4.92)	0	0	0	5
Group 1:	D	15 (24.59)	0	0	3 (4.92)	26
Chem102	E	7 (11.48)	1 (1.64)	0	0	13
Semester 2, 2011		**Delayed Post-test** (*n* = 14)				
	A	0	0	3 (21.43)	0	21
	B	0	0	2 (14.29)	*7 (50.00)	64
	C	0	0	0	0	0
	D	0	0	0	0	0
	E	0	0	2 (14.29)	0	14

[a] The total percentages have been reduced to the nearest one per cent.

5.3.4 Stereoisomers *(Item 4)*

The 2-deoxyribose, a five carbon sugar component of DNA (deoxyribonucleic acid) with phosphate groups to form the backbones of DNA polymer, has the following structure:



How many stereoisomers are possible for 2-deoxyribose?

A. 8 B. 6 C. 4 D. 0

Reason

1. presence of 4 asymmetric carbons
2. presence of 3 stereocentric carbons
3. presence of 2 asymmetric carbons
4. 2^n rule valid only to acyclic molecules

For item 4 of SCDT, when the students were able to identify the number of stereocentres, it is relatively easy to estimate the possible number of stereoisomers arising from them. A generalised statement (Bettelheim, Brown, Campbell, Farrell, & Torres, 2012; Blackman et al., 2008) is that, for a molecule with *n* stereocentres, the maximum possible number of stereoisomers is 2^n. The 2-deoxyribose molecule has 3 stereocentres that may give rise to 8 stereoisomers.

As Table 5.4 shows, 16.39% of the students have correctly answered this question (A2). Nearly 36% of the students have incorrectly identified stereocentric carbons on 2-deoxyribose molecule (C1, C3). This indicates that, students have an incorrect understanding of the association between the number of stereocentres and the number of resulting isomers.

A 41% increase in the students' response to this item (A2) in the delayed post-test indicated that POGIL style discussion may have helped them overcome their difficulty in estimating the possible number of isomers on the basis of the number of stereocentres for a chiral molecule.

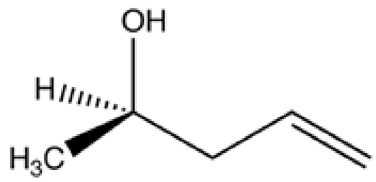
Table 5. 4: Percentage of Group 1 (Chem102, Sem 2, 2011) student response pattern to Item 4

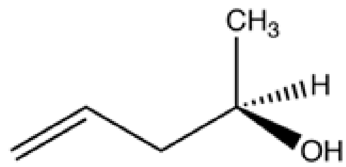
Cohort	Content Choice	Reason Choice				Total (%)[a]
		1	2	3	4	
		Post-test (*n* = 61)				
	A	4 (6.56)	*10 (16.39)	2 (3.28)	2 (3.28)	30
	B	5 (8.20)	4 (6.56)	0	2 (3.28)	18
Group 1:	C	7 (11.48)	1 (1.64)	15 (24.59)	3 (4.92)	43
Chem102	D	4 (6.58)	0	0	2 (3.28)	10
Semester 2, 2011		**Delayed Post-test** (*n* = 14)				
	A	0	*8 (57.14)	0	0	57
	B	0	2 (14.29)	0	0	14
	C	0	0	4 (28.57)	0	29
	D	0	0	0	0	0

[a] The total percentages have been reduced to the nearest one per cent.

5.3.5 Molecular Visualisation *(Item 5)*

What is the best way to describe the relationship between these two molecules?

A. 

B. 

A. they are enantiomers
B. they are constitutional isomers
C. they are diastereomers
D. they are identical

Reason
1. they are non-super imposable, they are also mirror images
2. the molecules are not non- superimposable and also are not mirror images
3. these molecules have same molecular formula and different connectivities
4. they are superimposable and are not mirror images

This item was aimed at testing students' ability to visualise the molecule in free space. The orientation of atoms of pent-4-en-2-ol ($C_5H_{10}O$) in space look different in both A and B, but they are identical. The molecule 'A' when rotated around the C─OH bond, forms a superimposable structure, 'B'. There are two rotations required to orient A over B. Rotation of molecule 'A' around the C─OH bond followed by rotation around C2─C3 bond would orient it to be superimposable on 'B'. The correct answer for this item is D4 – the molecules are identical and they are superimposable but they are not mirror images (Table 5.5).

In the post-test, 11.48% of students chose the correct response and reason; 14.75% of students from Chem102 viewed these molecules as enantiomers that are non-superimposable on their mirror images only. The delayed post-test data presented in Table 5.5 show that the Chem102 students' performance has improved from 11.48% in post-test to 35.71% in delayed post-test (D4). This result indicated that student misunderstandings at the end of the post-test were, however, resolved but about 28.57% of the students (from 6.58%) have developed a new misunderstanding that diastereomers have different connectivity of atoms (C3).

Table 5. 5: Percentage of Group 1 (Chem102, Sem 2, 2011) student response pattern to Item 5

Cohort	Content Choice	Reason Choice 1	2	3	4	Total (%)[a]
		Post-test (*n* = 61)				
	A	9 (14.75)	4 (6.56)	2 (3.28)	1 (1.64)	26
	B	5 (8.20)	3 (4.92)	6 (9.84)	3 (4.92)	28
Group 1:	C	3 (4.92)	5 (8.20)	4 (6.58)	0	20
Chem102	D	3 (4.92)	2 (3.28)	4 (6.58)	*7 (11.48)	26
Semester 2, 2011		**Delayed Post-test** (*n* = 14)				
	A	0	0	0	0	0
	B	0	2 (14.29)	3 (21.43)	0	36
	C	0	0	4 (28.57)	0	29
	D	0	0	0	*5 (35.71)	36

[a] The total percentages have been reduced to the nearest one per cent.

The following discussion was observed during the semi-structured interview while the students were answering the item 5 of SCDT delayed post. A full transcript of the conversation is available in the Appendix I.

S1: What is the best way to describe the relationship between these two molecules?
S2: ….
S1: they are not superimposable
S2: no
S1: no
S2: OK
S1: because they got four units (referring to the groups of atoms around the carbon)
S2: ya
R: Why it is not superimposable?, as such it is not superimposable and the reason …. As you twist it around the carbon, what would happen? Can you make them superimposable?
S1: no
R: on their mirror images?
S1: wait… wait…wait a second… they are all messed around, they are all same here….
R: Just one turn, would those molecules are superimposable?
S1: This H goes there, this OH goes there, if you rotate around like this, the OH goes to here, the H goes to here, and the H goes here where the OH was here,
R: aha

S1: I would guess they are non-superimposable here
S2: ya.. ya.. It is…
S1: they are non-superimposable and they are also mirror images
S2: no.. no.. they are not mirror images, that one is not
R: can I just point out one thing, you take one of the molecules as standard and try to manipulate with the second one. So, let us take this one (molecule 'B'), what happens is, just make a turn, so the methyl goes up and OH goes down. So in that scenario, alright, visualise that, the OH going down, methyl going up, alright, and look at the images of both the molecules,
S1: OK

S1 showed highly developed visualisation skills and employed a mental-rotation method. S1 mentally rotated the axis at CH_3 - C - OH. S1 described the strategy in the interview:

This H goes there, this OH goes there, if you rotate around like this, the OH goes to here, the H goes to here, and the H goes here where the OH was here (S1)

5.4 Group 1 (Chem102) Students' Overall Performance in the SCDT

The overall performance of the students in this post-test and delayed-post SCDT was obtained by comparing the percentage of students who scored both parts correctly in each two-tier item with the percentage who scored only the first part correctly. The data are tabulated in Table 5.6 and shown as a bar chart in Figure 5.1. The Group1 students had taken post-test individually and the delayed post-test as POGIL groups.

The percentage of students who correctly answered the item 1 has increased from 46% in the post-test to 64% in the delayed post-test. When the item 1 was excluded, the percentage of students who correctly answered the first tier of the multiple choice items ranged from 26% to 43% in the post-test as compared to 36% to 64% in the delayed post-test. The percentage of students who answered both parts of the two-tier items ranged from 12% to 16% in post-test as compared to 36% to 57% in the delayed post-test. This trend indicates that the small group POGIL style delayed post-test had offered the students the opportunity to discuss and decide their options more clearly in comparison to the individualised post-test set-up.

Table 5. 6: Percentage of students (Chem102, Semester 2, 2011) who correctly answered the first part and both parts of the items in the diagnostic test (Post-Test and Delayed Post-Test)

Item	Percentage of Students Who Correctly Answered			
	Post Test		Delayed Post Test	
	First Part	Both Parts	First Part	Both Parts
1	46	NA*	64	NA*
2	43	15	57	43
3	36	16	64	50
4	30	16	57	57
5	26	12	36	36

*NA – Not Applicable

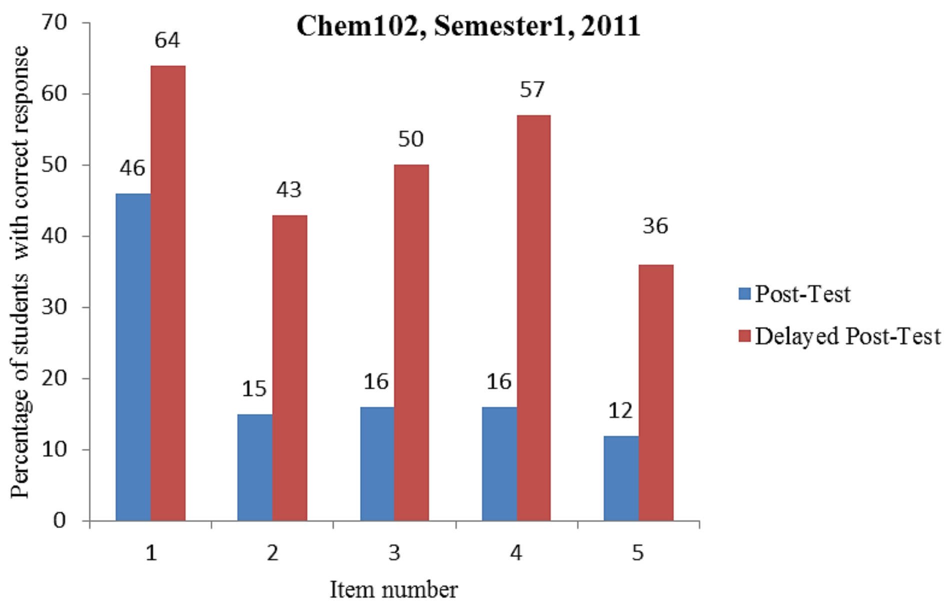


Figure: 5. 1. The percentages of Chem102 students who provided the correct response to both tiers of the 5 items in the Stereochemistry concept diagnostic test.

The most common misunderstandings of stereochemistry concepts after the post-test are presented in Table 5.7. A higher proportion of Chem121 students displayed a misunderstanding of the concept of stereocentres. The prevalence of misunderstanding about the connectivity of atoms in stereocentric molecules is about 40% higher amongst Chem121 students as compared to Chem102 students. Similarly, 53% of Chem121 students believe that stereocentred compounds are always asymmetrical as compared to about 25% of Chem102 students. However, Chem121 students (22.78%) did not appear to possess any misunderstanding of the interpretation of the plane of symmetry and chirality of molecules but they seemed to have difficulty in understanding non-superimposability of chiral molecules, as evidenced from their choice combination. Another misunderstanding that had spread among both cohorts was related to the stereocentres in 2-deoxyribose molecule. As shown in the Table 5.7, about 36% Chem102 and 28% Chem121 students held a misunderstanding that 2-deoxyribose molecule has two asymmetric carbons. A further 22% of Chem121 students believed that only one stereoisomer is possible from every stereo-centric carbon.

Students' inaccurate visualisation of molecules in item 5 of SCDT may have led to the development of a misunderstanding that enantiomers are identical. This was evidenced from the selection of incorrect choice combination (A1) by Chem102 (14.75%) and Chem121 (21.52%) students. A further 10.13% of Chem121 students misunderstand that enantiomers have different order of atomic connectivity.

Table 5. 7: Comparison of students' misunderstanding of stereochemistry concepts at the end of post-test of SCDT

Students' misunderstanding	Item no	Choice combination	% of students	
			Chem102	Chem121
Stereocentres				
Stereocentres are determined by atoms bonded directly to the central atom	1	B, C	44.26	60.78
Stereocentred compounds are always asymmetrical	1	B	24.59	53.17
Enantiomers				
Achiral compounds have an enantiomer	2	A1	11.48	11.39
Chiral compounds do not have an enantiomer	2	B1	13.11	-
Chirality				
Achiral molecule has no internal plane of symmetry	3	B1	14.75	-

Chiral molecules have internal plane of symmetry	3	B1	14.75	-
Chiral molecules form identical mirror images	3	D4	-	22.78
Stereoisomers				
2-deoxyribose has 2 asymmetric	4	C1	11.48	15.19
carbons	4	C3	24.59	13.92
One stereoisomer is resulted from every stereo-centric carbon	4	B2	-	21.52
Molecular Visualisation				
Enantiomers are identical	5	A1	14.75	21.52
Enantiomers have different order of atom connectivity	5	B3	-	10.13

5.5 Group 2: Chem121, Semester 1, 2012

The results included in the sections 5.5.1 to 5.5.5 are in response to the Research Question 3.2: What understandings of stereochemistry are held by first year chemistry students following lectures in the post-test and in the delayed post-test? (Group 2: Chem121, Sem 1, 2012)

5.5.1 Stereocentres *(Item 1)*

The results presented in Table 5.8 show that 31.65% of Chem121 students had correctly answered this question. About 53% of Chem121 students who chose 'B' were able to identify stereogenic centres when all four atoms bonded to the central carbon atom are different but were unable to generalise the stereogenic nature of tetrahedral carbon to all the molecules in this question. The very low selection rate for molecule 'A' may suggest difficulty in identifying stereocentres in cyclic systems.

For the Chem121 cohort, who had an individually administered delayed post-test, the correct response had increased to 59.30% compared to their post-test answer (31.65%). However, 41% of the students were unable to identify the stereocentres in all of the molecules.

Table 5. 8: Percentage of Group 2 (Chem121, Sem 1, 2012) student response pattern to Item 1

		Content Choice			
Group 2:		A	B	C	D
Chem121,	**Post-Test**	4 (5.06)	42 (53.17)	6 (7.61)	25* (31.65)
Sem1,					
2012	**Delayed**	A	B	C	D
	Post-Test	1 (1.56)	18 (28.13)	7 (10.94)	38* (59.30)

5.5.2 Enantiomers *(Item 2)*

In the post-test, for this item, 21.52% of the students gave a correct response and reason (C3). A further 24.05% of the students have chosen an incorrect response (B) but a correct reason (3). Also, 11.39% of students who chose 'A1' displayed a misunderstanding of chirality with respect to enantiomerism. In the delayed post-test, a minor improvement (5%) in Chem121 students' understanding of the concept of enantiomerism was evident from the data presented. A significant number of the students (47%) still continued to hold the misunderstanding that chiral compounds do not have an enantiomer (B1, B2 and B3).

Table 5. 9: Percentage of Group 2 (Chem121, Sem 1, 2012) student response pattern to Item 2

Cohort	Content Choice	Reason Choice 1	2	3	4	Total (%)[a]
	Post-test (*n* = 79)					
	A	9 (11.39)	2 (2.53)	0 (0.00)	1 (1.27)	15
Group 2:	B	2 (2.53)	10 (12.66)	19 (24.05)	5 (6.33)	46
Chem121	C	5 (6.33)	5 (6.33)	*17 (21.52)	3 (3.80)	38
Semester 1, 2012	**Delayed Post-test** (*n* = 64)					
	A	6 (9.38)	1 (1.56)	1 (1.56)	0 (0.00)	13
	B	0 (0.00)	8 (12.50)	18 (28.13)	4 (6.25)	47
	C	4(6.25)	3 (4.69)	*17 (26.56)	2 (3.13)	41

[a] The total percentages have been reduced to the nearest one per cent.

5.5.3 Chirality *(Item 3)*

Only a minority of students (6.33%) of Chem121 chose the correct answer (B4) where 22.78% of the students chose molecule 'D' as achiral and reasoning that its mirror image is identical. The percentage of students with correct response and reason has increased from 6.33% in the post-test to 21.88% in the delayed post-test (B4). Also, 17.19% of the students, at the end of the delayed post-test chose E3 indicating a misunderstanding that an achiral molecule has a tetrahedral carbon atom with four different groups of atoms connected to it.

Table 5. 10: Percentage of Group 2 (Chem121, Sem 1, 2012) student response pattern to Item 3

Cohort	Content Choice	Reason Choice				Total (%)[a]
		1	2	3	4	
	Post-test (*n* = 79)					
Group 2: Chem121 Semester 1, 2012	A	0 (0.00)	0 (0.00)	3 (3.80)	7 (8.86)	13
	B	3 (3.80)	1 (1.27)	2 (2.53)	*5 (6.33)	14
	C	1(1.27)	3 (3.80)	0 (0.00)	3 (3.80)	9
	D	5 (6.33)	3 (3.80)	5 (6.33)	18 (22.78)	39
	E	1(1.27)	5 (6.33)	11(13.92)	0 (0.00)	22
	Delayed Post-test (*n* = 64)					
	A	1 (1.56)	1 (1.56)	1 (1.56)	5 (7.81)	13
	B	1 (1.56)	4 (6.25)	2 (3.13)	*14 (21.88)	33
	C	1 (1.56)	0 (0.00)	0 (0.00)	2 (3.13)	5
	D	0 (0.00)	1 (1.56)	1 (1.56)	10 (15.63)	19
	E	3 (4.69)	5 (7.81)	11 (17.19)	1 (1.56)	31

[a] The total percentages have been reduced to the nearest one per cent.

5.5.4 Stereoisomers *(Item 4)*

As Table 5.11 shows, 6.33% of Chem121 students have correctly (A2) answered this question. About 29% of the students who chose either 'C1' or 'C3' as their response and the reason to this question displayed a lack of understanding of the estimating the possible number of isomers, given the number of stereocentres in a molecule.

Compared to the post-test performance, an increase to 26% for A2 in the delayed post-test was observed for the Chem121 cohort.

Table 5. 11: Percentage of Group 2 (Chem121, Sem 1, 2012) student response pattern to Item 4

Cohort	Content Choice	Reason Choice 1	2	3	4	Total (%)[a]
		Post-test (*n* = 79)				
	A	1(1.27)	*5 (6.33)	3 (3.80)	2 (2.53)	14
	B	0 (0.00)	17 (21.52)	3 (3.80)	5 (6.33)	32
Group 2:	C	12 (15.19)	7 (8.86)	11(13.92)	1(1.27)	39
Chem121	D	2 (2.53)	2 (2.53)	2 (2.53)	4 (5.06)	13
Semester 1, 2012		**Delayed Post-test** (*n* = 64)				
	A	1 (1.56)	*17 (26.56)	3 (4.69)	0 (0.00)	33
	B	0 (0.00)	13 (20.31)	2 (3.13)	0 (0.00)	23
	C	9 (14.06)	5 (7.81)	7 (10.94)	2 (3.13)	36
	D	0 (0.00)	2 (3.13)	5 (7.81)	0 (0.00)	11

[a] The total percentages have been reduced to the nearest one per cent.

5.5.5 Molecular Visualisation *(Item 5)*

As displayed in Table 5.12, only two students chose the correct response and reason to this item, while, 21.52% of students have incorrectly identified the molecules A and B as enantiomers. A further eight students have identified the molecular representation of A and B as constitutional isomers having the same molecular formula but different connectivity of atoms. There has not been a significant change in the delayed post-test for this group of students. The persistence of the students' misunderstanding about molecules A and B as enantiomers continued as evidenced by the delayed post-test. This was hypothesised as being mainly due to the lack of opportunity for POGIL style interaction among the students.

Table 5. 12: Percentage of Group 2 (Chem121, Sem 1, 2012) student response pattern to Item 5

Cohort	Content Choice	Reason Choice 1	2	3	4	Total (%)[a]
		Post-test (*n* = 79)				
	A	17 (21.52)	6 (7.59)	2 (2.53)	5 (6.33)	38
	B	3 (3.80)	4 (5.06)	8 (10.13)	7 (8.86)	28
Group 2:	C	5 (6.33)	6 (7.59)	1(1.27)	6 (7.59)	23
Chem121	D	3 (3.80)	1(1.27)	2 (2.53)	*2 (2.53)	10
Semester 1, 2012		**Delayed Post-test** (*n* = 64)				
	A	17 (26.56)	3 (4.69)	7 (10.94)	7 (10.94)	53
	B	0 (0.00)	8 (12.50)	5 (7.81)	3 (4.69)	25
	C	5 (7.81)	3 (4.68)	3 (4.69)	1 (1.56)	19
	D	0 (0.00)	0 (0.00)	0 (0.00)	*2 (3.13)	3

[a] The total percentages have been reduced to the nearest one per cent.

5.6 Group 2 (Chem121) Students' Overall Performance in the SCDT

The overall performance of Chem121 students in the post-test and delayed post-test was estimated by comparing the percentage of students who scored both parts of each item of the two-tier SCDT correctly with the percentage of students who scored only the first part correctly. The results are presented in Table 5.13 and Figure 5.2. The Group 2 students had taken post-test and delayed-post individually without any POGIL group interaction.

Table 5. 13: Percentage of students (Chem121, Semester 1, 2012) who correctly answered the first part and both parts of the items in the diagnostic test (Post-Test and Delayed Post-Test)

Item	Percentage of Students Who Correctly Answered			
	Post Test		Delayed Post Test	
	First Part	Both Parts	First Part	Both Parts
1	32	NA*	58	NA*
2	38	22	41	27
3	14	6	33	22
4	14	6	33	27
5	10	3	3	3

*NA – Not Applicable

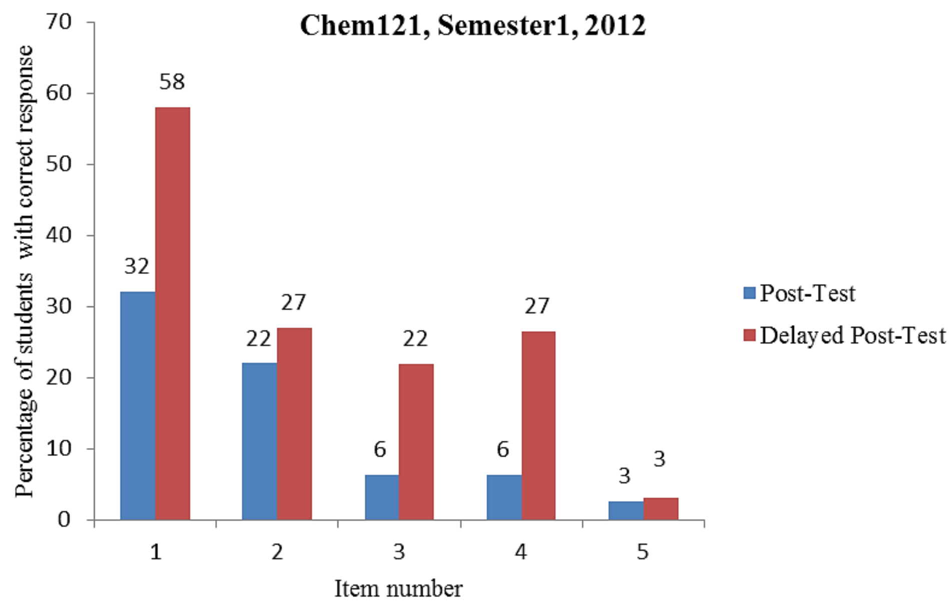


Figure: 5. 2. The percentages of Chem121 students who provided the correct response to both tiers of the 5 items in the Stereochemistry concept diagnostic test.

The percentage of the students who correctly answered the first tier of multiple-choice items in the post-test ranged from 10% to 38% in comparison to the delayed post-test where the percentage ranged between 3% and 41%. Likewise, the percentage of students who answered both the two-tier items ranged from 3% to 22% in the post-test as compared to 3% to 33% in the delayed post-test.

5.7 Stereochemistry Learning Gains: Group 1 and Group 2

The results included in this section are in response to the ancillary Research Question 3.3: Are there any statistical differences between learning gains for Group 1 and Group 2? A paired samples t-test was conducted to compare the differences in the learning gains of Group 1 (Chem102, Sem 2, 2011) and Group 2 students (Chem121, Sem 1, 2012) students and the results were presented in Table 5.14. The analysis of the data for the paired samples two tailed *t*-test included only the students who had participated in both the post-test and the delayed post-test of the SCDT. The data presented in Table 5.14 corresponds to 14 Chem102 and 64 Chem121 students.

For the Chem102 cohort, a paired samples two-tailed *t*-test indicated that students' delayed post-test scores (M = 2.43, SD = 0.51) were significantly higher than their post-test scores [(*M* = 1.29, *SD* = 0.91), *t* (13) = 5.56, *p* = 0.004]. The mean increase in SCDT scores was 1.14 with a 95% confidence interval ranging from 0.70 to 1.58. Similarly, for the Chem121 cohort, the paired samples t-test results also indicated that students' delayed post-test scores (*M* = 1.28, *SD* = 1.33) were also moderately higher than their post-test scores, [(*M* = 0.74, *SD* = 0.94), *t* (53) = 4.26, *p* = 0.004]. The mean increase in SCDT scores was 0.54 with a 95% confidence interval ranging from 0.21 to 0.75.

The effect sizes for the paired samples *t*-test were also computed to understand the effect of the POGIL discussion during the delayed post-tests. The guidelines for interpreting the eta squared values were: 0.01 = small effect, 0.06 = moderate effect, 0.14 large effect (Cohen, 1988). The eta squared statistic (0.60) indicated a very large effect size for the Chem102 cohort and a large effect (0.13) for the Chem121 cohort. Based on the eta squared values, we can conclude that there was a large effect for both the chemistry cohorts; however there was a substantial difference in the SCDT scores for Chem102.

These results suggest that Chem102 students' understanding of the concepts of stereochemistry had significantly improved after the POGIL group discussion.

In order to examine the difference in learning gains (subtracting the post-test achievement mean from that of the delayed post-test mean) between Group 1 (Chem102) and Group 2 (Chem121) students, an independent samples t-test was conducted. There was a significant difference in the means for Group 1 students (*M* = 1.14, *SD* = 0.77) and the Group 2 students [(*M* = 0.54, *SD* = 0.93), *t* (23.74) = 2.25, *p* < 0.012]. As represented in the Figure 3.1 (see Chapter 3), the Group 1 students had followed typical POGIL interaction during the delayed post-test whereas the Group 2 students had answered post and delayed post-tests individually. These findings suggest that the POGIL instruction was more effective compared to the traditional instruction in organic chemistry topics.

A further verification of this finding was performed by comparing the differences in learning gains of Group 1 and Group 2 students after the post-test using an independent samples t-test. There was a significant difference in the means for

Group 1 students (*M* = 1.29, *SD* = 0.91) and the Group 2 students [(*M* = 0.74, *SD* = 0.94), *t* (66) = 2.69, $p < 0.009$]. The post-test data presented in Tables 5.6 and 5.13 indicated that the Group 1 students did better than Group 2 students in all the items for both parts of the SCDT than Group 2 students except for item 2.

Table 5. 14: Descriptive statistics for students' achievement in SCDT

	Group 1 Chem102, Semester 2, 2011			Group 2 Chem121, Semester 1, 2012		
	Post-Test	Delayed Post-Test	*t* value	Post-Test	Delayed Post-Test	*t* value
Maximum Score Possible	5	5		5	5	
Mean	1.29	2.43	5.56*	0.74	1.28	4.26*
Median	1.00	2.00		0.00	1.00	
Standard Deviation	0.91	0.51		0.94	1.16	
Variance	0.83	0.26		0.87	1.33	
Minimum	0.00	2.00		0.00	0.00	
Maximum	3.00	3.00		3.00	4.00	

*$p<0.001$

A Cronbach's alpha reliability analysis performed using SPSS v20 as a measure of internal consistency of the items of SCDT for the Chem102 and Chem121 cohorts gave a coefficient of 0.70 and 0.65, respectively. Ideally, a value of 0.70 or higher is considered satisfactory (Nunnally, 1978).

The difficulty of the test items display the discriminatory power of the test (Jiang, Xu, Garcia, & Lewis, 2010). The difficulty index of the items of SCDT when the test was administered as post and delayed post-tests to Chem102 and Chem121 cohorts was estimated from the values presented in Tables 5.6 and 5.13. Items with a difficulty index value of 0.75 and above were treated as being easy and those items with a value below 0.25 were treated as being difficult.

The item difficulty index indicated that the level of difficulty of the items was reduced when the students of Chem102 cohort answered the questions of the SCDT as POGIL groups. Arguably, for the Chem121 cohort who answered the post-test and delayed post-test individually, the evidenced variation *(except for item 5)* in the difficulty level may have occurred due to active reviewing of the worksheets during tutorial sessions and their strong chemistry background.

5.8 Summary

Group 1 and Group 2 students had studied the same content of organic chemistry. Group 1 students (Chem102, Semester 2, 2011) had POGIL style lectures whereas the Group 2 students (Chem121, Semester 1, 2012) had received instruction in a traditional lecture format though both groups had used POGIL style activity sheets. The analysis of the five items of SCDT revealed that 11 (in Table 5.7) misunderstandings were held by Group 1 and Group 2 students. The SCDT post-test was administered individually to both Group 1 and Group 2 students. For the delayed post-test, the Group 1 students were allowed to answer the test items as POGIL groups and the Group 2 students had taken the delayed post-test individually. The delayed post-test performance was significantly higher than the post-test performance for Group 1 students suggesting the positive impact of POGIL style instruction in first year chemistry classes.

Ancillary Research Question 3.1: What understandings of stereochemistry are held by first year chemistry students following POGIL instruction in the post-test and in the delayed post-test? (Group 1: Chem102, Sem 2, 2011)

The Group 1 students completed the SCDT post-test individually and the delayed post-test as POGIL groups. The analysis of students' responses to Item 1 of SCDT revealed their difficulty in recognising stereocentred carbons based on their atomic connectivity. This finding is in line with a study by Taagepera et al. (2011) who reported students' difficulty in characterising the molecules based on stereocentres, chirality, a plane of symmetry and image formation.

Item 2 of the SCDT was aimed at assessing students' application of their knowledge of chirality with the possibility of a molecule existing as an enantiomer. As shown in

Table 5.2 more than one third (39.34%) of the students from Group 1 chose the incorrect molecule with a third of these (13.11%) selecting an incorrect molecule with a correct reason. The students appeared to lack the ability to make a distinction between a chiral and achiral molecule on the basis of 'superimposable' mirror images. For this item, the percentage of students who gave the correct answer combination increased from 14.75% in the post-test to 42.86% in the delayed post-test indicating an overall significant improvement in their understanding of the concepts of enantiomerism.

Item 3 of SCDT tested students' ability to apply the knowledge of a plane of symmetry and mirror image formation in assessing the chirality of the given molecules. The findings of the post-test SCDT results (Table 5.3) revealed that one third (37.70%) of the students incorrectly identified achiral molecules with a reason that they lacked internal plane of symmetry. The percentage of students who gave the correct answer combination increased from 16.39% to 50% after the delayed post-test indicating the disappearance of certain misunderstandings as a result of POGIL interaction.

For Item 4, the findings of the present study identified that 36% of Group 1 students (Table 5.4) have incorrect understanding of the possible number of isomers from a stereocentre in an organic molecule. These students appeared to lack ability to identify the stereocentres of the given molecules (Lujan-Upton, 2001). In the delayed post-test, the students' correct answer combination has increased to 57.14% which showed that these students had overcome the difficulty of estimating the number of possible isomers from a stereocentre of an organic molecule.

Responses to Item 5 revealed the students' difficulty in mentally visualising the given molecules based on the finding that only 11.48% of students (Table 5.5) had provided a correct answer combination and in the delayed post-test, the performance has improved to 35.71%.

In conclusion, the results of the investigation showed an improvement in students' understanding of stereochemistry in the delayed post-test; however, the students have developed new misunderstandings, possibly due to their argumentative discussions in the delayed post-test. The tendency for the students to continue their misunderstanding may be attributed to the confusion arising from the ability to move back and forth between 2-D and 3-D representations of the molecules (Abraham, Varghese, & Tang, 2010).

Ancillary Research Question 3.2: What understandings of stereochemistry are held by first year chemistry students following lectures in the post-test and in the delayed post-test? (Group 2: Chem121, Sem 1, 2012)

The Group 2 students completed both post and delayed post-tests individually. For Item 1 of the SCDT, the analyses of post-test results (Table 5.8) indicate that students have difficulty in identifying stereocentres in cyclic systems.

For Item 2 of SCDT, the results (Table 5.9) showed the misunderstanding of Group 2 students with respect to the chirality and enantiomerism: chiral molecules do not have an enantiomer, and achiral molecules have an enantiomer. A minor improvement (5%) in understanding of the principle of enantiomerism was evident after the delayed post-test, whereas, for a significant number (47%) of students, the misunderstanding remained unresolved even after the delayed post-test.

For Item 3 of SCDT, more than a third (39%) of the Group 2 students (Table 5.10) chose a correct reason and an incorrect response, indicating a misunderstanding that chiral molecules are identical to their mirror images. After the delayed post-test, a few students (17.19%) had exhibited a misunderstanding that an achiral molecule has a tetrahedral carbon with four different groups of atoms connected to it. However, for Group 2 students, the correct answer combination has increased from 6.33% in the post-test to 21.88% in the delayed post-test.

For Item 4, about 29% of students (Table 5.11) displayed a lack of understanding of estimating the possible number of isomers when the number of stereocentres in the molecule is known. The delayed post-test data for the correct answer combination was 26.56% as compared to 6.33% in the post-test.

Group 2 students (21.52%) have incorrectly identified the molecules A and B, given in Item 5, as enantiomers (Table 5.12). A further 28% of the students have represented the molecules as constitutional isomers, of which 10% of the students reasoned that molecules A and B have same molecular formula but different atomic connectivity. In the delayed post-test, data revealed the persistence of the misunderstanding that both molecules are enantiomers. In conclusion, the data showed that the continuity of students' misunderstanding may have arisen due to the lack of POGIL style interaction in the delayed post-test.

Ancillary Research Question 3.3: Are there any statistical differences between learning gains for Group 1 and Group 2?

The delayed post-test performance was significantly higher than post-test performance for Group 1 (Table 5.14), suggesting a positive impact of POGIL style instruction in first year chemistry classes. The results of the independent samples t-test indicated a significant difference in the means for Group 1 students (M = 1.10, SD = 0.78) and the Group 2 students [(M = 0.33, SD = 0.75), t (19.66) = 2.86, $p < 0.010$] suggesting that the POGIL instruction was more effective compared to the traditional instruction in organic chemistry topics.

A Cronbach's alpha reliability coefficient of 0.70 (Group 1, Chem102, Semester 2, 2011 students) and 0.72 (Group 2, Chem121, Semester 1, 2012 students) for the diagnostic test, SCDT was obtained which is greater than the threshold value of 0.5 suggested by (Nunnally, 1978). The level of difficulty of items had eased when the students answered the delayed post-test SCDT as POGIL groups.

Chapter 6
The Perceived Curriculum

6.1 Introduction

The study attempted to answer among others, Research Question 4. In what ways do students perceive their learning while engaged in POGIL classes? The study used the Student Assessment of Their Learning Gains (SALG) instrument (Seymour et al., 2000) and semi-structured interviewing of students in an effort to answer this research question.

Section 6.2 describes the significance of the perceived curriculum and its relevance to the research study. An introduction to the Students' Assessment of Their Learning Gains (SALG) instruments, the need and the process of validation of the SALG instrument are included in Sections 6.3, 6.3.1, and 6.3.2. The exploratory factor analyses results, reported in Section 6.4, examined both the convergent and discriminant validity of the SALG instrument. The confirmatory factor analyses results, reported in Sections 6.5 and 6.6 examined the construct validity of the SALG instrument with the utilisation of SPSS and structural equation modelling. The qualitative results from semi-structured student interviews and responses to open-ended statements on the SALG instrument are included in Section 6.7.

6.2 Perceived Curriculum

The perceived or experienced curriculum, according to Rogers (1989), refers to students' recounting their learning in the form of meaningful conclusions or interpretations from a class and laboratory or field work. Several approaches are proposed and practised (Mills & Treagust, 2003; Rogers, 1989; Treagust, 1986b) in an effort to assess the curriculum as perceived or experienced by the students. These approaches generally include end-of-course survey instruments and semi-structured student interviews. The examination of the curriculum as perceived by students in a POGIL class is an area of research in chemistry/science education that is of interest to chemistry educators.

6.3 Students' Assessment of Their Learning Gains (SALG)

According to Seymour (2000), the SALG instrument helps instructors in gaining the desired feedback from the students on their perceptions of learning during the semester, which, in return helps the instructors to examine and revise their pedagogical methods aimed at enhancing the students' learning gains. Despite wide usage of the SALG in chemistry classrooms (Chamely-Wilk, Galin, Kasdorf, & Haky, 2009; Gafney & Varma-Nelson, 2007; Hoffman, Britton, Cadwell, & Walz, 2010; Middlecamp, Jordan, Shachter, Kashmanian Oates, & Lottridge, 2006), surprisingly, there is no literature available describing the factorial or internal construct validity of the SALG questionnaire.

Following the introduction to the SALG, as outlined in Chapter 2, this research study adapted the questionnaire and the generated data were statistically analysed to validate the instrument and further explore how POGIL-influenced learning had helped students during their studies in chemistry.

The development and validation of the SALG instrument had several stages:

- Stage 1 involved the selection of a suitable instrument from the SALG site
- Stage 2 involved developing the face validity in this context by amending items to make the instrument more suitable to this Australian POGIL classroom
- Stage 3 involved administration of the SALG to Chem102 students at the end of semester 2 in 2011 in preparation for exploratory factor analysis.
- Stage 4 involved administration of the refined SALG instrument to Chem102 students at the end of semester 2 in 2012 in preparation for confirmatory factory analysis.

6.3.1 Stages 1 and 2

The website of the SALG (http://www.salgsite.org/about) offers students and instructors, access to the SALG instruments to complete, to enable instructors to compute the results from the questionnaire. Instructors have access to the template-style web-based instruments to which they can add or delete questions or edit existing questions. Alternatively, instructors can build their own SALG instrument from scratch by using a template-driven interface available on the website. The researcher had identified a pool of items from the POGIL instruments that were developed and administered in other POGIL classes and modified some of the items. In addition, content-specific items were incorporated to make the instrument more suitable to the Australian version of POGIL. The adapted and modified SALG instrument was moderated by an instructor at the Department of Chemistry who has extensive experience in trans-national studies of students' active learning pedagogies in chemistry. The SALG instruments developed and used in this study are available in Appendices C and J.

6.3.2 Stages 3 and 4

The SALG instrument was administered to Chem102 cohorts in 2011 and in 2012 to obtain data for exploratory and confirmatory analyses. The SALG instrument containing 62 5-point Likert scale items was administered during the second semester of 2011 for exploratory factor analysis (n = 114). Based on the results, the instrument was refined and the 44 item 5-point Likert scale SALG instrument was administered to Chem102 students during the second semester of 2012 for confirmatory factor analysis (n = 154). In addition to the Likert scale items, SALG also included items that were aimed at seeking students' written responses on various aspects of the POGIL class. An outline on the development and administration of the SALG instrument is presented in Figure 6.1.

For establishing convergent validity of SALG, the factor loadings and internal consistency reliability measures were computed. Brown (2006) suggested a strong interrelation of different measures of theoretically similar or overlapping constructs for convergent validity.

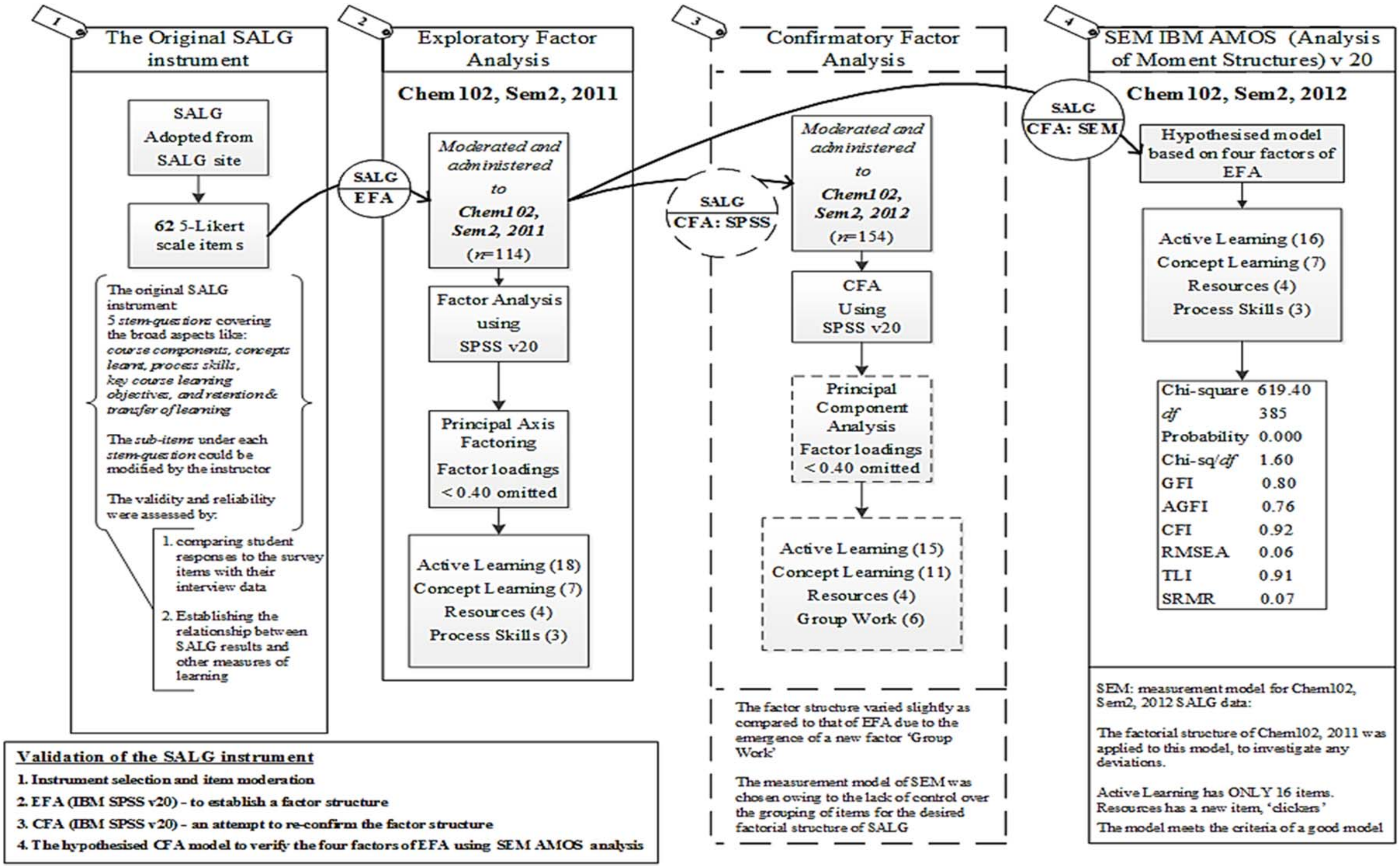


Figure: 6. 1. An outline showing the administration and data analysis of SALG

6.4 Exploratory Factor Analysis (EFA) of SALG Instrument

EFA is generally employed in the process of scale development and construct validation (Brown, 2006). EFA is a data driven approach to see the relevant common factors emerging from it (Johnson & Stevens, 2001). The purpose of EFA was to investigate the factors encompassing the SALG instrument. Subsequently, EFA was performed on all 62 items of SALG. A principal axis factoring analysis with varimax rotation procedure performed using SPSS version 20 extracted 32 items identified as four sets of factors, subsequently named students' active learning, concept learning, resources, and process skills.

The feasibility of factor analysis was determined by examining the Kaiser–Meyer–Olkin measure of sampling and Bartlett's test of sphericity. The Kaiser–Meyer–Olkin measure of sampling adequacy was 0.785, indicating that the data were appropriate for exploratory factor analysis (Tabachnick & Fidel, 1989). Bartlett's test of sphericity indicated that X^2 = 2196.521 which was statistically significant ($p<0.001$). Items loading on more than one factor with a loading score of equal to or greater than 0.40 on each factor were eliminated from the analysis. Table 6.1 shows the results of the varimax rotation and the factors obtained after EFA are presented in Table 6.2. Factor loadings indicate how strongly each item is related to a particular factor, eigenvalues show the relative importance of each factor, and the cumulative variance can be used to check whether a sufficient number of factors have been retained. The eigenvalue for each factor was greater than 1, as per Kaiser Criterion (Kaiser, 1960) and the cumulative variance for all the four factors was 45.79%.

Table 6. 1: Factor loading, eigenvalue and percentage of variance for SALG (Chem102, 2011) (n = 114)

Item Number	Factor Loadings			
	Active Learning	Concept Learning	Resources	Process Skills
1	.45			
2	.55			
3	.60			
4	.42			
5	.48			
6	.52			
7	.64			
8	.61			
9	.64			
10	.49			
11	.62			
12	.71			
13	.41			
14	.52			
15	.55			
16	.61			
17	.56			
18	.61			
19		.55		
20		.52		
21		.77		
22		.77		
23		.72		
24		.58		
25		.56		
26			.80	
27			.87	
28			.89	
29			.46	
30				.89
31				.68
32				.80
% Variance	18.12	10.69	9.33	7.65
Eigenvalue	9.46	2.86	2.64	1.90
Cumulative % Variance	18.12	28.82	38.15	45.79

Extraction Method: Principal Axis Factoring.
Rotation Method: Varimax with Kaiser Normalization.
Factor loadings smaller than 0.40 have been omitted

Table 6. 2: Scale development of SALG

Scales of SALG			
	Active Learning (18 items)		**Concept Learning (7 items)**
1	Pace of class	19	Molecular Forces
2	Attending class	20	SN1 SN2 rxn mechanism
3	Working with Peers	21	Distinguishing Isomers
4	Working with Peers outside the class	22	Classifying chiral-achiral molecules
5	Explanation of instructor for involving small groups	23	Identifying StereoCentres
6	Explanation of focus on topics presented	24	Ideas VS ideas other classes
7	Confidence understanding material	25	Ideas VS Major
8	Confidence in ability to do POGIL activities		**Resources (4 items)**
9	Comfort level involving complex ideas	26	Mini lectures
10	Participating in class discussions	27	Pencasts
11	Listening to discussions	28	Pencasts solutions HW problems
12	Participating in Group Work	29	Interacting with Instructor office hours
13	Class Activities help learning		**Process Skills (3 items)**
14	Number and spacing of tests	30	Argument use of evidence
15	Grading system what I need to work	31	Identify Data Pattern
16	Feedback on my work tutorials	32	Develop logical argument
17	Connecting key ideas to other knowledge		
18	Seeking help from others		

Internal consistency reliability was established by calculating the Cronbach's alpha coefficient for each factor. The guidelines (Cohen, Mannion, & Morrison, 2000; Nunnally, 1978) indicate that an alpha coefficient of 0.70 is adequate for an instrument in the early stage of development; a coefficient of at least 0.80 is adequate for a more developed instrument. The results portrayed in Table 6.3 show that the Cronbach's alpha coefficient for each factor was above 0.80, affirming the reliability of the scales of SALG. The factor loadings and internal consistency measure confirmed the convergent validity of the SALG questionnaire.

Table 6. 3: Internal consistency reliability (Cronbach's alpha) for the SALG scales

Factor	Number of items	Cronbach's Alpha
Active Learning	18	0.90
Concept Learning	7	0.84
Resources	4	0.81
Process Skills	3	0.89

The discriminant validity of the items of the instrument was assessed by comparing the construct correlations with the square root of the average variance extracted (AVE). Fornell and Larcker (1981) specify that discriminant validity is achieved when the square root of the AVE of a construct is larger than its correlation with other constructs. The square roots of the AVE were calculated and are represented in bold on the main diagonal of Table 6.4. The off diagonal elements represent the correlations among the latent variables. The results reported in Table 6.4 confirm that the discrimination validity was achieved by all scales.

Discriminant validity according to Brown (2006) is expressed by results showing that indicators of theoretically distinct constructs are not highly inter-correlated. He further argued that, factor correlations above 0.80 imply overlap of items and point towards poor discrimination validity. As shown in the Table 6.4, the component correlation matrix obtained from varimax rotation ranged from 0.17 to 0.51, providing further evidence in support of the discriminant validity.

Table 6. 4: Inter construct correlations and square roots of average variance extracted for the SALG scales

	Active Learning	Concept Learning	Resources	Process Skills
Active Learning	**0.78**			
Concept Learning	0.45	**0.82**		
Resources	0.31	0.17	**0.89**	
Process Skills	0.51	0.41	0.35	**0.94**

Note. Square root of average variance extracted (AVE) is shown on the diagonal of the matrix

6.5 Confirmatory Factor Analysis

Confirmatory factor analysis was used to determine whether the factor structure resulting from the exploratory factory analysis could be confirmed on the data obtained from the Chem102 cohort during semester 2 in 2012 when a refined SALG was used. Subsequently, 154 students completed the SALG questionnaire containing 44 5- Likert scale items. SPSS v20 was used to analyse the data which resulted in a slight variation from the factor structure obtained in EFA. In lieu of the items grouped as 'resources' in EFA, a new group of items has emerged which was identified as 'group work'.

The distinct nature of the data used for EFA and CFA analysis may have resulted in a partial correspondence between the results obtained (Jan-Willem Van & Willem, 2001). Methodological issues were attributed to the EFA and CFA results originating from the same data set (Kroonenberg & Lewis, 1982). As in the case of cross-validation or comparative studies, the non-alignment of EFA and CFA results were commonly reported because the results originated from different data sets (Van de Vijver, 2011). As indicated earlier, the data used in this study for EFA has come from Chem102 of Semester 2, 2011 whereas, for CFA, the data came from Chem102 of Semester 2, 2012. The initial outcome of CFA, as shown in Table 6.5, does have a reasonable match of items with that of EFA, but the SPSS v20 did not yield the desired group of items that are potentially able to elaborate students' perception of POGIL.

Modelling where a specification of the number of factors is possible prior to the analysis. The confirmatory factor analysis in Structural Equation Modelling (SEM), enabled the researcher to carefully specify the constructs and their indicators in order to assess the reliability and validity of the measurements prior to their actual testing with the data (Marcoulides, 2001).

Table 6. 5: Factor loading after CFA for SALG – Chem102, 2012

Item No	Item	Factor Loadings			
		Active learning	Concept Learning	Group work	Resources
1	recognising argument and use of evidence	.69			
2	developing logical argument	.68			
3	connecting key class ideas	.67			
4	use of systematic reasoning in problem solving	.66			
5	connecting key ideas	.65			
6	number and pacing of tests	.60			
7	the pace of the class	.59			
8	applying learning in other situations	.59			
9	instructors explanation	.59			
10	why class focused on topics presented	.59			
11	feedback on my work	.56			
12	listening to discussions	.54			
13	inter-relationship of activities	.53			
14	attending class	.51			
15	clickers	.40			
16	sn1 sn2 reaction mechanisms		.75		
17	distinguishing types of isomers		.75		
18	nucleophilic substitution reactions		.73		
19	curved arrow conventions		.70		
20	classifying chiral and achiral molecules		.69		
21	identifying stereocenters in molecules		.69		
22	molecular forces		.61		
23	main concepts		.56		
24	identifying functional groups		.55		
25	relationships between concepts		.54		
26	representing molecules with lewis structures		.48		
27	working with peers			.67	
28	small group activities help my learning			.67	
29	participating in discussions during class			.59	
30	participating in group work			.59	
31	working with others			.59	
32	working with peers outside class			.57	
33	mini-lectures				.84
34	pencasts				.80
35	pencast solutions for homework				.78
36	blackboard				.59

Extraction method: Principal Component Analysis
Rotation Method: Varimax with Kaiser Normalisation

The researcher also used a more rigorous approach like CFA of Structural Equation

The SEM models constitute two components – the *measurement model* and the *structural model*. The path diagram (Figure 6.2) shows a measurement model depicting three latent variables or factors, the arrows pointing to the observed variables represent the factor loadings and the residuals for each observed variable. Also included is the structural model displaying the direct effects among the latent factors. CFA is a type of structural equation modelling that uses a measurement model specifying the relationship between observed measures and latent variables or factors (Brown, 2006). The structural model of SEM specifies the association between the latent variables or factors. The double headed arrows shown in Figure 6.2 represent the correlation between the latent variables. The residuals represent the variance between the proposed model and the observed data.

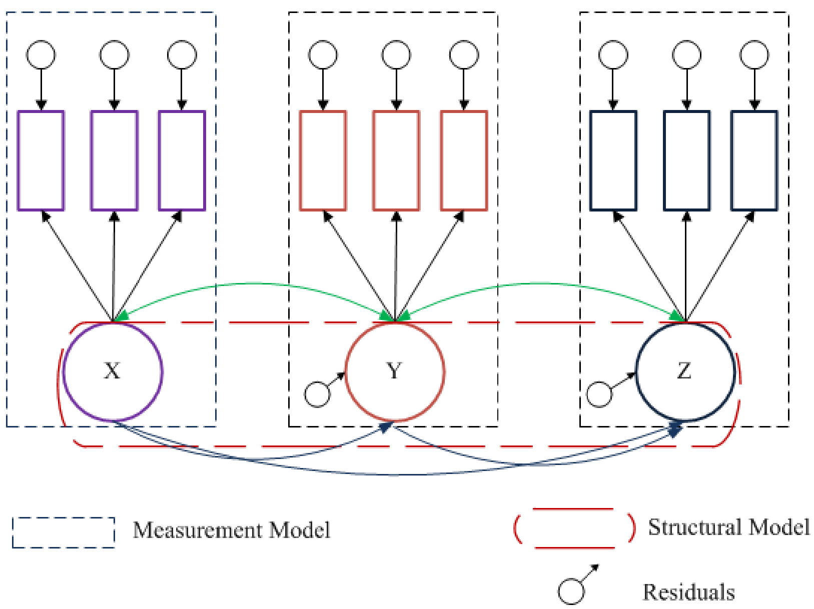


Figure: 6. 2. The measurement and structural models of SEM: with three latent factors.

In structural equation modelling, the data application of confirmatory factor analysis has two purposes (Hox & Bechger, 1998). The primary purpose is to obtain the estimates of the *parameters* of the model-like factor loadings, the variances and covariances of the factor, and the residual error variances of the observed variables.

The second purpose is to assess whether or not the model provides a good fit to the data.

The advantages of CFA over EFA, which are well documented (Brown, 2006; Hong, Purzer, & Cardella, 2011; Joreskog, 2007), include specification of conceptually viable measurement models, the ability to estimate the relationships among variables for measurement error, the ability to examine whether the measurement and structural parameters of the factor model are equivalent along the multiple groups, evaluation of measurement invariance, superiority in modelling flexibility, scale reliability estimation and robust evidence in the form of goodness of fit measures for construct validity.

6.6 The Hypothesised Model

The CFA model hypothesised *a priori* that Chem102 students' perceptions of POGIL would be explained by the four factors of SALG revealed by the exploratory factor analysis – Active Learning, Concept Learning, Resources, and Process Skills. In this study, for CFA the four-factor (Figure 6.3) measurement model was evaluated using IBM AMOS (Analysis of Moment Structures) v20 software that comes packaged with IBM SPSS. All tested models used maximum likelihood estimations. Model goodness of fit was evaluated using several indices: Chi-square, Chi-square/*df* ratio, Goodness-of-fitness index (GFI), Adjusted Goodness-of-Fit Index (AGFI), Comparative Fit Index (CFI), Root-Mean-Square Error of Approximation (RMSEA), Standardised Root Mean Squared Residual (SRMR), and the Tucker-Lewis Index (TLI). The measurement value indices proposed by Hu and Bentler (2009), Comparative Fit Index (CFI $\geq$0.9), Tucker-Lewis Index (TLI $\geq$0.9), SRMR ($\leq$0.08), and RMSEA ($\leq$0.08) were used in this study.

The SEM model may sometimes be modified to attain the goodness of fit. A modified model may have a parameter either added or deleted to improve the fit (Hox & Bechger, 1998). The AMOS v20, software used for SEM, computes modification indices suggesting the addition of various covariances between error terms. The CFA model in Figure 6.3 displays few of the error terms having such covariance. For example, in Figure 6.3, the covariance between e8 (participating in group work) and e14 (working with peers) is theoretically justifiable because these are strongly related parameters and have something specific in common. The analyses had identified such error terms and established covariance to improve the model fit. The factor loadings of the items of CFA, their corresponding item number in EFA and the squared multiple correlation values are presented in Table 6.6. Squared multiple correlations are an indication of how much of the variance of each factor is explained by the model. To take the variable *RES2 (pencasts)* as an example, 91% of its variance is accounted for by the latent factor *resources*. The remaining 19% of the variance is accounted for by the unique factor *e25*. Similarly, for *AL4 (working with peers outside the class)*, only 15% of its variance is accounted for by the latent factor *active learning*. The remaining 85% of the variance is accounted for by the factor *e13*.

The four-factor measurement model of CFA of SALG based on the values listed in Table 6.6 appeared to have met the criteria of the acceptable model fit (Bentler, 1990; Hu & Bentler, 1999) values of CFI (≥0.9), TLI (≥0.9), SRMR (≤0.08), and RMSEA (≤0.08). The chi square value was statistically significant and the lower GFI and AGFI values could be due to a relatively small size of the student population of 154 participating in the confirmatory factory analysis study (Fan, Thompson, & Wang, 1990). For the four-factor model, the following fit statistics; chi square goodness-of-fit value = 619.40, *df* = 385, chi-square/*df* = 1.61, GFI = 0.80, AGFI = 0.76, CFI = 0.92, TLI = 0.91, SRMR = 0.07, and RMSEA = 0.06 meet the adequacy criteria (Hu & Bentler, 1999).

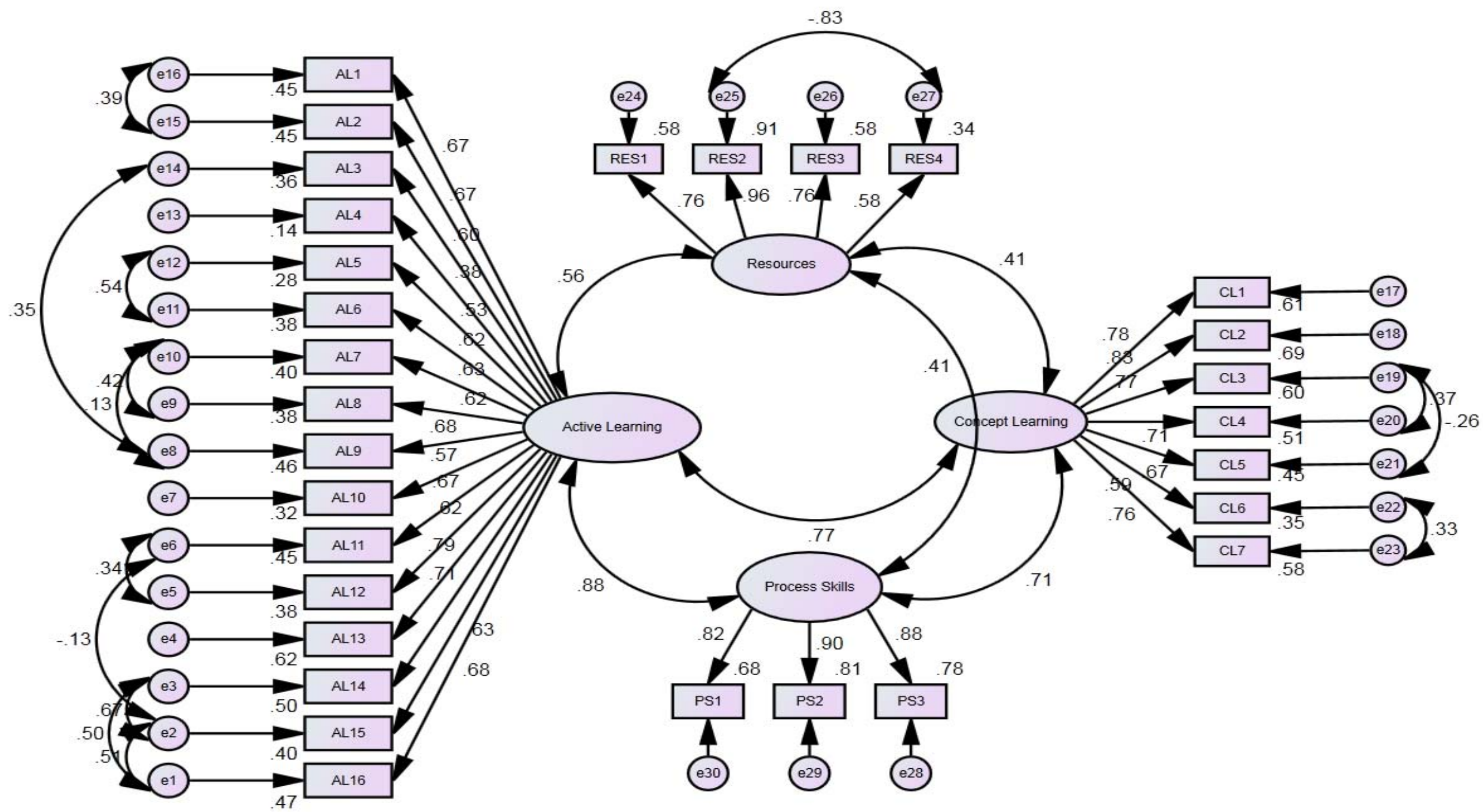


Figure: 6. 3. Confirmatory factor model obtained with SALG data from Chem102, Semester 2, 2012

Table 6. 6: Factor loadings of four-factor SEM and Squared Multiple Correlations (SMC)

Item	Item No in EFA	Scales of SALG				SMC
		Active Learning	Concept Leaning	Resources	Process Skills	
AL1	2	.67				0.45
AL2	1	.67				0.45
AL3	3	.60				0.36
AL4	4	.38				0.15
AL5	5	.53				0.28
AL6	6	.62				0.38
AL7	10	.63				0.40
AL8	11	.62				0.38
AL9	12	.68				0.46
AL10	13	.57				0.32
AL11	14	.67				0.45
AL12	16	.62				0.38
AL13	17	.79				0.62
AL14	7	.71				0.50
AL15	8	.63				0.40
AL16	9	.68				0.47
CL1	20		.78			0.61
CL2	21		.83			0.69
CL3	22		.77			0.60
CL4	23		71			0.51
CL5	19		.67			0.45
CL6			.59			0.35
CL7			.76			0.58
RES1	26			.76		0.58
RES2	27			.96		0.91
RES3	28			.76		0.58
RES4				.58		0.34
PS1	31				.82	0.68
PS2	30				.90	0.81
PS3	32				.88	0.78

The internal consistency reliability of the items of SALG after CFA was calculated and the values are presented in Table 6.7. The Cronbach's Alpha values for the SALG constructs after CFA resembled with those reported values of SALG EFA (Table 6.3). All of the four constructs exhibited high levels of reliability.

Table 6. 7: Internal consistency reliability of SALG scales after CFA

Factor	Number of items	Cronbach's Alpha
Active Learning	16	0.92
Concept Learning	7	0.89
Resources	4	0.82
Process Skills	3	0.90

The hypothesised structural model has been used to answer Research Question 4: In what ways do students perceive their learning while engaged in POGIL classes? The CFA model of the relationships between active learning, concept learning, resources and process skills is shown in Figure 6.4. The four-factor measurement model obtained from the confirmatory factor analysis was tested using IBM AMOS v20 for causal relationships between the four constructs, in an effort to answer the research question.

The fitness indexes; Chi-square = 623.67, *df* = 388, chi-square/*df* = 1.60, GFI = 0.80, AGFI = 0.76, CFI = 0.92, TLI = 0.91, SRMR = 0.07, and RMSEA = 0.06 meet the adequacy criteria (Hu & Bentler, 1999) for the four-factor structural model.

Standardized regression weights explained the extent of increase or decrease in terms of standard error that a variable can cause. Standard regression weights for the four constructs in the structural model are shown in Table 6.8. The estimated standardized regressions weights for all other factors are included in Appendix K.

Table 6. 8: Standardized regression weights

Constructs			Estimate
Process Skills	<---	Active Learning	.88
Concept Learning	<---	Active Learning	.78
Resources	<---	Active Learning	.54

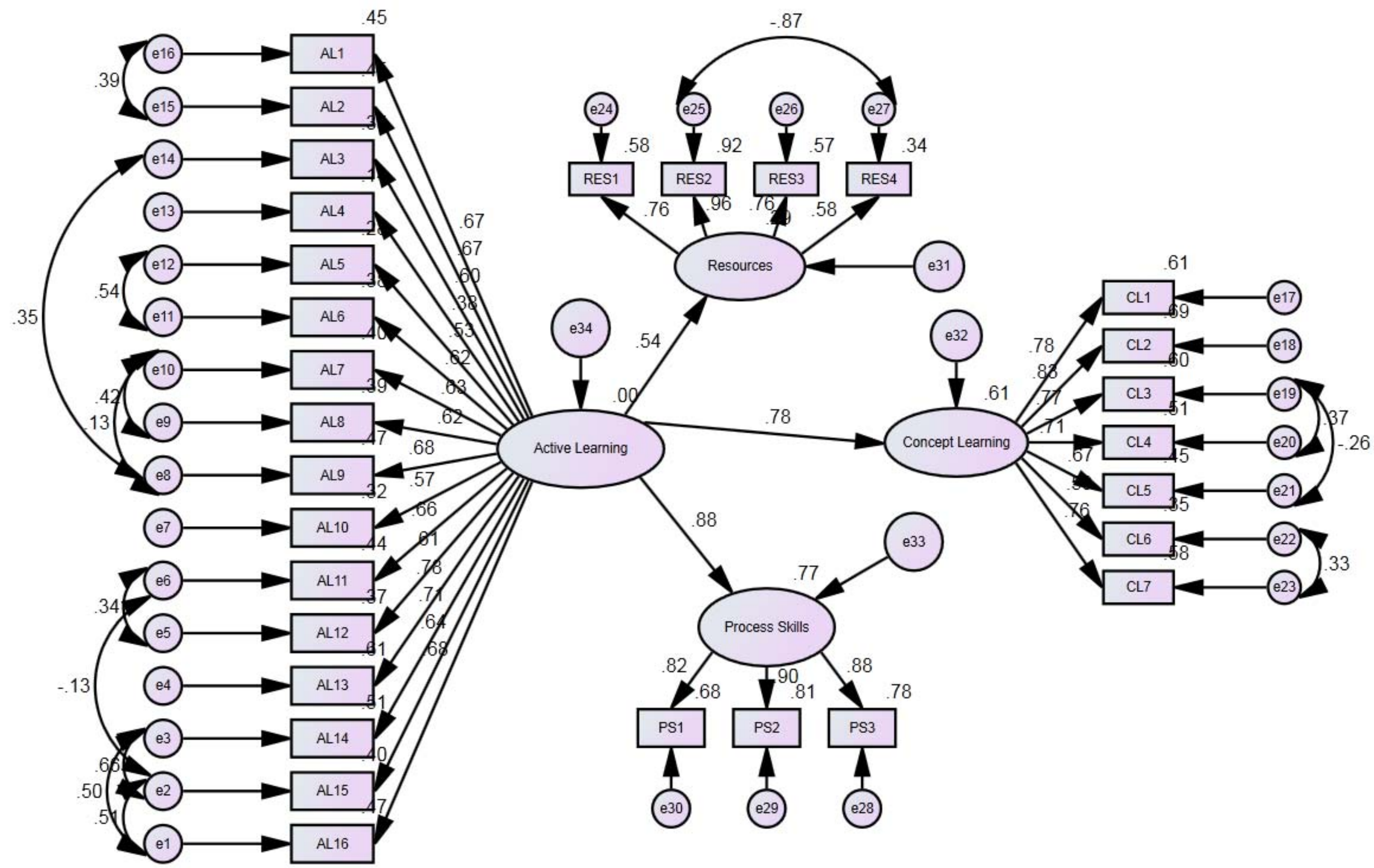


Figure: 6. 4. Structural model showing relationship between the latent constructs

Squared multiple correlations (SMC) for the four constructs in the structural equation model are shown in Table 6.9. The SMC provide information about how much variance the factors account for in the observed variables (Gorsuch, 1983). The SMC values of all the other factors are included in the Appendix K. The data showed the strong effects of active learning on the process skills of the students (0.77) followed by concept learning (0.65) and resources (0.29). These results suggest that, the students' POGIL participation has a positive effect on the development of their process skills and conceptual understanding.

Table 6. 9: Squared multiple correlations

Construct	Estimate
Process Skills	0.77
Concept Learning	0.61
Resources	0.29

Descriptive statistics of the items of the four scales were computed to further understand how students had self-reported their learning gains on each item of the scales. The mean scores, as shown in the Table 6.10, ranged from 2.74 to 3.66 and the adequate reliability ($\alpha > .70$) for the four scales as shown in the Table 6.8 indicate that all domains were rated highly by the student for the overall assessment of their improvement in learning.

Further, a comparison of the mean scores of the four scales revealed that the students consistently gave *concept learning* (7 items, maximum = 5, Mean = 3.47, SD = 1.05) and *active learning* (16 items, maximum = 5, Mean = 3.36, SD = 1.07) the highest rating. A look at the rating for organic chemistry topics like molecular forces (CL5), curved arrow conventions (CL6) and nucleophilic substitution reactions (CL7) revealed that the students gave highest scores indicating a greatest impact of POGIL in understanding these topics. Besides assigning high rating for the learning gains in organic chemistry topics, the students also felt that the instructional approach had a positive impact on their confidence and comfort levels (AL14, AL15 and AL16). Further, the learning gains due to the *active learning* were strongly attributed to attending class (AL1), working with peers (AL3), listening to discussions (AL8), participating in group work (AL9). However, for the *resources* section, the mean score was low (4 items, Mean = 3.00, SD = 1.41) except for RES4 where the students had strongly agreed (Mean = 3.40, SD = 1.40) that the use of clicker questions during lectures and tutorials/workshops had helped their learning. The learning gains due to the process skills were consistently attributed to the three items: PS1, PS2, and PS3.

Table 6. 10: Student assessment of their learning gains (SALG) mean scores Chem102, 2012

Item Number	Item	Mean	Std. Deviation
	Active Learning	3.36	1.07
AL1	Attending class	3.56	1.16
AL2	Pace of class	3.16	1.06
AL3	Working with Peers	3.66	1.11
AL4	Working with Peers outside the class	3.28	1.23
AL5	Explanation of instructor for involving small groups	2.92	1.15
AL6	Explanation of focus on topics presented	3.19	1.06
AL7	Participating in class discussions	3.20	1.03
AL8	Listening to discussions	3.47	0.97
AL9	Participating Group Work	3.56	1.02
AL10	Class Activities help learning	3.39	1.06
AL11	Number and spacing of tests	3.22	1.11
AL12	Feedback on my work tutorials	3.33	1.17
AL13	Connecting key ideas to other knowledge	3.40	0.92
AL14	Confidence understanding material	3.51	1.03
AL15	Confidence in ability to do POGIL activities	3.55	0.98
AL16	Comfort level involving complex ideas	3.31	1.06
	Concept Learning	3.47	1.05
CL1	SN1 SN2 reaction mechanism	3.39	1.11
CL2	Distinguishing Isomers	3.39	1.11
CL3	Classifying chiral-achiral molecules	3.39	1.07
CL4	Identifying StereoCentres	3.31	1.14
CL5	Molecular Forces	3.66	0.94
CL6	Curved arrows	3.64	1.03
CL7	Nucleophilic substitutions	3.50	0.95

	Resources	3.00	1.41
RES1	Mini lectures	2.92	1.30
RES2	Pencasts	2.74	1.44
RES3	Pencasts solutions homework problems	2.93	1.52
RES4	Clickers	3.40	1.38
	Process skills	3.26	1.09
PS1	Identify data pattern	3.23	1.02
PS2	Argument use of evidence	3.26	1.00
PS3	Develop logical argument	3.29	1.03

Correlation studies of the mean scores of the factors of SALG are presented in Table 6.11.

A Pearson correlation coefficient was computed to assess the relationship between the four factors of the SALG instrument. Overall, there was a positive correlation between the four factors of the SALG instrument.

Table 6. 11: Pearson correlation coefficient values of four factors of the SALG instrument

	Active Learning	Concept Learning	Resources	Process Skills
Active Learning		0.69	0.54	0.77
Concept Learning			0.42	0.66
Resources				0.41
Process Skills				

$p < 0.01$ level (2-tailed)

6.7 Qualitative Data Analysis

Further to the semi-structured interviews, open-ended questions also were included in the SALG questionnaire for the students to include their feedback on their learning experiences and perceptions in active learning chemistry classes in the form of written statements. This procedure was intended to corroborate the findings from the students' interviews and identify areas for further exploration. In other words, these open-ended responses on questionnaires allow the research to explore participants' perspectives and provide information in support of the emerging theories (Creswell, 2005).

6.7.1 The Profile of the Interviewees

All ten students were studying Chem102 at the time of the interview. For the purpose of protecting their anonymity, these students were assigned with codes which started with 'CS'. Table 6.12 provides a summary of the profile of the interviewees.

Table 6. 12: Demographics profile of the interviewees (N= 10)

Student Data Source Code	Major	Status	Gender	Level of Chemistry Background
CS1	Science	Australian	Male	Mature Age
CS2	Engineering	Australian	Male	High School Chem
CS3	Engineering & Commerce	Australian	Male	High School Chem
CS4	Engineering	International	Male	High School Chem
CS5	Chemical Engineering	Australian	Male	Bridging Units
CS6	Chemical Engineering	International	Female	High School Chem
CS7	Petroleum Engineering	Australian	Female	High School Chem
CS8	Petroleum Engineering	Australian	Male	High School Chem
CS9	Petroleum Engineering	Australian	Female	High School Chem
CS10	Science	Australian	Male	High School Chem

6.7.2 Approach to the Interview Analysis

The data pertaining to the ten interviews were transcribed and quality assured by the researcher. The quality assurance procedure involved the researcher listening to the tapes for clarity while transcribing. The Chem102 students' (*n* = 114) written responses to the open ended questions of the SALG were also transcribed. The transcripts were entered into NVivo (NVivo, 2012) and coded to generate themes and which were later explored across for meaningful conclusions. For the purpose of categorisation of nodes into themes, the guidance of a postdoctoral researcher experienced in the QSR NVivo analysis was sought. The inter-rater agreement scores (evaluate agreement between two classifications) were not performed as the entire coding process was independently completed by the researcher.

The SALG constructs obtained from CFA provided guidance in terms of analysing and interpreting the qualitative data. As shown in the Table 6.13, the thematic content analysis of the qualitative data resulted in six broad categories: teaching, learning, resources, process skills, attitudes and resistance. In an effort to seek an explanation to the Research Question 4 outlined in section 6.2, these broad categories are further divided into themes, categories and sub-categories in order to analyse and cluster systematically the students' responses.

Table 6. 13: The six categories that emerged out of the coding of student qualitative data

Category	Themes
Teaching	Instructional approach, atmosphere, participation
Learning	Understanding of concepts/subject, key ideas
Process Skills	Teamwork, group work, communication, logical/critical thinking, study skills etc.,
Resources	Text book, learning management system (blackboard), lecture capture (iLectures), tests, quizzes
Attitude	Enthusiasm, confidence, interest
Resistance	Disagreement, lack of interest

6.7.3 Students' Perception of their Learning Gains in POGIL Classes

This section presents the results and findings in response to the Research Question 4 according to the identified categories and themes listed in Table 6.13.

Category: Teaching

This category was used to ascertain students' perceptions about the small group learning in chemistry class. The responses were clustered into themes, namely, instructional approach, atmosphere of the class and their participation.

Theme: Instructional approach, atmosphere and participation

CS9, CS6 and CS4 believed that the instructional approach in the POGIL class prepared them for inquiring into the concepts by way of finding solutions to the critical thinking questions. From the following excerpts, it is evident that students identify this teaching approach in chemistry as an innovative way to problem solving and conceptual understanding.

> *I guess with a small group you are going to be with different people with different ideas and I guess different approaches towards a chemistry problem, so I guess that can help you learn, not just new aspects of the chemistry world, but new ways on how to tackle certain questions in the chemistry world. (CS9)*

> *Yes, because it makes you think about… you know, the processes involved on your own, and I guess it helps the thing get stuck into your mind. (CS6)*

> *We discuss it, and then we see the logic behind the concept. And then we have the lecture notes, some internet, so we can carefully research it. And then we come up with, like, our ideas and then we discuss again, and then we come up again with the right concept. I pick up the concept in my lectures and activity, and then we have to pick up the concept really quickly, so for example, it can really help me with picking up the concept. (CS4)*

CS8 admitted that the role of the facilitator in a POGIL session allowed students to seek clarification on questions which he found difficult in a traditional mode of lecturing. CS9 also underpinned the need for solutions to critical thinking questions that were included in the activity sheets, to avoid any misunderstandings or misconceptions.

In some ways it is good. But in some ways I do like traditional training where you go in, you take notes, you learn stuff. Sometimes it can be frustrating because, yes you can ask questions and they will, like, they won't get time to answer your questions, and you kind of like not knowing the concepts. (CS8)

I think it is pretty good in a way, but is better if we can get the answers because we don't have solutions. We have to find a solution our self, and sometimes if we understand a wrong concept we might get it wrong, and then when you bring that to the exam you just mess it up. (CS9)

CS9 considered that participation in class activities help retain the knowledge gained from them.

Yes, more active learning I guess, because while I listen in a lecture, when I walk out I forget visibly, yes because I have to learn something. I have to … if I learn something I have to actually do it, because I am not a person who can read and remember. (CS9)

The following excerpts from the open-ended SALG statements revealed that, apart from the understanding of the concepts, students' participation in POGIL group discussions is dependent on the atmosphere of the class, in other words, a positive learning environment had maximised the student participation.

"the instructors and help on the tutorials helped me understand things better", "I participated regularly but enjoyed listening to discussions", "all the time small group learning helped me deepen my understanding", "I participated as much as possible and the atmosphere encourages this", "personally had little participation, preferred to listen and construct my own ideas", "I sometimes participated in class discussions, the classroom atmosphere encouraged participation as the lecturer was pleasant even if the answer was wrong", "it contributed to the group discussions often and the atmosphere of the class is encouraging".

In contrast, two factors appeared to impede the student participation, namely, the noise level and individual learning style.

> *"Participated in every group discussion in every class. Noisy atmosphere of the class, comfortable asking for help", "I sometimes participated, as I prefer solidifying concepts by my own logic. If I did not understand them, then I would discuss. The class becomes somewhat chaotic with mass discussion, which can be distracting", "participated often in my immediate group. However as a shy person I felt the class too large to join in class discussions", "I often participate in class discussions and it is helpful however sometimes not that encouraged because of the partners are not so proactive"*

Category: Learning
Theme: understanding of concepts/subject, key ideas

The following responses to the open-ended SALG items were associated with this category in support of a positive impact of the POGIL activities on the students' learning.

> *"the activities helped me remember key ideas in this class, however it would be helpful to have solutions posted so we can check our answered which is particularly helpful for exam study and preparation", "The activities are a good method of identifying key concepts and ideas, help to remember them", "the activities generally help in understanding and remembering concepts and ideas. "Summaries also reinforce this", "the workshops were taught well but the only lecturer that was out to learn from was …... The others were not as entertaining and didn't draw my attention as well. Just my personal opinion", "I still struggle remembering all the different reactions but the key concepts were exemplified numerous times which helped drill them into us".*

These findings suggest that POGIL activities helped these students' to master concepts in preparation for examinations in addition to active revision of the content.

Comparing the nature of the POGIL approach to that of a seminar-type discussion between presenter (lecturer) and audience (students), CS8 felt that the facilitator assisted or guided completion of activities helped these students attain their learning goals.

> *Yes. Completion of the activities or worksheets with the guidance of the facilitator is a very good pathway in achieving the learning goals, but I think, maybe, we do not have it solely active learning, and maybe, just more of a mix, so if we had it as part of a lecture where we do take notes and we learn from the lecturer. And then have almost like a seminar discussion afterwards, where we can complete the activity and go from there, rather than learning solely through the activity. For me that is … I would find that more productive. (CS8)*

On the contrary, CS7 and CS8, the students who chose to do Chem102 directly without Chem101, indicated that the examining the perspectives of POGIL instruction in Chem102 is difficult without experiencing it in Chem101.

> *So it was a bit hard to know whether you were on the right track. Also, not doing Chem101, and then coming into Chem102, and all this, like, interactive learning blah blah, and they expected you to know how it worked in second semester as well. So it was a bit … so we were a bit on the back-foot kind of thing. (CS7)*

> *Even if it is just a simple one that, say for example, we didn't learn Chem101, but we need to know it for this topic. It is sort of just assumed that you know it, then, it can be a little bit frustrating because it is sort of … like well, get the book, and learn it yourself. It's like, well, I would still like to be able to have some recognition on that. This is important. You should know this, and this is how you can go about it. (CS8)*

These excerpts attest to the finding that POGIL learning may be beneficial when the students study the chemistry units, Chem101 and Chem102 consecutively. More specifically, Petroleum engineering students like CS7, CS8 and CS9 who did not study Chem101 but had to complete Chem102 as part of their course requirement, were unable to recognise the importance of POGIL in chemistry classes.

Category: Process Skills

This category was used to ascertain students' perceptions of the use of process skills in a POGIL class and how such skills have influenced their chemistry learning. Two themes were included in this category to cluster the students' responses. Theme 1 represents group work / teamwork and theme 2 represents the clustering of students' responses related to Communication, logical thinking, problem solving skills.

Theme 1: Group work / Teamwork

Seven responses were related to group work/teamwork.
CS1 regarded small group learning as social interaction in the class.

> *Look … I am comfortable with all that kind of thing. It's just growing up with, I suppose, a different way of learning, Absolutely, I mean, it is not just a little about learning, it is also about the socialisation part. (CS1)*

Speaking on the dynamics of the group members, CS2 said that when group members are motivated, they tend to learn, and he also felt that inter-group consultation may help in the affirmation of conceptual understanding.

> *I think that in regards to the small group … working in the small groups, it does work but only if you have got a group that is actually willing to work. It is only those groups that are willing to...are actually want to learn in that lecture. (CS2)*

> *Yes. I mean, fortunately, where I normally sit, we have got a pretty good group. Or our group in general has been formed is quite good, so there is my group and also the group also sits near us that are always working on the pros, so that we do cross communicate and check. (CS2)*

Group work in POGIL is characterised by the assignment of roles to the group members. CS3 identified the importance of self-actualisation of group role before interacting with other group members.

> *I would … I personally, I am not quite sure what I … if I had a choice I would probably treat myself as one of the .. as like a reporter, as someone who likes to research the information, or likes to get it … because I personally don't want to get … I personally want to know the aspects myself before I send it to my group so that I can understand it and then place into my workload and then use that and then communicate with my whole group, so that they can understand it as well – see where I am coming from. (CS3)*

In addition, CS5 considered that small group discussion is valuable in terms of verification of conceptual understanding in the classroom as it offers a peer-lead learning opportunity.

> *It is not a waste of time; it is good just to share your answers and double check. Like reassure yourself that you get it right, and if you don't you can discuss it, because obviously there is only 1 tutor, so if she was busy with someone else, it is obviously of benefit to have discussed it with someone else. So, I wouldn't say it was a waste of time. Yes. (CS5)*

Further, CS5 believed that the POGIL activity-driven identification of concepts helped them to advance their knowledge of a particular idea or concept.

> *That is the activities kind of benefit, is you are like exploring something to get you going, you are figuring it out yourself rather just taking information and not meaning anything. A lot of activities provide that systematic kind of optimal progression through an idea. So that is … when we group. (CS5)*

CS6 and CS9 believed that group-assisted learning is helpful in understanding the concepts more than individual participation.

Not really. Just sort.. it was just working together. It's an unstructured group work. Small groups are pretty helpful, because it is different people, ways of thinking, then it is oh so … you know it helps.. It is much easier to understand something when you are in a group and people are telling you, than instead of being on your own and in a big lecture hall. Yes. As engineers need to work as a group, and then it is pretty much group work solving a problem. (CS6)

Pretty good. Pretty … how should I put it … a lot of work where we group together in a lecture instead of sit there and listen. (CS19)

These findings suggest that students' placing in POGIL classes as small groups and their active discussions help them understand the concepts more easily than working independently. Research evidence (Cole et al., 2012) show that students' active discussions and argumentations improve their understanding of concepts. Furthermore, the factors like motivation, group roles, and divergent thinking appear to influence their learning in first year chemistry classes.

Theme 2: Communication, logical thinking, problem solving skills

CS3 felt that group discussions help improve communication skills and the student asserts this as an essential skill for multi-disciplinary learning contexts.

Group work, I personally don't believe that it is a waste of time, because it helps you improve on your communication skills, I know for a fact that it is not just applicable for the engineering course, but for any sort of world you have to have that communication skill or you are just not going be able to go, so yes. (CS3)

Contrary to CS3, CS5 considered the gain of logical thinking ability. The following excerpt attests to the finding:

I think so. The logical skills, yes definitely. I wouldn't say communication. I think the logical properties of some of the … just like patterns and reading *patterns and then you need something to simply I find a lot of it is just following patterns. Sort of working through an idea and, okay, if this is the case, then is this is the case, then what can you infer, what can you suggest about this. So it is like leading on the logical kind of reply. (CS5)*

In their open-ended statements on SALG instruments, the students reported that the group work had strengthened their problem solving skills. It helped them understand the critical thinking questions based on the limited information available from the worksheets. The group work also helped to mind-map the concepts, and write the answers quickly and efficiently during the lectures or tutorials or laboratory sessions. Students have also reported the development of logical questioning, connecting key class ideas, and the skill of reporting of the progress of the group back to the facilitator. The following excerpts provide evidence for the finding that students have self-reported the development of evidence-based logical argument and analytical skills:

"better communication, learning to tackle problems. Using rules and logic rather than just looking at the single problem", "this class let me gained the skills which I can connect some knowledge to others what we had learnt before", "communication, logical questioning and more independent", "pattern information is greater than memorising information", "the discussion among others and the activity helps with connecting key class ideas", "interpersonal skills, lots of improvement there", "analytical skills, communication skills among peers and problem solving skills", "writing quickly and efficiently in labs".

Category: Resources

This category was aimed at seeking the students' perceptions on the use of resources like the textbook, tests, and technology like clickers, the learning management system (Blackboard), lecture capture (iLecture), and pencasts.

Theme: textbook, clickers, learning management system (Blackboard), lecture capture (iLecture) and Tests

CS3 and CS5 felt that resources like textbook and clicker questions helped them understand and revise the concepts.

> *The list, I would first have to say that the lecture notes and the book especially, because ….. I like the lecturer. It is just that with his activity sheets you have to be really independent, and that is where the book came in to help and that is why I found the book to be very resourceful. So yes. (CS3)*
> *Clicker questions are good, and to see how the rest of the class is going and you can find out which points are important key things you have to be knowledge of. It is good for that purpose … (CS5)*

The following students' statements from the open-ended items of the SALG instrument indicate a positive effect of the use of technology and other traditional resources like textbook and lecture notes on their learning. The findings suggest enhanced students' learning when POGIL lessons are blended with the use of technology.

> *"the textbook and lecture notes were the main source of learning", "clicker questions: it makes me have a better understanding of the content and enhanced my learning and confidence", "blackboard helps the most, post all the information", "many resources gave good gains in result", "the lecture notes were helpful. Anything further was clarified in the textbook", "clickers were extremely helpful and usually learnt the immediate knowledge better", "the group activities in lecture helped me understand the key concepts", "the clicker questions were good, helped my understanding and confidence in the subject", "clicker questions were fun. The textbook and lectures are the best resources for this unit", "blackboard/internet used in the lab", "the textbook help me mostly in Chem102, there are no pencast and mini lectures in Chem102 like in Chem101 it helped me a lot, "resources, especially pencast solutions help me to their understanding".*

Category: Attitude

This category exemplified the students' measure of their perceptions about POGIL class in terms of enthusiasm, confidence and interest.

Theme: Enthusiasm, confidence and interest

The findings in this theme, based on the data generated, indicate that the students who reported increased confidence, enthusiasm, and interest had a better understanding of the content. The following excerpts from the open-ended SALG questions indicate that students developed a positive attitude towards their learning in chemistry using small group active learning.

> *"This class has increased my enthusiasm for the subject as I can see some practical examples and applications for what I am learning", "more passionate for the subject of chemistry", "I am positive about getting good marks in chemistry", "I found aspects interesting which may be more positive in doing independent study", "increased confidence in my ability to understand ideas", "completing tutorials confirmed my understanding of each topic, giving me confidence", "the class has helped in learning more complex ideas which were greatly helpful", "made me appreciate the complexity and beauty of physical sciences", "it changed a lot and gave me new idea how to study other subjects", "understand more than before, it gives me confidence".*

Expressing a more confident attitude towards chemistry, CS7 felt that peer-assisted learning is a way to transfer knowledge within a group.

> *I think rather than our knowledge, the confidence is raised. I think it has been more confidence in being able to help someone else if they had a problem, because obviously you are sharing what you know, but I think it probably encourages you to ask questions more. (CS7)*

> *It has, kind of, because you have a bit more confidence in your analytical skills, you know you have to give things out and kind of discover concepts for*

yourself, so you kind of you think I was capable of figuring it out. So you do have more confidence in knowing the fundamental laws. Not just knowing how to answer questions. (CS9)

Category: Resistance

This category was used to elicit students concerns about the implementation of active learning strategies like POGIL activities. Students' feedback ranged from the timing of the lecture to the dynamics of the student participation in class discussion. Whereas it is interesting to note that no student had spoken negatively about the fundamental aspects of active learning such as the design and the delivery of the instruction. However the volunteer interviewees were likely to self-select aspects like timing of the lecture, their own approach to participation in group work.

Theme: Disagreement, and lack of interest

Students express their resistance to pedagogical innovations in various forms. The excerpts from the interviews with three Chem102 students reflected this. According to CS4, an International student who studies Engineering believed that timing of the lecture is a motivating factor for not having a positive feeling about small group active learning.

It is kind of annoying because now they have a 1 hour small lecture, right, and then most of the time it is on the days when there are no other classes, so it is like it is only a 1 hour lecture on a Wednesday and I don't have any other classes. I don't know if it is worth it. Sometimes people think that they can, like, they don't have to go to the lectures because it is group work, so you can just do it at home. (CS4)

Another student CS10 felt that they spend most of the class time finding answers to the critical thinking questions by a way of class discussion which in turn becomes distractive due to the presence of non-participants.

I feel like I don't really learn as much in … and even when we have been doing questions that sometimes feel like I am not learning as much as we *would be if we were writing notes. And a lot of the class gets distracted and they don't end up doing their activity, so they become distracting in the background to try and not to work. (CS10)*

CS1 argued that class discussion among the group members is challenging when the members do not recognise the learning context.

I don't think it is an efficient exchange of information. It depends, and as I said, if you're partnered with two other people who really don't know what is going on, in the lecture they just have no idea. (CS1)

The following responses from the open-ended statements part of the SALG instrument point towards a very minimal resistance based on the count of such negative statements from the student population.

Active learning was a horrible teaching method. I felt I learnt nothing from attending those lectures, which resulted in me not attending more than five lectures throughout the semester, it gave me a more negative attitude towards chemistry. I enjoy chemistry classes but the way this unit is taught makes less comfortable with the group, do not really like it any more than before.

Triangulation studies of data presented in Table 5.14, 6.12 and the resulting NVivo themes of teaching and learning indicated a positive correlation between the concept learning and active learning scales of the SALG instrument. That means that the students have reported a greater understanding of concepts as a result of POGIL interaction and POGIL activities. A strong positive correlation also existed between active learning and the process skills revealing that students have reported a greater development of process skills due to participation in POGIL activities.

6.8 Summary

The fourth research question investigated the students' perception of POGIL learning using quantitative and qualitative methods. The data analyses occurred in two phases. First, the factor structure was established for the SALG instrument and later the resultant scales were utilised to gauze the students' perceptions. The need for establishing the validity of the SALG instrument was discussed and the EFA study had yielded a four-factor model for the SALG instrument. In the CFA study, a different data set was used to examine the latent structure of the SALG instrument. The hypothesised four-factor measurement model of CFA of SALG had met the acceptable model fit criteria.

The mean scores of the items of the four scales and the inter-scale reliability results indicate that the students rated highly about their improvement in learning. The instructional approach seemed to be beneficial particularly for organic chemistry topics like molecular forces, curved arrow conventions, and nucleophilic substitution reactions based on the students' rating for these items on SALG instrument. A positive impact of the instructional approach was also evident on students' confidence and comfort levels. Further, the use of clicker questions during lectures and tutorials/workshops had also helped the students' in understanding the concepts in POGIL classes.

The qualitative analysis of the semi-structured student interviews and their responses on open-ended statements in the SALG instrument indicated the positive impact on chemistry learning because the students had reported an improved understanding of chemistry concepts when they actively participated in small group discussions in a POGIL class. Students have also reported the development of process skills as a result of small group POGIL interaction besides a better understanding of the content.

Chapter 7
Discussion and Conclusions

7.1 Introduction

Section 7.2 outlines the summary of every chapter of the thesis. Section 7.3 presents the major findings in relation to the four research questions of the investigation. Section 7.4 describes the limitations of the investigation and Section 7.5 outlines the opportunities for future research.

7.2 Summary of the Thesis

The purpose of this study was to explore the outcomes of using process-oriented guided inquiry learning in first year chemistry classes at Curtin University. Subsequently, students' understanding of chemistry concepts in a modified POGIL class was investigated in addition to these students' perceptions about learning chemistry using the POGIL approach. The premise was demonstrated by concerns that traditional lecturing was not meeting the educational needs of the students. A large number of recent research studies have focussed on the evaluation of small group active learning pedagogies like POGIL, principally in terms of student achievement in tests or end-of semester examinations. However, students' understanding of concepts, especially those of first year chemistry, still remains unaddressed. Therefore, the main focus of this study included both students' conceptual understanding of stereochemistry and their perceptions of learning in POGIL chemistry classes. The stereochemistry concept diagnostic test (SCDT) was devised to investigate students' understanding of stereochemistry and the students' assessment of their learning gains (SALG) instrument was administered to explore students' perceptions of their learning.

In the introductory chapter of the thesis, the background and significance for investigating the process-oriented guided inquiry learning in first year chemistry classes was described. The objectives and research questions of the study were outlined.

Chapter 2 presented a review of literature regarding the research on the curriculum framework adopted for the research study and the theoretical framework that underlay the philosophy of the POGIL approach. The literature related to POGIL activities and the intended process skills were presented. Since the study followed students' understanding of chemistry concepts in POGIL classes, an overview of the related research on student conceptions and the origin of alternate conceptions were presented. Studies on students' alternative conceptions of organic chemistry including stereochemistry, methodologies for investigating alternate conceptions using two-tier diagnostic tests, implementation and effectiveness of POGIL, students' perception of POGIL and POGIL in Australia were reviewed.

In Chapter 3, the exploration of process-oriented guided inquiry learning was approached from the perspectives of the intended and the implemented, the achieved, and the perceived curriculum (Keeves, 1995; Treagust & Rennie, 1993). The required knowledge to conceptualise the principles of stereochemistry was presented as propositional content knowledge statements. The study utilised a mixed-method research design, involving qualitative and quantitative approaches to collect and analyse data (Creswell, 2003). Quantitative data were analysed using IBM SPSS v20 and IBM AMOS v20. The qualitative data were analysed using NVivo 10. Curriculum documents related to first year chemistry units were analysed to answer Research Question 1. The data from semi-structured interviewing of students and researcher's observation of lectures and tutorials/workshops were used to answer Research Question 2. For answering Research Question 3, the data were obtained using SCDT from 61 Group 1 (Chem102, Sem 2, 2011) and 79 Group 2 (Chem121, Sem 1, 2012) students. The SALG instrument was used to collect data from 268 students to answer Research Question 4. Ten students participated in semi-structured interviews. The data from the open-ended statements of the SALG instruments and the student interviews were used to complement the quantitative results about their understanding of stereochemistry concepts in POGIL classes.

Chapter 4 reported the results and findings in response to Research Questions 1 and 2 on the skills needed for students to succeed and the implementation of the required learning in POGIL classes. Chapter 5 presented results and findings of student understanding of stereochemistry concepts in response to Research Question 3.

Chapter 6 presented the results of the validation of the SALG instrument, quantitative and qualitative results and findings on students' perception of their learning in POGIL class in response to Research Question 4.

A summary of the major findings of this study are now provided in this chapter. Limitations of the study and recommendations for future research and conclusions are considered.

7.3 Major Findings

The following section discusses the findings of the research study in the context of the research questions and the literature review.

7.3.1 Research Question 1

How do the skills that students learn in POGIL classroom align with university graduate attributes?

This research question was concerned with the intended curriculum described in Chapter 4, which was answered by analysing the course content of the first year undergraduate chemistry units to see how the learning outcomes were articulated with respect to an active learning pedagogy like POGIL in terms of process skills and graduate attributes. The coherence between the university's graduate attribute policy and the philosophy of POGIL indicated that the instructors emphasised the classroom implementation of process skills development. Consistent with university policy and the goals of POGIL, Hanson and Wolfskill (1998), Moog and Spencer (2008), and Burke (2009) had reported discipline-based approach for the simultaneous development of content knowledge and process skills. The existence of a good fit, as shown in Table 4.5 (Chapter 4), between the graduate attributes and process skills in POGIL classes was evident from the nature of POGIL materials, students' interactions and instructors' rich experience in POGIL facilitation.

7.3.2 Research Question 2

How can these learning requirements be implemented through a POGIL based curriculum?

The research question was concerned with the implemented curriculum described in Chapter 4. The implemented curriculum matched the intended curriculum. The delivery of the content was aimed at the students' understanding of discipline-specific concepts together with the development of graduate attributes is similar to what Bailey et al. (2012) had reported. The development and acquisition of process skills was intrinsic to the curriculum and the modified POGIL approach appeared conducive to the desired learning requirements. The qualitative data were examined and compared with the quantitative findings as a means of mixed-method triangulation of both the quantitative and qualitative data. The results from the analyses of curriculum documents, POGIL materials, students' written responses to the SALG items and interview excerpts indicated that the use and development of transferable generic skills in POGIL class were consistent with other POGIL implementations from the literature (Criasia et al., 2009; Douglas, 2009; Geiger, 2010). As described in section 4.7 of Chapter 4, the modified POGIL approach in the form of embedded mini-lectures, small group POGIL discussions, followed by clicker questions appeared to be an appropriate way of developing the intended process skills along with chemistry content knowledge. The students' consistent reporting of learning gains due to process skills was attributed to the skills of identifying data pattern, argument use of evidence and the development of logical argument.

7.3.3 Research Question 3

How effectively do students achieve the intended learning outcomes using a POGIL approach?

The third question was concerned with the achieved curriculum described and analysed in Chapter 5 and was limited to stereochemistry for the discipline-content of this investigation. The required knowledge to conceptualise the principles of stereochemistry in the form of propositional content knowledge statements was presented in Section 3.8.2.2 of Chapter 3. The ancillary research questions 3.1 and 3.2 explored students' misunderstanding of the concepts which were grouped based on the items of the SCDT, namely, stereocentres, enantiomers, chirality, stereoisomers, and molecular visualisation.

Stereocentres

The post-test SCDT results revealed students' difficulty in recognising stereocentred carbons based on their atomic connectivity. Another misunderstanding that was prevalent among the students was that stereocentred compounds are always asymmetrical. This finding is in line with a study by Taagepera et al. (2011) and Zoller (1990) who reported students' difficulty in characterising molecules based on stereocentres, chirality, a plane of symmetry and image formation. Further, at the end of the delayed post-test, the students appeared to have difficulty identifying stereocentres in cyclic systems.

Chirality and Enantiomers

The analyses of the post-test SCDT data identified two misunderstandings. They are: Achiral compounds have an enantiomer and chiral compounds do not have an enantiomer. The students' difficulty in distinguishing the terms *chial* and *achiral* for geometrical models has been extensively reported (Lloyd-Williams & Giralt, 2005; Lujan-Upton, 2001; Taagepera et al., 2011). These misunderstandings occurred for propositions SC5 and SC6 (see Table 3.3) which were clearly caused by students believing that achiral molecules form non-superimposable mirror images and chiral molecules form superimposable mirror images. The students appeared to lack the ability to make a distinction between chiral and achiral molecules on the basis of superimposable mirror images.

Similarly, the students' incorrect response-reason combinations revealed a misunderstanding that achiral molecules have no internal plane of symmetry and chiral molecules have an internal plane of symmetry.

Stereoisomers

The students appeared to lack the ability to identify the stereocentres of the given molecules as they incorrectly estimated the possible number of isomers when the number of stereocentres in the molecule is known. Two misunderstandings occurred for propositions SC10, SC13, and SC14 (see Table 3.3). Students incorrectly identified that 2-deoxyribose has two asymmetric carbons and another misunderstanding was that one stereoisomer resulted from every stereo-centric carbon.

Molecular Visualisation

The students had experienced difficulty in mentally visualising the given molecules in item 5. The data analysis revealed students' misunderstanding that the two molecules are enantiomers which are non-superimposable on their mirror images. This finding is consistent with earlier work that demonstrated the difficulty that many students find with tasks that involve interpreting a 2-dimensional representation into a 3-dimensional image, performing mental operations like rotation on the 3-dimensional image, and re-representation of newly visualised 3-dimensional image as a 2-dimensional representation (Bucat & Mocerino, 2009; Head & Bucat, 2002; Steiff, 2007; Tuckey & Selvaratnam, 1993)

The third ancillary research question 3.3 investigated the statistical differences between learning gains for Group 1 and Group 2 students. The results as shown in section 5.7 (see Chapter 5) indicated a positive effect of POGIL instruction and more specifically that the POGIL discussions showed a very large effect size on SCDT scores for the Chem102 cohort. The results presented in Table 5.14 support similar POGIL intervention studies in undergraduate chemistry courses (Bailey et al., 2012; S. D. Brown, 2010; Criasia et al., 2009; Geiger, 2010; Hale & Mullen, 2009). Each of these studies focused on the identification of students' gaps in their content knowledge and their misunderstandings in undergraduate courses.

7.3.4 Research Question 4

In what ways do students perceive their learning while engaged in POGIL classes?

For answering this question, which was concerned with the perceived curriculum reported in Chapter 6, both qualitative and quantitative data were collected and analysed. The criterion validation of the SALG instrument was first established using exploratory (EFA) and confirmatory factor analyses (CFA). Later, the CFA causal model of structural equation modelling (SEM) and Pearson correlations between the SALG constructs were used to estimate the students' perceptions of POGIL.

The factor analysis of the data obtained from 114 students of Chem102, Sem 2, 2011 cohort resulted in a four factorial structure of the SALG instrument, namely, Active Learning, Concept Learning, Resources, and Process Skills. The internal consistency reliability (Table 6.3) was highly satisfactory where each factor scored a Cronbach's alpha coefficient value greater than 0.80.

For CFA, the explored four factor model was fitted to the data obtained from Chem102, Sem 2, 2012 (*n* = 154) cohort, using a measurement model of structural equation modelling (SEM); the fit statistics met the criteria of a good fit. The Cronbach's alpha internal consistency reliability values (see Table 6.7) of the SALG constructs after CFA were also highly satisfactory (>0.80). The findings give support to Hong, Purzer, and Cardella's (2011) suggestion that, for adapted instruments, the CFA be used to test the fit of the factor structure from a sample different to the EFA. The CFA causal model of relationships (see Figure 6.4) between Active Learning, Concept Learning, Resources, and Process Skills met the adequacy criteria (Hu & Bentler, 1999) indicating the positive impact of POGIL on understanding of concepts and process skills. The mean scores for the items of all of the four scales (see Table 6.10) in this study indicated that the students rated all the domains highly for the overall assessment of their improvement in learning. This finding is in line with those of Johnson, Corazzini and Shaw (2011) and Seymour (2000) who reported similar summary scale descriptive statistics for all the items of SALG.

Based on the students' rating for these items on SALG instrument, the instructional approach of the adapted POGIL was shown to be beneficial, particularly for organic chemistry topics like molecular forces, curved arrow conventions, and nucleophilic substitution reactions. This finding supports similar studies (Browne & Blackburn, 1999; Farrell et al., 1999; Paulson, 1999) that reported an improvement of understanding of organic chemistry concepts by students when the topics were delivered using an active learning format. A positive impact of the instructional approach was also evident on students' confidence and comfort levels. Further, based on the clustering of students' positive feedback under the thematic category of resources as presented in section 6.7.3 (see Chapter 6), it was evident that the use of clicker questions during lectures and tutorials/workshops had also helped the students understand the concepts in POGIL classes.

The positive alignment between the POGIL approach and the perceived learning gains was evident from the students' high rating to the core elements of active learning, like attending class, working with peers, listening to discussions, and participating in group work (see Table 6.10). This conclusion is consistent with the findings of Hinde and Kovac (2001), Knight and Wood (2005), Kovac (1999) and Prince (2004) who investigated active learning strategies in STEM courses. In each study, the students felt that active learning sessions were valuable and they were more positive about learning chemistry.

The qualitative analysis of the semi-structured student interviews and their responses to open-ended statements in the SALG instrument indicated a positive impact on chemistry learning because the students had reported an improved understanding of chemistry concepts when they had actively participated in small group discussions during POGIL sessions. The results of the thematic content analysis of the qualitative data presented in section 6.7.3 of Chapter 6 provided evidence that students recognised the influence of POGIL interaction in the development of generic process skills like critical thinking, logical argument, problem solving, communication, and teamwork.

The findings from the sophisticated use of EFA and CFA indicated that the SALG questionnaire has high convergent and discriminant validity when used with first year chemistry classes. Therefore, data collected using this survey is likely to be valid and reliable.

7.4 Limitations of the Study

For any research study, what it intends to accomplish is very important. Similarly, there are a number of limitations evident in this research even though the findings are supported by literature from previous studies. The research findings may not be generalizable to other contexts or populations as they are specific to an evolving field of POGIL-influenced first year chemistry at one Australian university. The limitations include the sample, the validity of instruments, data analysis and interpretation. Each of these limitations is discussed.

7.4.1 The Sample

The major limitation of this study is the relatively small sample of students who participated in the study, which has been restrained by the availability of lectures/workshops that used predominant POGIL interaction, accessibility to students, and time limitations. The data gathered were dependent on the volunteered participants taking time from their busy schedules to take part in diagnostic testing and complete the SALG survey. The delayed post-test for Group 1 students had a lower participation as it was administered when the end-of-semester examinations were just two weeks away. There were no distinct POGIL and non-POGIL streams/sections for Chemistry classes, and selected modules were used with both groups. However, only the Group 1 students responded to the delayed post-test as POGIL groups; students in Group 2 worked independently on the delayed post-test. This situation was not a fair test of the delayed post-tests from the two groups; hence limiting the researcher from making a generalisation involving a comparison of the delayed post-tests of the two cohorts.

7.4.2 Instruments, Data Analysis and Interpretation

Item 1 of SCDT lacked a valid second tier choice, hence the analysis of results for this item reflected students' selection of content choice without reasoning. Another limitation is dependent on the researcher's interpretation and analysis of SALG data for the structural equation modelling (SEM). Despite its rigor and the depth of the interpretation of the results, the research based on self-report data has a potential for continuous errors in self-assessment to confound the results (Beghetto, 2007; Dunning, Heath, & Suls, 2004).

7.5 Recommendations Relating to this Study

Suggestions arising from this study could further benefit the POGIL practitioners in enhancing their level of teaching and learning of chemistry at university and senior secondary levels. The suggestions are discussed under appropriate headings.

7.5.1 Improving the Validity of the Instruments

The two instruments that the study had utilised can be improved by carrying out trials on a wider scale. Extending the administration of the instruments to other ALIUS institutions and senior secondary schools where innovative approaches to teaching and learning are implemented in first year science, technology, engineering, and mathematics courses.

7.5.2 Further Research on Diagnostic Tests Suitable to POGIL

The use of two-tier diagnostic testing in POGIL is found to be scarcer than their usage in the traditional lectures from the available literature. More research can be done on the development and use of diagnostic tests in POGIL classes to elicit students' understanding of chemical kinetics, redox reactions, and general principles of organic chemistry. Also, by following the recommendations of Treagust (1986a) the data from interviewing of students in POGIL tutorials/workshops may provide an insight into the students' understanding of chemistry concepts.

7.5.3 Future Research on Trans-national Study of POGIL Implementation

Multi-institutional POGIL implementations have been assessed in the US in an effort to study the effectiveness of the small group learning and there is a scope for trans-national study of students' understanding of concepts with the use of POGIL materials, diagnostic tests, and their perceptions using the new four-factor SALG instrument, as it could initiate opportunities to POGIL practitioners to share and compare their POGIL implementations and experiences.

7.5.4 Future Research on Australian POGIL Implementations

POGIL practitioners from the US visit Oceania regularly and liaise with ALIUS members to conduct seminars and POGIL workshops for the staff aspiring to take up POGIL instruction at undergraduate and senior secondary levels. As ALIUS leaders have reported (Bedgood Jr et al., 2012), Australian implementations of POGIL are different to that of US implementations in many aspects. Future research could disseminate the findings to the global POGIL community on a multi-institutional study of the Australian version of POGIL.

7.6 Summary

In conclusion, this final chapter of the thesis has discussed the findings of the research study by answering the research questions that were posed at the beginning. The constraints within which the research was conducted were also mentioned. Further opportunities for research involving POGIL-influenced students' understanding of chemistry concepts, their perceptions as well as other recommendations are presented.

References

Abraham, M. R. (2005). Inquiry and the learning cycle approach. In N. Pienta, Cooper, M. M., Greenbowe, T. J. (Ed.), *Chemists' guide to effective teaching* (Vol. 1, pp. 41-52). Upper Saddle River, NJ: Pearson Education, Inc.

Abraham, M. R. (2008). Importance of a theoretical framework for research. In D. M. Bunce & R. S. Cole (Eds.), *Nuts and Bolts of Chemical Education Research* (Vol. 976, pp. 47-66). Washington DC: American Chemical Society.

Abraham, M. R., & John, W. R. (1986). The sequence of learning cycle activities in high school chemistry. *Journal of Research in Science Teaching, 23*(2), 121-143.

Abraham, M. R., Varghese, V., & Tang, H. (2010). Using molecular representations to aid student understanding of stereochemical concepts. *Journal of Chemical Education, 87*(12), 1425-1429. doi: 10.1021/ed100497f

Adadan, E., & Savasci, F. (2011). An analysis of 16–17-year-old students' understanding of solution chemistry concepts using a two-tier diagnostic instrument. *International Journal of Science Education, 34*(4), 513-544. doi: 10.1080/09500693.2011.636084

Adedokun, O. A., & Burgess, W. D. (2011). Uncovering students' preconceptions of undergraduate research experiences. *Journal of STEM Education: Innovations and Research, 12*(5/6), 12-22.

Ameyaw, Y., & Sarpong, L. (2011). The application of some conceptual approaches in rectifying teachers' miconceptions on some science topics in the GA south disctrict in the greater Accra region of Ghana. *Journal of Education, 1*(1), 16-24.

Anderson, R. D. (2002). Reforming science teaching: What research says about inquiry. *Journal of Science Teacher Education, 13*(1), 1-12. doi: 10.1023/a:1015171124982

Anderson, T. R., & Rogan, J. M. (2011). Bridging the educational research-teaching practice gap: Curriculum development, Part 1: Components of the curriculum and influences on the process of curriculum design. *Biochemistry and Molecular Biology Education, 39*(1), 68-76.

Apple, D. K. (2004). Both content and process are essential. from http://www.pkal.org/documents/hanson-apple_process--the-missing-element.pdf

Arnott, J., & Carroll, D. (2013). Graduate outlook 2012: Employers perspective on graduate recruitment. Melbourne, Vic: Graduate Careers Australia.

Baddeley, A. (2003). Working memory: looking back and looking forward. *Nature Reviews. Neuroscience, 4*(10), 829-839.

Baddeley, A., & Hitch, G. J. (1974). Working memory. In G. A. Bower (Ed.), *Recent Advances in Learning and Motivation* (Vol. 8, pp. 47-90). New York: Academic Press.

Bailey, C. P., Minderhout, V., & Loertscher, J. (2012). Learning transferable skills in large lecture halls: Implementing a POGIL approach in biochemistry. *Biochemistry and Molecular Biology Education, 40*(1), 1-7.

Banerjee, A. C., & Power, C. N. (1991). The development of modules for the teaching of chemical equilibrium. *International journal of Science Education, 13*(3), 355-362.

Barnea, N. (2000). Teaching and learning about chemistry and modelling with a computer managed modelling system. In J. K. Gilber & C. J. Boulter (Eds.), *Developing models in science education* (pp. 307-323). Dordrecht, the Netherlands Kluwer.

Barrie, S. C. (2004). A research-based approach to generic graduate attributes policy. *Higher Education Research & Development, 23*(3), 261-275. doi: 10.1080/0729436042000235391

Barrie, S. C., Jain, P., & Carew, A. (2003). Generic graduate attributes: A research-based framework for a shared vision. *Staff and Educational Development International, 7*(3), 191-1999.

Barthlow, M. (2011). *The effectiveness of process oriented guided inquiry learning to reduce alternate conception in secondary chemistry*. Ph.D. Thesis. Liberty University. Lynchburg, VA.

Basu-Dutt, S., Slappey, C., & Bartley, J. K. (2010). Making chemistry relevant to the engineering major. *Journal of Chemical Education, 87*(11), 1206-1212. doi: 10.1021/ed100220q

Bauer, C. F., & Cole, R. S. (2012). Validation of an assessment rubric via controlled modification of a classroom activity. *Journal of Chemical Education, 89* (9), 1104-1108.

Bedgood Jr, D. R., Bridgeman, A., Buntine, M., Gardiner, M., Lim, K., Mocerino, M., Zadnik, M. (2012). In D. R. Bedgood Jr. (Ed.), *Developing leaders of change in the teaching of large university chemistry classes* (pp. 1-64). Sydney, NSW: Australian Learning & Teaching Council.

Bedgood Jr., D. R. (2008). Why are we still teaching the way we were taught in the 1980s? . *Chemistry in Australia, 75*(11), 22-23.

Beghetto, R. A. (2007). Factors associated with middle and secondary students' perceived science competence. *Journal of Research in Science Teaching, 44*(6), 800-814. doi: 10.1002/tea.20166

Bell, B., & Cowie, B. (2001). *Formative assessment and science eduation*. Dordrecht, The Netherlands: Kluwer.

Ben-Zvi, R., Eylon, B., & Silberstein, J. (1986). Is an atom of copper malleable? *Journal of Chemical Education, 63*(1), 64. doi: 10.1021/ed063p64

Ben-Zvi, R., Eylon, B., & Silberstein, J. (1987). Students' visualisation of a chemical reaction. *Education in Chemistry, 24*, 117-120.

Bentler, M. (1990). Comparative fit indeces in structural models. *Psychological Bulletin, 107*, 238-246.

Bergquist, W., & Heikkinen, H. (1990). Student ideas regarding chemical equilibrium. *Journal of Chemical Education, 67*(12), 1000-1003.

Bettelheim, F. A., Brown, W. H., Campbell, M. K., Farrell, S. O., & Torres, O. J. (2012). *Introduction to organic and biochemistry*. Belmont, CA: Thomson Brooks/Cole.

Birk, J. P., & Kurtz, M. J. (1999). Effect of experience on retention and elimination of misconceptions about molecular structure and bonding. *Journal of Chemical Education, 76*, 124-128.

Blackman, A., Bottle, S., Schmid, S., Mocerino, M., & Wille, U. (2008). *Chemistry*. Milton, Qld: John Wiley & Sons Australia, Ltd.

Bodner, G. M. (1986). Constructivism: A theory of knowledge. *Journal of Chemical Education, 63*(10), 873-877.

BouJaoude, S. B. (1991). A study of the nature of students' understanding about the concept of burning. *Journal of Research in Science Teaching, 28*(8), 689-704.

Boukhechem, A. S., Dumon, A., & Zouikri, M. (2011). The acquisition of stereochemical knowledge by Algerian students intending to teach physical sciences *Chemistry Education Research and Practice, 12*(331-343).

Boulabiar, A., Bouraoui, K., Chastrette, M., & Abderrabba, M. (2004). A historical analysis of the Daniell cell and elektrochemistry teaching in French and Tunisian textbooks. *Journal of Chemical Education, 81*(5), 754-757.

Bowen, C. W. (1994). Think-aloud methods in chemistry education: Understanding student thinking. *Journal of Chemical Education, 71*(3), 184. doi: 10.1021/ed071p184

Bretz, S. L. (2008). Qualitative research designs in chemistry education research. In D. M. Bunce & R. S. Cole (Eds.), *Nuts and Bolts of Chemical Education Research*. Washington, DC: American Chemical Society.

Brown, P. J. P. (2010). Process-oriented guided-inquiry learning in an introductory anatomy and physiology course with a diverse student population. *Advances in Physiology Education, 34*(3), 150-155. doi: 10.1152/advan.00055.2010

Brown, S. D. (2010). A process-oriented guided inquiry approach to teaching medicinal chemistry. *American Journal of Pharmaceutical Education, 74*(7), 121.

Brown, T. A. (2006). *Confrimatory factor analysis for applied research*. New York: The Guildford Press.

Browne, L. M., & Blackburn, E. V. (1999). Teaching introductory organic chemistry: A problem-solving and collaborative-learning approach. *Journal of Chemical Education, 76*(8), 1104-1107.

Bruck, L. B., Towns, M., & Bretz, S. L. (2010). Faculty perspectives of undergraduate chemistry laboratory: Goals and obstacles to success. *Journal of Chemical Education, 87*(12), 1416-1424. doi: 10.1021/ed900002d

Bucat, B., & Mocerino, M. (2009). Learning at the sub-micro level: Structural representations. In J. K. Gilbert & D. F. Treagust (Eds.), *Multiple Representations in Chemical Education*. Dordrecht: Springer Netherlands.

Burke, K., Lawrence, B., El-Sayed, M. & Apple, D. (2009). Process education - past, present, and future. *International Journal of Process Education, 1*(1), 35-42.

Carmines, E. G., & Zeller, A. (1979). Reliability and validity assessment. *Sage University Paper Series on Quantitative Applications in the Social Sciences*. Thousand Oaks, CA: Sage Publications.

Carroll, S. B. (2010). Engaging assessment: Using the sencer-salg to improve teaching and learning. In R. D. Sheardy (Ed.), *Science Education and Civic Engagement: The SENCER Approach* (Vol. 1037, pp. 149-198). Oxford: Oxford University Press.

Cartrette, D. P., & Mayo, P. M. (2011). Students' understanding of acids/bases in organic chemistry contexts. *Chemistry Education Research and Practice, 12*(1), 29-39.

Caulfield, S. L., & Persell, C. H. (2006). Teaching social science reasoning and quantitative literacy: Role of collaborative groups. *Teaching Sociology, 34*(1), 39-53.

Cawley, A. (2008). Chemical education: Where to from here for the RACI? *Chemistry in Australia, 75*(7), 13-16.

Chamely-Wilk, D., Galin, J., Kasdorf, K., & Haky, J. (2009). Combining chemistry and college writing: A new model for an honors undergraduate chemistry course. *Honors in Practice--Online Archive, 99*.

Chandrasegaran, A. L., Treagust, D. F., & Mocerino, M. (2005). *Diagnostic assessment of secondary students' use of three levels of representation to explain simple chemical reactions.* Paper presented at the 36th Annual Conference of the Australian Science Education Research (ASERA), Hamilton, New Zealand.

Chiu, M. H., Chiu, M. L., & Ho, C. Y. (2002). *Using dynamic representaions to diagnise students' mental models of characteristics of particles.* Paper presented at the Asia Pacific Symposium on Information and Communication Technology in Chemical Education, Research and Development (ICTinCERD), Kuala Lumpur, Malaysia.

Cohen, J. (1988). *Statistical power analysis for the behavioural sciences*. Hillsdale, NJ: Erlbaum.

Cohen, L., Mannion, L., & Morrison, K. (2000). *Research methods in education*. New York: RoutledgeFalmer.

Colburn, A., & Clough, M. P. (1997). Implementing the learning cycle. *The Science Teacher, 65*(5), 30-33.

Cole, R. S., & Bauer, C. F. (2008). Assessing POGIL Implementation. In R. S. Moog & J. N. Spencer (Eds.), *Process Oriented Guided Inquiry Learning*. Washington, DC: American Chemical Society.

Cole, R. S., Becker, N., Towns, M., Sweeney, G., Wawro, M., & Rasmussen, C. (2012). Adapting a methodology from mathematics education research to chemistry education research: Documenting collective activity. *International Journal of Science and Mathematics Education, 10*(1), 193-211. doi: 10.1007/s10763-011-9284-1

Coleman, B. L., M. (2012). *Collaboration across the curriculum: A disciplined approach to developing team skills*. Paper presented at the 43rd ACM Technical Symposium on Computer Science Education, Raleigh, North Carolina, USA.

Cooper, M. M. (1997). Distinguishing critical and post-positivist research. *College Composition and Communication, 48*(4), 556-561.

Cooper, M. M. (2005). An introduction to small-group learning. In N. Pienta, Cooper, M. M., Greenbowe, T. J. (Ed.), *Chemists' guide to effective teaching* (Vol. II, pp. 117-128). New Jersey: Pearson Education Inc.

Cracolice, M. (2005). How students learn: Knowledge construction in college chemistry courses. In N. Pienta, Cooper, M. M., Greenbowe, T. J. (Ed.), *Chemists' guide to effective teaching* (Vol. 1). Upper Saddle River, NJ: Pearson Education Inc.

Creswell, J. W. (2003). *Research design, qualitative, quantitative, and mixed methods approaches* (2 ed.). Thousand Oaks, CA: Sage Publications, Inc.

Creswell, J. W. (2005). *Educational research. planning, conducting, and evaluating quantitative and qualitative research.* Thousand Oaks, CA: Sage Publications.

Creswell, J. W., & Plano-Clark, V. L. (2007). *Designing and conducting mixed methods research.* Thousand Oaks, CA: Sage Publications.

Criasia, R. T., Lees, A. B., Mongelli, M. T., Shin, Y.-G. K., & Stokes-Huby, H. (2009). Non-linear POGIL for developing cumulative skills and multidisciplinary chemical concepts for non-science and chemistry majors. In M. Gupta-Bhowon, S. Jhaumeer-Laulloo, H. Li Kam Wah & R. Ponnudurai (Eds.), *Chemistry Education in the ICT Age*. Dordrecht: Springer Netherlands.

Cuban, L. (1993). The lure of curricular reform and its pitiful history. *The Phi Delta Kappan, 75*(2), 182-185.

Curtin Teaching and Learning. (2010). Curtin's philosophy of teaching and learning. *Teaching and Learning at Curtin 2010*, 6-9.

Curtin University. (2011a). 7039 chemistry 101: Semester 1, 2011. *Courses Handbook 2011*.

Curtin University. (2011b). 7040 chemistry 102: Semester 2, 2011. *Courses Handbook 2011*.

Curtin University. (2011c). Unit outline policy. Retrieved 3 April, 2013, from http://policies.curtin.edu.au/findapolicy/docs/Unit%20Outline%20Policy%20-%20Feb%202011.pdf

Day, J. H., & Houk, C. C. (1970). Student paced learning for large classes. *Journal of Chemical Education, 47*(9), 629. doi: 10.1021/ed047p629

Denson, D. W. (1986). *The relationship between cognitive styles, methods of instruction, knowledge, and process skills of college chemistry students*. Ph.D. Thesis. The University of South Mississippi. Hattiesburg, MS.

Dickinson, M. (2000). Giving undergraduates managerial experience. *Education and Training, 42*(3), 159-170.

Dinah, R. D. (2008). A rationale for employing mixed methods design in doctoral research about female students' academic achievement in secondary schools in Papua New Guinea. *International Journal of Pedagogies & Learning, 4*(2), 59-67.

Douglas, E. P., & Chiu, C. C. (2009). *Use of guided inquiry as an active learning technique in engineering.* Paper presented at the Proceedings of the Research in Engineering Education Symposium 2009, Palm Cove, Qld, Australia.

Doyle, T. (2011). *Learner centered teaching.* Sterling, VA: Stylus Publishing.

Drossman, H., Benedict, J., McGrath-Spangler, E., Van Roekel, L., & Wells, K. (2011). Assessment of a constructivist-motivated mentoring program to enhance the teaching skills of atmospheric science graduate students. *Journal of College Science Teaching, 41*(2), 72.

Duffy, M. E. (1987). Methodological triangulation: A vehicle for merging quantitative and qualitative research methods. *Journal of Nursing Scholarship, 19*(3), 130-133. doi: 10.1111/j.1547-5069.1987.tb00609.x

Duis, J. M. (2011). Organic chemistry educators' perspectives on fundamental concepts and misconceptions: An exploratory study. *Journal of Chemical Education, 88*(3), 346-350. doi: 10.1021/ed1007266

Duit, R., & Treagust, D. F. (1995). Students' conceptions and constructivist teaching approaches. In B. J. Fraser & H. J. Walberg (Eds.), *Improving science education* (pp. 49-60). Chicago, IL: University of Chicago Press.

Dunning, D., Heath, C., & Suls, J. M. (2004). Flawed self-assessment: Implications for health, education, and the workplace. , 5, 69–106. *Psychological Science in the Public Interest, 5*(3), 69-106.

Eberlein, T., Kampmeier, J., Minderhout, V., Moog, R. S., Platt, T., Varma-Nelson, P., & White, H. B. (2008). Pedagogies of engagement in science: A comparison of PBL, POGIL, and PLTL. *Biochemistry and Molecular Biology Education, 36*(4), 262-273.

Eggen, T. J. H. M., Pelgrum, W. J., & Plomp, T. (1987). The implemented and attained mathematics curriculum: Some results of the second international mathematics study in The Netherlands. *Studies in Educational Evaluation, 13*(1), 119-135.

Epstein, M. S. (1998). Using bad science to teach good chemistry. *Journal of Chemical Education, 75*(11), 1399-1404.

Ericsson, K. A., & Simon, H. A. (1998). How to study thinking in everyday life: Contrasting think-aloud protocols with descriptions and explanations of thinking. *Mind, Culture & Activity, 5*(3), 178-186.

Ezzy, D. (2002). *Qualitative analysis: Practice and innovation*. London: Routledge.

Fan, X., Thompson, B., & Wang, L. (1990). Effects of sample size, estimation methods, and model specification on structural equation modelling indexes. *Structural Equation Modeling: A Multidisciplinary Journal, 6*, 56-83.

Farrell, J. J., Moog, R. S., & Spencer, J. N. (1999). A guided-inquiry general chemistry course. *Journal of Chemical Education, 76*(4), 570. doi: 10.1021/ed076p570

Felder, R. M. (1996). Active-inductive-cooperative learning: An instructional model for chemistry? *Journal of Chemical Education, 73*(9), 832-null. doi: 10.1021/ed073p832

Fereday, J., & Muir-Cochrane, E. (2008). Demonstrating rigor using thematic analysis: A hybrid approach of inductive and deductive coding and theme development. *International Journal of Qualitative Methods, 5*(1), 80-92.

Fornell, C., & Larcker, D. F. (1981). Evaluating structural equation models with unobservable variables and measurement error *Journal of Marketing Research, 18*(1), 39-50.

Fossey, E., Harvey, C., McDermott, F., & Davidson, L. (2002). Understanding and evaluating qualitative research. *Australian and New Zealand Journal of Psychiatry, 36*(6), 717-732. doi: 10.1046/j.1440-1614.2002.01100.x

Francisco, J. S., Nicoll, G. (1998). Integrating multiple teaching methods into a general chemistry classroom. *Journal of Chemical Education, 75*(2), 210-213.

Frost, D. L. (2010). Creating a relevant, learner-centered classroom for allied health chemistry. In S. Basu-Dutt (Ed.), *Making chemistry relevant: Strategies for including all students in a learner sensitive classroom environment* (pp. 127-144). Hoboken, New Jersey: John Wiley & Sons Publication

Furió, C., & Calatayud, M. L. (1996). Difficulties with the geometry and polarity of molecules: Beyond misconceptions. *Journal of Chemical Education, 73*(1), 36. doi: 10.1021/ed073p36

Gabel, D. L. (2005). Enhancing students' conceptual understanding of chemistry through integrating the macroscopic, particle, and symbolic representation of matter. In N. Pienta, Cooper, M. M., Greenbowe, T. J. (Ed.), *Chemists' Guide to Effective Teaching* (Vol. I, pp. 77-88). Upper Saddle River, NJ: Pearson Education Inc.

Gabel, D. L., Sherwood, R. D., & Enochs, L. (1984). Problem-solving skills of high school chemistry students. *Journal of Research in Science Teaching, 21*(2), 221-233. doi: 10.1002/tea.3660210212

Gafney, L., & Varma-Nelson, P. (2007). Evaluating peer-led team learning: A study of long-term effects on former workshop peer leaders. *Journal of Chemical Education, 84*(3), 535. doi: 10.1021/ed084p535

Gallagher, D., Ting, L., & Palmer, A. (2008). A journey into the unknown; taking the fear out of structural equation modeling with AMOS for the first-time user. *Marketing Review, 8*(3), 255-275. doi: 10.1362/146934708x337672

Garnett, P. J., Garnett, P. J., & Hackling, M. W. (1995). Students' alternative conceptions in chemistry: A review of research and implications for teaching and learning. *Studies in Science Education, 25*(1), 69-96. doi: 10.1080/03057269508560050

Garnett, P. J., & Treagust, D. F. (1990). Implications of research on students understanding of electrochemistry for improving science curricula and classroom practice. *International Journal of Science Education, 12*(2), 147-156.

Garoutte, M. P. (2008). POGIL in the general, organic, and biological chemistry course. In R. S. a. S. Moog, J. N. (Ed.), *Process-Oriented Guided Inquiry Learning* (pp. 120-130). Washington, DC: American Chemistry Society.

Gefen, D., Straub, D., & Boudreau, M. (2000). Structural Equation Modelling techniques and regression: Guidelines for research practice. *Communications of the Association for Information Systems, 7*, 1-78.

Geiger, M. (2010). Implementing POGIL in allied health chemistry courses: Insights from process education. *International Journal of Process Education, 2*(1), 19-34.

Georgiou, H., & Sharma, M. (2012). University students' understanding of thermal physics in everday contexts. *International Journal of Science and Mathematics Education, 10*(5), 1119-1142. doi: 10.1007/s10763-011-9320-1

Gilbert, J. K., Osborne, R. J., & Fensham, P. J. (1982). Children's science and its consequences for teaching. *Science Education, 66*(4), 623-633.

Gilbert, J. K., & Watts, D. M. (1983). Concepts, misconceptions and alternative conceptions: changing perspectives in science education. *Studies in Science Education, 10*, 61-98.

Goh, N. K., & Chia, L. S. (1989). Using the learning cycle to introduce periodicity. *Journal of Chemical Education, 66*(9), 747-749. doi: 10.1021/ed066p747

Gorsuch, R. L. (1983). *Factor analysis* (2nd ed.). Hillsdale, NJ: Lawrance Erlbaum Associates, Inc.

Gosser, D. K., Kampmeier, J. A., & Varma-Nelson, P. (2010). Peer-led team learning: 2008 James Flack Norris award address. *Journal of Chemical Education, 87*(4), 374-380. doi: 10.1021/ed800132w

Griffard, P. B., & Wandersee, J. H. (2001). The two-tier instrument on photosynthesis: What does it diagnose? *International Journal of Science Education, 23*(10), 1039-1052. doi: 10.1080/09500690110038549

Griffiths, A. K., & Preston, K. R. (1992). Grade 12 students' misconceptions relating to fundamental characteristics of atoms and molecules. *Journal of Research in Science Teaching, 29*(6), 611-628.

Guba, E. G. (1985). What can happen as a result of a policy? *Policy Studies Review, 5*, 11-16.

Habraken, C. L. (2004). Integrating into chemistry teaching today's students' visuospatial talents and skills, and the teaching of today's chemistry's graphical language. *Journal of Science Education and Technology, 13*(1), 89-94.

Hager, P., & Holland, S. (2006). Introduction. In P. Hager & S. Holland (Eds.), *Graduate Attributes, Learning and Employability* (pp. 1-15). Dordrecht, The Netherlands.: Springer.

Hager, P., Sleet, R., Logan, P., & Hooper, M. (2003). Teaching critical thinking in undergraduate science courses. *Science & Education, 12*(3), 303-313.

Hale, D., & Mullen, L. G. (2009). Designing process-oriented guided inquiry activities: A new innovation for marketing classes. *Marketing Education Review, 19*(1), 73-80.

Halloun, I. A. (2006). Learning cycles *Modeling Theory in Science Education* (Vol. 24, pp. 185-235). Dordrecht, the Netherlands: Springer Netherlands.

Hannon, C. (2008). Paper-based computing. *Educause Quarterly, 31*(4), 15-16.

Hanson, D. M., & Wolfskill, T. (1998). Improving the teaching/learning process in general chemistry: Report on the 1997 stony brook general chemistry teaching workshop. *Journal of Chemical Education, 75*(2), 143. doi: 10.1021/ed075p143

Hanson, D. M., & Wolfskill, T. (2000). Process workshops - A new model for instruction. *Journal of Chemical Education, 77*(1), 120-130.

Hanson, S., & Overton, T. (2010). Skills required by new chemistry graduates and their development in degree programmes (pp. 1-36). Hull: UK Physical Sciences Centre, Higher Education Academy.

Hastings, J. (2008). Pulse smartpen digital audio recorder with "paper replay". *School Library Journal, 54*(11), 21-n/a.

Head, J., & Bucat, B. (2002). Visualisation and mental manipulation of molecular structures *Australian Journal of Education in Chemistry, 59*, 25-29.

Heady, J. E. (2002). Guaging students' learning in the classroom *Innovative Techniques for Large Group Instruction* (pp. 57-62). Arlington, VA: National Science Teachers Association Press.

Hein, S. M. (2012). Positive impacts using POGIL in organic chemistry. *Journal of Chemical Education, 89* (7), 860-864. doi: 10.1021/ed100217v

Henard, F. (2010). *Learning our lesson: Review of quality teaching in higher education*. Paris: OECD Publishing.

Hesse III, J. J., & Anderson, C. W. (1992). Students' conceptions of chemical change. *Journal of Research in Science Teaching, 29*(3), 277-299.

Hinde, R. J., & Kovac, J. (2001). Student active learning methods in physical chemistry. *Journal of Chemical Education, 78*(1), 93-null. doi: 10.1021/ed078p93

Hoffman, A. R., Britton, S. L., Cadwell, K. D., & Walz, K. A. (2010). An integrated approach to introducing biofuels, flash point, and vapor pressure concepts into an introductory college chemistry lab. *Journal of Chemical Education, 88*(2), 197-200. doi: 10.1021/ed100004x

Hong, T., Purzer, S., & Cardella, M. E. (2011). A psychometric re-evaluation of the design, engineering and technology (DET) survey. *Journal of Engineering Education, 100*(4), 800-818.

Hox, J. J., & Bechger, T. M. (1998). An introduction to structural equation modelling. *Family Science Review, 11*, 354-373.

Hsieh, H.-F., & Shannon, S. E. (2005). Three approaches to qualitative content analysis. *Qualitative Health Research, 15*(9), 1277-1288. doi: 10.1177/1049732305276687

Hu, L., & Bentler, M. (1999). Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Structural Equation Modeling: A Multidisciplinary Journal, 6*(1), 1-55.

Hu, L., & Bentler, M. (2009). Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Structural Equation Modeling: A Multidisciplinary Journal, 6*(1), 1-55.

Jacobs, J. K., Kawanaka, T., & Stigler, J. W. (1999). Integrating qualitative and quantitative approaches to the analysis of video data on classroom teaching.

International Journal of Educational Research, 31(8), 717-724. doi: Doi: 10.1016/s0883-0355(99)00036-1

Jan-Willem Van, P., & Willem, A. V. D. K. (2001). Confirmatory analysis of exploratively obtained factor structures. *Educational and Psychological Measurement, 61*(5), 777-792.

Janice, K. K. (1999). The use of triangulation in a study of refugee well-being. *Quality and Quantity, 33*(2), 169-183.

Jiang, B., Xu, X., Garcia, A., & Lewis, J. E. (2010). Comparing two tests of formal reasoning in a college chemistry context. *Journal of Chemical Education, 87*(12), 1430-1437. doi: 10.1021/ed100222v

Jin, G., & Bierma, T. J. (2011). Guided-inquiry learning in environmental health. *Journal of Environmental Health, 73*(6), 80-85.

Johnson, B., & Stevens, J. J. (2001). Exploratory and confirmatory factor analysis of the school level environment questionnaire (SLEQ). *Learning Environments Research, 4*(3), 325-344.

Johnson, C. (2011). Activities using process-oriented guided inquiry learning (POGIL) in the foreign language classroom. *Die Unterrichtspraxis, 44*(1), 30.

Johnson, C. M., Corazzini, K. N., & Shaw, R. (2011). Assessing the feasibility of using virtual environments in distance education. *Knowledge Management and E-Learning: An International Journal, 3*(1), 5-16.

Johnstone, A. H. (1997). Chemistry teaching - science or alchemy? 1996 Brasted lecture. *Journal of Chemical Education, 74*(3), 262.

Johnstone, A. H., MacDonald, J. J., & Webb, G. (1977). Chemical equilibrium and its conceptual difficulties. *Education in Chemistry, 14*, 169-171.

Joliffe, W. (2007). *Cooperative learning in the classroom: Putting into practice.* London, UK: Paul Chapman Publishing.

Joreskog, K. G. (2007). Factor analysis and its extensions: Historical developments and future directions. In R. Cudeck & R. C. MacCallum (Eds.), *Factor analysis at 100* (pp. 47-77). Mahwah, NJ: Lawerence Erlbaum Associates

Kaiser, H. F. (1960). The application of electronic computers to factor analysis. *Educational and Psychological Measurement, 20*, 141-151.

Karplus, R., & Butts, D. P. (1977). Science teaching and the development of reasoning. *Journal of Research in Science Teaching, 14*(2), 169-175. doi: 10.1002/tea.3660140212

Keeney-Kennicutt, W. L., Gunersel, A. B., & Simpson, N. J. (2008). Overcoming student resistance to a teaching innovation. *The International Journal for the Scholarship of Teaching and Learning, 2*(1), 1-26.

Keeves, J. P. (1995). The contribution of IEA research to Australian education. In W. Bos, & Lehmann, R. H. (Ed.), Reflections on Educational Achievement (pp. 137-158). New York: Waxmann.

Kelly, R. M., Barrera, J. H., & Mohamed, S. C. (2010). An analysis of undergraduate general chemistry students' misconceptions of the submicroscopic level of precipitation reactions. *Journal of Chemical Education, 87*(1), 113-118.

Kendeou, P., & van den Broek, P. (2005). The effects of readers' misconceptions on comprehension of scientific text. *Journal of Educational Psychology, 97*(2), 235-245.

Kilic, D., & Saglam, N. (2009). Development of a two-tier diagnostic test concerning genetics concepts: the study of validity and reliability. *Procedia - Social and Behavioral Sciences, 1*(1), 2685-2686. doi: 10.1016/j.sbspro.2009.01.474

Killian, C. R., & Warrick, C. (1980). Steps to abstract reasoning: An interdisciplinary program for cognitive development. *Alternative Higher Education, 4*(3), 189-200. doi: 10.1007/BF01079870

Klein, D. (2012). *Organic chemistry: as a second language*. Hoboken, NJ: John Wiley & Sons, Inc.

Knight, J. K., & Wood, W. B. (2005). Teaching more by lecturing less. *Cell Biology Education, 4*(4), 298-310.

Kovac, J. (1999). Student active learning methods in general chemistry. *Journal of Chemical Education, 76*(1), 120-124.

Kroonenberg, P. M., & Lewis, C. (1982). Methodological issues in the search for a factor model: Exploration through confirmation. *Journal of Educational Statistics, 7*(2), 69-89. doi: 10.2307/1164958

Krylova, I. (1997). *Investigation of causes of differences in student performance on the topics of stereochemistry and reaction mechanisms in an undergraduate organic chemistry course*. Ph.D. Thesis. The Catholic University of America. Washington, DC.

Kurbanoglu, N. I., Taskesenligil, Y., & Sozbilir, M. (2006). Programmed instruction revisited: A study on teaching stereochemistry. *Chemistry Education Research and Practice, 7*(1), 13-21.

Kussmaul, C. (2011a). Process-oriented guided inquiry learning (POGIL) in computer science: tutorial presentation. *The Journal of Computing in Small Colleges, 26*(3), 83-84.

Kussmaul, C. (2011b). Process oriented guided inquiry learning for soft computing. In A. Abraham, J. L. Mauri, J. F. Buford, J. Suzuki & S. M. Thampi (Eds.), *Advances in Computing and Communications* (Vol. 192, pp. 533-542). Heidelberg: Springer Berlin

Lamba, R. S. (2008). Information overload, rote memory, and recipe following in chemistry. In R. S. Moog & J. N. Spencer (Eds.), *Process Oriented Guided Inquiry Learning* (Vol. 994, pp. 26-39). Washington, DC: American Chemical Society.

Lawrie, G. A., Matthews, K. E., Gahan, L. R. (2010). *Forming groups to foster collaborative learning in large enrolment courses.* Paper presented at the Australian Conference on Science and Mathematics Education (formerly UniServe Science Annual Conference), University of Sydney, Australia.

Lawson, A. E. (2003). Rejecting nature of science misconceptions by preservice teachers. In A. E. Lawson (Ed.), *The neurological basis of learning, development and discovery: Implications for science and mathematics instruction* (Vol. 18, pp. 211-224). New York: Springer.

Lawson, A. E., Abraham, M. R., & Renner, J. W. (1989). A theory of instruction: Using the learning cycle to teach science concepts and thinking skills. . Cincinnati, OH: National Association of Research in Science Teaching.

Lawson, A. E., Baker, W. P., Didonato, L., Verdi, M. P., & Johnson, M. A. (1993). The role of hypothetico-deductive reasoning and physical analogues of molecular interactions in conceptual change. *Journal of Research in Science Teaching, 30*(9), 1073-1085. doi: 10.1002/tea.3660300906

Lees, A. B. (2008). Making science accessible in the lives of nonscience mjors using POGIL and project-based learning. In R. S. Moog & J. N. Spencer (Eds.), *Process Oriented Guided Inquiry Learning* (pp. 173-185). Washington, DC: Amercial Chemical Society.

Lewis, S. E. (2006). *An evaluation of a pedagogical reform designed for college chemistry teaching with large classes.* (Ph.D. Unpublished), University of South Florida, Tampa, FL.

Lewis, S. E., & Lewis, J. E. (2005). Departing from lectures: An evaluation of a peer-led guided inquiry alternative. *Journal of Chemical Education, 82*(1), 135. doi: 10.1021/ed082p135

Libby, D. R. (2008). Phasing into POGIL. In R. S. Moog & J. N. Spencer (Eds.), *Process Oriented Guided Inquiry Learning* (Vol. 994, pp. 49-59). Washington, DC: American Chemical Society.

Liu, X. (2010). *Essentials of science classroom assessment.* Thousand Oaks, CA: Sage Publications.

Lloyd-Williams, P., & Giralt, E. (2005). Stereogenic centers and axes: A comparison of the chiral topologies available to Cabcd and abC=C=Ccd. *Journal of Chemical Education, 82*(7), 1031-1033.

Lujan-Upton, H. (2001). Introducing stereochemistry to non-science majors. *Journal of Chemical Education, 78*(4), 475. doi: 10.1021/ed078p475

Luxford, C. J., Crowder, M. W., & Bretz, S. L. (2011). A symmetry POGIL activity for inorganic chemistry. *Journal of Chemical Education, 89*(2), 211-214.

Lyon, D. C., & Lagowski, J. J. (2008). Effectiveness of facilitating small-group learning in large lecture classes. *Journal of Chemical Education, 85*(11), 1571-null. doi: 10.1021/ed085p1571

Mamo, M., Kettler, T., Husmann, D., & McCallister, D. (2004). Assessment of an on-line erosion lesson as a teaching tool in introductory soil science. *NACTA Journal, 48*(3), 47-52.

Marcoulides, G. A. (2001). *New developments and techniques in structural equation modelling*. Mahwah, New Jersey: Lawrence Erlbaum Associates.

Marshall, G. (2010). Student-centered, active learning pedagogies in chemistry education. In S. Basu-Dutt (Ed.), *Making chemistry relevant: Strategies for including all students in a learner sensitive classroom environment* (pp. 107-125). Hoboken, New Jersey: John Wiley & Sons Publication.

McClary, L. M., & Bretz, S. L. (2012). Development and assessment of a diagnostic tool to identify organic chemistry students' alternative conceptions related to acid strength. *International Journal of Science Education, 34*(15), 2317-2341. doi: 10.1080/09500693.2012.684433

Menis, J. (1994). Chemistry in Israeli 12th grade classes: The intended, the implemented, and the achieved curricula. *Studies in Educational Evaluation, 20*(3), 349-364. doi: 10.1016/0191-491x(94)90021-3

Micari, M., Streitwieser, B., & Light, G. (2005). Undergraduates leading undergraduates: Peer facilitation in a science workshop program. *Innovative Higher Education, 30*(4), 269-288. doi: 10.1007/s10755-005-8348-y

Middlecamp, C. H., Jordan, T., Shachter, A. M., Kashmanian Oates, K., & Lottridge, S. (2006). Chemistry, society, and civic engagement (Part 1): The SENCER project. *Journal of Chemical Education, 83*(9), 1301.

Mills, J. E. (2002). *The effectiveness of project-based learning in structural engineering*. Science and Mathematics Education Centre. Unpublished Ph.D Thesis. Curtin University of Technology. Bentley.

Mills, J. E., & Treagust, D. F. (2003). Engineering education - is problem-based or project-based learning the answer? *Australasian Journal of Engineering Education, 3*, 2-16.

Minderhout, V., & Loertscher, J. (2007). Lecture-free biochemistry: A process oriented guided inquiry approach. *Biochemistry and Molecular Biology Education, 35*(3), 172-180.

Minderhout, V., & Loertscher, J. (2008). Facilitation: The role of the instructor. In R. S. Moog & J. N. Spencer (Eds.), *Process Oriented Guided Inquiry Learning* (Vol. 994, pp. 72-86). Washington, DC: American Chemical Society.

Mitchell, E., & Hiatt, D. (2010). Using POGIL techniques in an information literacy curriculum. *The Journal of Academic Librarianship, 36*(6), 539-542. doi: DOI: 10.1016/j.acalib.2010.08.010

Molitor, L. L., & George, K. D. (1976). Development of test of science process skills. *Journal of Research in Science Teaching, 13*(5), 405-412.

Moog, R. S., Creegan, J. F., Hanson, M. D., Spencer, N. J., Straumanis, A., & Bunce, M. D. (2009). POGIL: Process-oriented guided-inquiry learning. In N. Pienta, M. M. Cooper & T. J. Greenbowe (Eds.), *Chemists' Guide To Effective Teaching* (Vol. 2, pp. 90-101). Upper Saddle River, NJ: Prentice Hall.

Moog, R. S., & Farrell, J. J. (2011). *Chemistry: A guided inquiry* (5 ed.). Hoboken, NJ: John Wiley & Sons, Inc.

Moog, R. S., & Spencer, J. N. (2008). POGIL: An overview. In R. S. Moog & J. N. Spencer (Eds.), *ACS Symposium Series 994: Process Oriented Guided Inquiry Learning* (pp. 1-13). Washington, DC: American Chemical Society.

Muijs, D. (2011). *Doing quantitative research in education with SPSS* (2nd ed.). Thousand Oaks, CA: Sage Publications.

Murphy, K. L., Picione, J., & Holme, T. A. (2010). Data-driven implementation and adaptation of new teaching methodologies. *Journal of College Science Teaching, 40*(2), 80-86.

Murray, J. (2012). Pencasts for introductory macroeconomics. *The Journal of Economic Education, 43*(3), 348-348. doi: 10.1080/00220485.2012.686829

Myers, T., Monypenny, R., & Trevathan, J. (2012). Overcoming the glassy-eyed nod: An application of process-oriented guided inquiry learning technique in information technology. *Journal of Learning Design, 5*(1), 12-22.

Naah, B. M., & Sanger, M. J. (2012). Student misconceptions in writing balanced equations of dissolving ionic compounds in water. *Chemistry Education Research and Practice, 13*(3), 186-194.

Nakhleh, M. B. (1992). Why some students don't learn chemistry: Chemical misconceptions. *Journal of Chemical Education, 69*(3), 191-196. doi: 10.1021/ed069p191

Niaz, M., & Lawson, A. A. (1985). Balancing chemical equations: The role of developmental level and metal capacity. *Journal of Research in Science Teaching, 22*, 41-51.

Novick, S., & Nussbam, J. (1981). Pupils' understanding of the particulate nature of matter: A cross-age study. *Science Education, 65*(2), 187-196.

Nunnally, J. C. (1978). *Psychometric Theory* (2nd ed.). New York: McGraw-hill.

Nurrenburg, S. C., & Pickering, M. (1987). Concept learning versus problem solving: Is there a difference? *Journal of Chemical Education, 64*, 508-510.

NVivo, Q. S. R. (2012). What is qualitative research software? Retrieved 22 March, 2013, from http://www.qsrinternational.com/what-is-qualitative-research.aspx

Nyachwaya, J. M., Mohamed, A.-R., Roehrig, G. H., Wood, N. B., Kern, A. L., & Schneider, J. L. (2011). The development of an open-ended drawing tool: an alternative diagnostic tool for assessing students' understanding of the particulate nature of matter. *Chemistry Education Research and Practice, 12*(2), 121-132.

O'Toole, P., Rice, J. (2010). A call for change in science teaching at universities. *Chemistry in Australia, 77*(2), 22-25.

Orgill, M., & Sutherland, A. (2008). Undergraduate chemistry students' perceptions of and misconceptions about buffers and buffer problems. *Chemistry Education Research and Practice, 9*(2), 131-143.

Osborne, R. J. (1980). Some aspects of the students' views of the world. *Research in Education, 10*, 11-18.

Osborne, R. J., & Gilbert, J. K. (1980). A technique for exploring students' views of the world. *Physics Education, 15*, 376-379.

Othman, J., Treagust, D. F., & Chandrasegaran, A. L. (2008). An investigation into the relationship between students' conceptions of the particulate nature of matter and their understanding of chemical bonding. *International journal of Science Education, 30*(11), 1531-1550.

Ozkan, B. C. (2004). Using NVivo to analyze qualitative classroom data on constructivist learning environments. *The Qualitative Report, 9*, 589-603.

Ozmen, H. (2004). Some student misconceptions in chemistry: A literature review of chemical bonding. *Journal of Science Education and Technology, 13*(2), 147-159.

Ozmen, H., & Ayas, A. (2003). Students' difficulties in understanding of the conservation of matter in open and closed-system chemical reactions. *Chemistry Education Research and Practice, 4*(3), 279-290.

Palmer, B., & Treagust, D. F. (1996). Physical and chemical change in textbooks: An initial view. *Research in Science Education, 26*(1), 129-140.

Paulson, D. R. (1999). Active learning and cooperative learning in the organic chemistry lecture class. *Journal of Chemical Education, 76*(8), 1136-1140. doi: 10.1021/ed076p1136

Pavelich, M. J., & Abraham, M. R. (1979). An inquiry format laboratory program for general chemistry. *Journal of Chemical Education, 56*(2), 100-103. doi: 10.1021/ed056p100

Peterson, R. F., Treagust, D. F., & Garnett, P. J. (1989). Development and application of a diagnostic instrument to evaluate grade 11 and 12 students' concepts of covalent bonding and structure following a course of instruction. *Journal of Research in Science Teaching, 26*, 301-314.

Phelps, A. J. (1994). Qualitative methodologies in chemical education research: Challenging comfortable paradigms. *Journal of Chemical Education, 71*(3), 191. doi: 10.1021/ed071p191

Piaget, J. (1963). *Origins of intelligence in children*. New York: Norton.

POGIL Project. (2008a). Author guidelines for developing pogil classroom activities. Retrieved 30 November, 2012, from http://pogil.org/

POGIL Project. (2008b). Process Skills. Retrieved 30 November 2012, from http://pogil.org/

Pope, C., Ziebland, S., & Mays, N. (2000). Analysing qualitative data *Qualitative Research in Health Care* (Second ed., Vol. 320, pp. 114-116). London, UK: BMJ Group.

Prince, M. (2004). Does active learning work? A review of the research. *Journal of Engineering Education, 93*(3), 223-231.

Purser, R. K., & Renner, J. W. (1983). Results of two tenth-grade biology teaching procedures. *Science Education, 67*(1), 85-98.

Rajan, N., & Marcus, L. (2009). Student attitudes and learning outcomes from process oriented guided-inquiry learning (POGIL) strategy in an introductory chemistry course for non-science majors: An action research study. *The Chemical Educator, 14*, 85-93.

Rasmussen, C., & Kwon, O. (2007). An inquiry oriented approach to undergraduate mathemactics. *Journal of Mathematical Behaviour, 26*, 189-194.

Reedman, M. (2011). La Trobe university's design for learning project transforming student lives through ... standards? *HERDSA News, 32,* 8-9.

Regmi, K. (2012). A review of teaching methods - lecturing and facilitation in higher education (HE): A summary of the published evidence. *The Journal of Effective Teaching, 12*(3), 61-76.

Renner, J. W., Abraham, M. R., & Birnie, H. H. (1985). Secondary school students' beliefs about the physics laboratory. *Science Education, 69*(5), 649-663.

Rice, J. W., Thomas, S. M., O'Toole, P., Pannizon, D., Learning, A., & Council, T. (2009). *Tertiary science education in the 21st century*. Strawberry Hills, NSW: Australian Council of Deans of Science.

Rogers, V. (1989). Assessing the curriculum experienced by children. *The Phi Delta Kappan, 70*(9), 714-717.

Rosier, M. J., & Keeves, J.P. (1991). *The IEA Study of science: Science education and curricula in twenty-three countries.* Oxford: Pergamon.

Ruder, S. M., & Hunnicutt, S. S. (2008). POGIL in chemistry courses at a large urban university: A case study. In R. S. Moog & J. N. Spencer (Eds.), *Process Oriented Guided Inquiry Learning*. Washington, DC: American Chemical Society.

Ruiz-Primo, M. A., Briggs, D., Iverson, H., Talbot, R., Shepard, L. A. (2011). Impact of undergraduate science course innovations on learning. *Science, 331,* 1269-1270.

Rushton, G. T., Hardy, R. C., Gwaltney, K. P., & Lewis, S. E. (2008). Alternative conceptions of organic chemistry topics among fourth year chemistry students. *Chemistry Education Research and Practice, 9*(2), 122-130.

Sandelowski, M. (1995). Qualitative analysis: What it is and how to begin. *Research in Nursing & Health, 18*, 371-375.

Savoy, L. G. (1988). Balancing chemical equations. *School Scince Review, 69*, 713-720.

Schmidt, H. (1992). Conceptual difficulties with isomerism. *Journal of Research in Science Teaching, 29*(9), 995-1003.

Schmidt, H. (1997). Students' misconceptions: Looking for a pattern. *Science Education, 81*(2), 123-135.

Schmidt, L. C., Hernandez, N. V., & Ruocco, A. L. (2012). Research on encouraging sketching in engineering design. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing : AI EDAM, 26*(3), 303-315.

Schneider, L. S., & Renner, J. W. (1980). Concrete and formal teaching. *Journal of Research in Science Teaching, 17*(6), 503-517.

Schroeder, J. D., & Greenbowe, T. J. (2008). Implementing POGIL in the lecture and the science writing heuristic in the laboratory--student perceptions and performance in undergraduate organic chemistry. *Chemistry Education Research and Practice, 9*(2), 149-156.

Selepe, M. C. (2011). *Engineering lecturers' and students' perceptions about teaching and learning practices in a South African University of Techology.* (PhD Unpublished doctoral thesis), Curtin University, Bentley, Australia.

Sewell, A. (2002). Constructivism and student misconceptions : Why every teacher needs to know about them. *Australian Science Teachers Journal, 48*(4), 24-28.

Seymour, E., Wiese, D., Hunter, A., & Daffinrud, S. M. (2000). *Creating a better mousetrap: On-line student assessment of their learning gains*. Paper presented at the National Meeting of the American Chemical Society, San Francisco, CA.

Seymour, E., Wiese, D., Hunter, A. & Daffinrud, S.M. (2000). *Creating a better mousetrap: On-line student assessment of their learning gains*. Paper presented at the National Meeting of the American Chemical Society, San Francisco, CA.

Shephard, K. (2008). Higher education for sustainability: Seeking affective learning outcomes. . *International Journal of Sustainability in Higher Education, 9*(1), 87-98.

Shibley, I. A., & Zimmaro, D. M. (2002). The influence of collaborative learning on student attitudes and performance in an introductory chemistry laboratory. *Journal of Chemical Education, 79*(6), 745. doi: 10.1021/ed079p745

Simonson, S. R., & Shadle, S. E. (2013). Implementing process oriented guided inquiry learning (POGIL) in undergraduate biomechanics: Lessons learned by a novice. *Journal of STEM Education : Innovations and Research, 14*(1), 56-62.

Sisovic, D., & Bojovic, S. (2000). Approaching the concepts of acids and bases by cooperative learning. *Chemistry Education Research and Practice, 1*(2), 263-275.

Smith, K. J., & Metz, P. A. (1996). Evaluating student understanding of solution chemistry through microscopic representations. *Journal of Chemical Education, 73*(3), 233-235.

Spencer, J. N. (1999). New directions in teaching chemistry: A philosophical and pedagogical basis. *Journal of Chemical Education, 76*(4), 566-569. doi: 10.1021/ed076p566

Spencer, J. N., & Moog, R. S. (2008). POGIL in the physical chemistry classroom. In R. S. Moog & J. N. Spencer (Eds.), *Process Oriented Guided Inquiry Learning* (pp. 148-156). Wachington, DC: American Chemical Society.

Sreenivasulu, B., & Subramaniam, R. (2012). University students' understanding of chemical thermodynamics. *International Journal of Science Education*, 1-35. doi: 10.1080/09500693.2012.683460

Staver, J. R. (1998). Constructivism: Sound theory for explicating the practice of science and science teaching. *Journal of Research in Science Teaching, 30*(4), 321-337.

Staver, J. R., & Halsted, D. A. (1984). The effect of reasoning on student performance on different sections of a posttest. *Science Education, 68*(2), 169-177. doi: 10.1002/sce.3730680210

Staver, J. R., & Jacks, T. (1988a). The influence of cognitive reasoning level, cognitive restructuring ability, disembedding ability, working memory capacity, and prior knowledge on students' performance on balancing equations by inspection. *Journal of Research in Science Teaching, 25*(9), 763-775. doi: 10.1002/tea.3660250906

Staver, J. R., & Jacks, T. (1988b). The influence of congnitive reasoning level, disembedding ability, working memory capacity and prior knowledge on students' performance on balancing equations by inspcetion. *Journal of Research in Science Teaching, 25*, 763-775.

Staver, J. R., & Lumpe, A. T. (1995). Two investigations of students' understanding of the mole concept and its use in problem solving. *Journal of Research in Science Teaching, 32*(2), 177-193. doi: 10.1002/tea.3660320207

Steel, N. M. (2012). Graduate ttributes. In *Encyclopedia of the sciences of learning* (pp. 1383-1383). New York: Springer US.

Steiff, M. (2007). Mental rotation and diagrammatic reasoning in science. *Learning and Instruction, 17*(2), 219-234.

Stevens, D. D., & Levi, A. J. (2005). *Introduction to rubrics*. Sterling, VA: Stylus Publishing.

Straumanis, A. (2009a). *Organic chemistry: A guided inquiry* (2 ed.). Boston, MA: Houghton Mifflin Harcourt Publishing Company.

Straumanis, A. (2009b). *Organic chemistry: A guided inquiry*. Boston, MA: Houghton Mifflin Harcourt Publishing Company.

Straumanis, A. (2010). *Classroom Implementation of POGIL: A practical guide for instructors* (pp. 56). Retrieved from http://guidedinquiry.org/misc/IG_2e.pdf

Straumanis, A. (2012a). *Organic chemistry: A guided inquiry for recitation* (Vol. 1). Belmont, CA: Brooks/Cole Cengage Learning.

Straumanis, A. (2012b). *Organic chemistry: A guided inquiry for recitation* (Vol. 2). Belmont, CA: Brooks/Cole Cengage Learning.

Straumanis, A., & Simons, E. A. (2008). A milti-institutional assessment of the use of POGIL in organic chemistry. In R. S. Moog & J. N. Spencer (Eds.), *ACS*

Symposium Series 994: Process-Oriented Guided inquiry Learning (pp. 226-239). Washington, DC: American Chemical Society.

Taagepera, M., Arasasingham, R. D., King, S., Potter, F., Martorell, I., Ford, D., . . . Kearney, A. M. (2011). Integrating symmetry in stereochemical analysis in introductory organic chemistry. *Chemistry Education Research and Practice, 12*(3), 322-330.

Taagepera, M., & Noori, S. (2000). Mapping students' thinking patterns in learning organic chemistry by the use of knowledge space theory. *Journal of Chemical Education, 77*(9), 1224. doi: 10.1021/ed077p1224

Taba, H. (1962). *Curriculum development: Theory and practice*. New York: Harcourt Brace and World.

Tabachnick, B., & Fidel, F. (1989). *Using multivariate statistics* (2nd ed.). New York: Harper Collins Publishers

Taber, K. S. (2006). Beyond constructivism: The progressive research programme into learning science. . *Studies in Science Education, 42*, 125-184.

Taber, K. S., & Watts, M. (1997). Constructivism and concept learning in chemistry: Perspectives from a case study. *Research in Education, 58*(10), 10.

Tan, K.-C. D., Taber, K. S., Goh, N.-K., & Chia, L.-S. (2005). The ionisation energy diagnostic instrument: A two-tier multiple-choice instrument to determine high school students' understanding of ionisation energy. *Chemistry Education Research and Practice, 6*(4), 180-197.

Tan, K.-C. D., Taber, K. S., Liu, X., Coll, R. K., Lorenzo, M., Li, J., . . . Chia, L. S. (2007). Students' conceptions of ionisation energy: A cross-cultural study. *International Journal of Science Education, 30*(2), 263-283. doi: 10.1080/09500690701385258

Tan, K.-C. D., Treagust, D. F., Goh, N.-K., & Chia, L.-S. (2002). Development and application of two-tier multiple choice diagnostic instrument to assess high school students' understanding of inorganic qualitative analysis. *Journal of Research in Science Teaching, 39*(4), 283-301.

Tashakkorri, A., & Teddlie, C. (1998). *Mixed methodology: Combining qualitative and quantitative approaches.* Thousand Oaks, CA: Sage Publications.

Tesch, R. (1990). *Qualitative research: analysis types and softward tools.* New York: Falmer.

Thompson, S. E., Ngambeki, I., Troch, P. A., Sivapalan, M., & Evangelou, D. (2012). Incorporating student-centered approaches into catchment hydrology teaching: A review and synthesis. *Hydrology and Earth System Sciences, 16*, 3263-3278.

Thurmond, V. A. (2001). The point of triangulation. *Journal of Nursing Scholarship, 33*(3), 253-258.

Towns, M. (2007). Mixed methods designs in chemical education research. In D. M. Bunce & R. S. Cole (Eds.), *Nuts and Bolts of Chemical Education Research* (pp. 135-148). Washington, DC: American Chemical Society.

Treagust, D. F. (1986a). Evaluating students' misconceptions by means of diagnostic multiple choice items. *Research in Science Education, 16*(1), 199-207.

Treagust, D. F. (1986b). Exemplary practice in high school biology classes. In K. Tobin & B. J. Fraser (Eds.), *Exemplary Practice in Science and Mathematics Education* (pp. 29-44). Perth, Australia: Key Centre for School Science and Mathematics, Curtin University of Technology.

Treagust, D. F. (1988). Development and use of diagnostic tests to evaluate students' misconceptions in science. *International Journal of Science Education, 10*(2), 159-169. doi: 10.1080/0950069880100204

Treagust, D. F. (1995). Diagnostic assessment of students' science knowledge. In S. M. Glynn & R. Duit (Eds.), *Learning Science in the Schools* (pp. 327-346). Mahwah, NJ.: Lawerence Erlbaum Associates Inc.

Treagust, D. F. (2006). *Diagnostic assessment in science as a means for improving teaching, learning and retention.* Paper presented at the Assessment in Science Teaching and Learning Symposium, University of Sydney.

Treagust, D. F., & Chandrasegaran, A. L. (2007). The Taiwan national science concept learning study in an international perspective. *International Journal of Science Education, 29*(4), 391-403. doi: 10.1080/09500690601072790

Treagust, D. F., Chittleborough, G., & Mamiala, T. (2003). The role of submicroscopic and symbolic representations in chemical explanations. *International Journal of Science Education, 25*(11), 1353-1368. doi: 10.1080/0950069032000070306

Treagust, D. F., & Chiu, M.-H. (2011). Diagnostic assessment in chemistry. *Chemistry Education Research and Practice, 12*(2), 119-120.

Treagust, D. F., & Rennie, L. J. (1993). Implementing technology in the school curriculum: A case study involving six secondary schools. *Journal of Technology Education, 5*(1), 38-53.

Trigwell, K., & Prosser, M. (1996). Changing approaches to teaching: A relational perspective. *Studies in Higher Education, 21*(3), 275-284.

Trochim, W. M., & Donnelly, J. P. (2006). *The research methods knowledge base* (3 ed.). Cincinnati, OH: Atom Dog.

Tsui, C. Y., & Treagust, D. F. (2010). Evaluating secondary students' scientific reasoning in genetics using a two-tier diagnostic instrument. *International journal of Science Education, 32*(8), 1073-1098.

Tuckey, H., & Selvaratnam, M. (1993). Studies involving three-dimensional visualisation skills in chemistry: A review *Studies in Science Education, 21*(1), 99-121.

Tyson, L., Treagust, D. F., & Bucat, B. (1999). The complexity of teaching and learning chemical equilibrium. *Journal of Chemical Education, 76*(4), 554-558.

Vacek, J. J. (2011). Process oriented guided inquiry learning (POGIL), A teaching method from physical sciences, promotes deep student learning in aviation. *Collegiate Aviation Review, 29*(2), 86-96.

Van de Vijver, F. (2011). Capturing bias in structural equation modelling. In E. Davidov, P. Schmidt & J. Billiet (Eds.), *Cross-cultural analysis methods and applications* (pp. 3-34). New York: Taylor & Francis Group, LLC.

Van den Akker, J. J. (1988). The teacher as learner in curriculum implementation. *Journal of Curriculum Studies, 20*(1), 47-55.

Van den Akker, J. J. (1998). The science curriculum: Between ideals and outcomes. In B. J. T. Fraser, K. G. (Ed.), *International handbook of science education* (pp. 421-447). Dordrecht, NL: Kluwer Academic Publishers.

Van Driel, J. H., & Graber, W. (2002). The teaching and learning of chemical equilibrium. In J. K. Gilbert, O. De Jong, R. Justi, D. F. Treagust & J. H. Van Driel (Eds.), *Chemical Education: Towards Research-based Practice* (pp. 271-292). Dordrecht, NL: Kluwer Academic Publishers.

van Rooij, S. W. (2009). Scaffolding project-based learning with the project management body of knowledge (PMBOK). *Computers and Education, 52*(1), 210-219. doi: 10.1016/j.compedu.2008.07.012

Villafañe, S. M., Bailey, C. P., Loertscher, J., Minderhout, V., & Lewis, J. E. (2011). Development and analysis of an instrument to assess student understanding of foundational concepts before biochemistry coursework. *Biochemistry and Molecular Biology Education, 39*(2), 102-109. doi: 10.1002/bmb.20464

Vygotsky, L. S. (1978). *Mind in society: the development of higher psychological processes*. Cambridge, MA: Harvard University Press.

Walker, D. (1990). *Fundamentals of curriculum*. San Diego, CA.: Harcourt Brace Jovanovich.

Wandersee, J. H., Mintzes, J. J., & Novak, J. D. (1994). Research on alternative conceptions in science. In D. L. Gabel (Ed.), *Handbook on Research in Science Teaching and Learning* (pp. 177-210). New York: Macmillan.

Watson, R., & Gore, P. A. (2006). A brief guide to structural equation modelling. *The Counselling Psychologist, 34*(5), 719-751.

Watters, D. J., & Watters, J. J. (2007). Approaches to learning by students in the biological sciences: Implications for teaching. *International Journal of Science Education, 29*(1), 19-43.

Wertsch, J. V. (1985). *Vygotsky and the social formation of mind*. Cambridge, MA: Harvard University Press.

Wheeler, A. E., & Kass, H. (1978). Student misconceptions in chemical equilibrium. *Science Education, 62*, 223-232.

Willis, J. W. (2007). *Foundations of qualitative research: Interpretive and critical theory approaches.* Thousand Oaks, CA: Sage Publications.

Yarroch, W. L. (1985). Student understanding of chemical equation balancing. *Journal of Research in Science Teaching, 22*, 449-459.

Yezierski, E. J., & Birk, J. P. (2006). Misconceptions about the particulate nature of matter. Using animations to close the gender gap. *Journal of Chemical Education, 83*(6), 954. doi: 10.1021/ed083p954

Zeegers, P., & Martin, L. (2001). A learning-to-learn program in a first-year chemistry class. *Higher Education Research & Development, 20*(1), 35-52.

Zoller, U. (1990). Students' misunderstandings and misconceptions in college freshman chemistry (general and organic). *Journal of Research in Science Teaching, 27*(10), 1053-1065. doi: 10.1002/tea.3660271011

Appendices

Appendix A

memorandum

Curtin
University of Technology

To	Ven Vishnu, SMEC
From	Pauline Howat, Coordinator for Human Research Ethics, Science and Mathematics Education Centre
Subject	Protocol Approval **SMEC-45-10**
Date	6 August 2010
Copy	David Treagust, SMEC

Office of Research and Development

Human Research Ethics Committee

TELEPHONE 9266 2784
FACSIMILE 9266 3793
EMAIL hrec@curtin.edu.au

Thank you for your "Form C Application for Approval of Research with Minimal Risk (Ethical Requirements)" for the project titled "*AN EXPLORATION OF PROCESS ORIENTED GUIDED INQUIRY LEARNING IN UNDERGRADUATE CHEMISTRY CLASSES*". On behalf of the Human Research Ethics Committee I am authorised to inform you that the project is approved.

Approval of this project is for a period of twelve months **3rd August 2010** to **2nd August 2011**.

If at any time during the twelve months changes/amendments occur, or if a serious or unexpected adverse event occurs, please advise me immediately. The approval number for your project is **SMEC-45-10**. *Please quote this number in any future correspondence.*

Pauline

PAULINE HOWAT
Coordinator for Human Research Ethics
Science and Mathematics Education Centre

Please Note: The following standard statement must be included in the information sheet to participants:
This study has been approved by the Curtin University Human Research Ethics Committee (Approval Number SMEC-45-10). If needed, verification of approval can be obtained either by writing to the Curtin University Human Research Ethics Committee, c/- Office of Research and Development, Curtin University of Technology, GPO Box U1987, Perth, 6845 or by telephoning 9266 2784.

J:\SMEC\office\Pauline\ETHICS\Ethics Approval Letter 2010\Vishnu.doc

Curtin University

Memorandum

To	Ven Vishnu, SMEC
From	Pauline Howat, Administrator, Human Research Ethics, Science and Mathematics Education Centre
Subject	**PROTOCOL APPROVAL – EXTENSION**
Date	12 August 2011
Copy	David Treagust, SMEC

Office of Research and Development

Human Research Ethics Committee

TELEPHONE 9266 2784
FACSIMILE 9266 3793
EMAIL hrec@curtin.edu.au

Thank you for keeping us informed of the progress of your research. The Human Research Ethics Committee acknowledges receipt of your Form B progress report for the project *"An Exploration of Process Oriented Guided Inquiry Learning in Undergraduate Chemistry Classes."*

Approval for this project is extended for the year to 2nd August 2012.

Your approval number remains SMEC-45-10. Please quote this number in any further correspondence regarding this project.

Please note: An application for renewal may be made with a Form B three years running, after which a new application form (Form A), providing comprehensive details, must be submitted.

Thank you.

Pauline

PAULINE HOWAT
Form C Ethics Administrator
Human Research Ethics Committee
Science and Mathematics Education Centre

J:\SAE\SMEC\office\Pauline\ETHICS\Form B Approval 2011\Vishnu.docx

Appendix B

Stereochemistry Concept Test

Curtin University

Directions

The purpose of the questions in this booklet is to find out your understanding of stereochemistry concepts. Your reason for choosing an answer is as important as the answer itself.

Record your answers to each question in the Answer Sheet provided. Please do not mark this booklet. Answer every question.

In answering each question, go through the following:

1. **Read the question carefully.**
2. **Take time to calculate and consider your answer.**
3. **Record your answer in the correct box on the Answer Sheet.**
   To register a response completely, fill the bubble ● corresponding to your chosen answer with a blue or black ballpoint pen.
4. **Read the set of possible reasons for your answer.**
5. **Carefully select the reason which best matched your thinking when you worked out the answer.**
6. **Record your answer in the correct reason box on the Answer Sheet.**
   To register a response completely, fill the bubble ● corresponding to your chosen answer with a blue or black ballpoint pen.
7. **If you change your mind about an answer, cross out the old answer and add the new choice.**
   Cross out your unwanted answer or reason ☒ with a blue or black ballpoint pen and completely fill the bubble ● with your new chosen answer
8. **Don't forget to record your name and other details on your Answer Sheet**

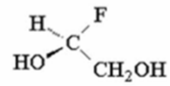
Stereochemistry concept test is being administered as part of a research studies and your involvement in this research is entirely voluntary. Your achievement in this stereochemistry concept test **doesn't** affect your semester grade in Chem 102.

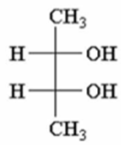
You are invited to participate in a focus group discussion to have a feedback on stereochemistry concept test and also revision help for the examinations.

Please contact Ven (email: venkat.vishnumolakala@curtin.edu.au) for more details:

Question 1
Determine which of the compounds have stereogenic carbon atoms (chiral centres)?

a. 

b. 

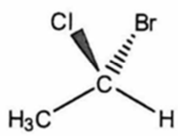
c. 

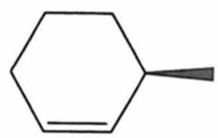
d. All of them

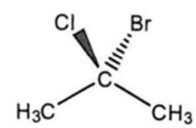
Reason

1. molecules are non-superimposable on their mirror images
2. molecules are super-imposable on their mirror images
3. the chiral carbon isn't bonded to four different groups
4. they do not have a plane of symmetry

Question 2
Which of the following doesn't have an enantiomer (is not an enantiomer)

a. 

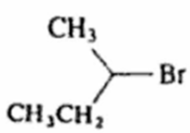
b. 

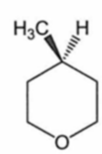
c. 

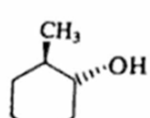
Reason

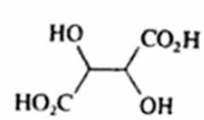
1. It has a chiral center
2. doesn't have a plane of symmetry
3. It is achiral
4. its a chiral molecule with no chiral centre

Question 3
Identify the achiral molecules

a. 

b. 

c. 

d. 

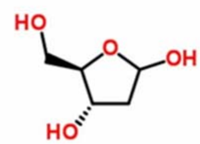
e. they are all chiral

Reason

1. the molecule has no internal plane of symmetry, hence it is not chiral
2. the mirror images are non-identical
3. the stereocentric carbon is bonded to four different groups
4. the mirror image is identical to the original, hence the molecule is not chiral

Question 4

The 2-deoxyribose, a five carbon sugar component of DNA (deoxyribonucleic acid) which alternates with phosphate groups to form the backbone of DNA polymer has the following structure:



How many stereosiomers are possible for 2-deoxyribose?

a. 8 b. 6 c. 4 d.0

Reason

1. presence of 4 asymmetric carbons
2. presence of 3 stereocentric carbons
3. presence of 2 asymmetric carbons
4. 2^n rule is valid only to acyclic molecules

Question 5

What is the best way to describe the relationship between these two molecules

a. they are enantiomers
b. they are constitutional isomers
c. they are diastereomers
d. they are identical

Reason

1. they are non-super imposable, they are also mirror images
2. the molecules are not non- superimposable and also are not mirror images
3. these molecules have same molecular formula and different connectivities
4. they are superimposable and are not mirror images

STUDENT CONSENT FORM

Curtin University

- I understand the purpose and procedures of the study.
- I have been provided with the participation information sheet.
- I understand that the procedure itself may not benefit me.
- I understand that my involvement is voluntary and I can withdraw at any time without problem.
- I understand that no personal identifying information like my name and address will be used in any published materials.
- I understand that all information will be securely stored for at least 5 years before a decision is made as to whether it should be destroyed.
- I have been given the opportunity to ask questions about this research.
- I agree to participate in the study outlined to me.

Name: ______________________________

Signature: ___________________________

Date: _______________

STUDENT ID								NAME	
								FAMILY NAME	GIVEN NAME(S)

0	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1
2	2	2	2	2	2	2	2
3	3	3	3	3	3	3	3
4	4	4	4	4	4	4	4
5	5	5	5	5	5	5	5
6	6	6	6	6	6	6	6
7	7	7	7	7	7	7	7
8	8	8	8	8	8	8	8
9	9	9	9	9	9	9	9

INSTRUCTIONS

- To register a response completely fill the bubble ● with a **blue** or **black** ballpoint pen.
- Completely fill each bubble underneath each digit in your student ID.
- Completely fill a single bubble corresponding to your answers and reasons given on the test.
- If you make an error, cross out the unwanted response ✖ and completely fill the circle corresponding to your wanted response.
- Do not make any other stray marks on the page.

	ANSWERS					REASON				
1	A	B	C	D	E	1	2	3	4	5
2	A	B	C	D	E	1	2	3	4	5
3	A	B	C	D	E	1	2	3	4	5
4	A	B	C	D	E	1	2	3	4	5
5	A	B	C	D	E	1	2	3	4	5

Appendix C

Chemistry 102

Student Assessment of their Learning Gains

Instructions:
Please fill in **one box only** for the following statements corresponding to the scale indicated by completely filling the circle ● with a **blue** or **black** ballpoint pen.

		no help	A little help	Moderate help	Much help	Great help
1	**As a result of your work in this class, what GAINS DID YOU MAKE in your UNDERSTANDING of each of the following?**					
1.1	The main concepts explored in this class	①	②	③	④	⑤
1.2	The relationships between the main concepts	①	②	③	④	⑤
1.3	The following concepts that have been explored in this class	①	②	③	④	⑤
1.3.1	The way that atoms bond to form molecules (ionic and covalent)	①	②	③	④	⑤
1.3.2	Representing molecules with Lewis structures, condensed structures, skeletal structures, and three-dimensional ball and stick	①	②	③	④	⑤
1.3.3	Identifying functional groups in organic molecules	①	②	③	④	⑤
1.3.4	Applying curved arrow conventions to describe bond forming and bond breaking processes	①	②	③	④	⑤
1.3.5	Attractive forces between molecules and the effect on physical properties	①	②	③	④	⑤
1.3.6	The reactions of alkyl halides, nucleophilic substitution reactions	①	②	③	④	⑤
1.3.7	predicting the products of reaction of alkyl halides with various nucleophiles	①	②	③	④	⑤
1.3.8	predict the products of elimination reactions of alkyl halides	①	②	③	④	⑤
1.3.9	S_N1 and S_N2 reaction mechanism	①	②	③	④	⑤
1.3.10	Distinguishing different types of isomers	①	②	③	④	⑤
1.3.11	Classifying compounds as chiral/achiral	①	②	③	④	⑤
1.3.12	Identifying stereocentres in molecules	①	②	③	④	⑤
1.3.13	Nomenclature, physical and chemical properties of aldehydes and ketones	①	②	③	④	⑤
1.4	How ideas from this class relate to ideas encountered in other classes within this subject area	①	②	③	④	⑤
1.5	How ideas from this class relate to ideas encountered in my major	①	②	③	④	⑤
1.6	How studying this subject area helps people address real world issues	①	②	③	④	⑤

1.7 Please comment on HOW YOUR UNDERSTANDING OF THE SUBJECT HAS CHANGED as a result of this class.

1.8 Please comment on how THE WAY THIS CLASS WAS TAUGHT helps you REMEMBER key ideas.

		no help	A little help	Moderate help	Much help	Great help
2	**As a result of your work in this class, what GAINS DID YOU MAKE in the following SKILLS?**					
2.1	Identifying patterns in data	①	②	③	④	⑤
2.2	Recognizing a sound argument and appropriate use of evidence	①	②	③	④	⑤
2.3	Developing a logical argument	①	②	③	④	⑤
2.4	Working effectively with others	①	②	③	④	⑤

2.5 Please comment on what SKILLS you have gained as a result of this class.

3	**As a result of your work in this class, what GAINS DID YOU MAKE in the following?**					
3.1	Enthusiasm for the subject	①	②	③	④	⑤
3.2	Interest in discussing the subject area with friends or family	①	②	③	④	⑤
3.3	Interest in taking or planning to take additional classes in this subject	①	②	③	④	⑤
3.4	Confidence that you understand the material	①	②	③	④	⑤
3.5	Confidence that you can do this subject area	①	②	③	④	⑤
3.6	Your comfort level in working with complex ideas	①	②	③	④	⑤
3.7	Willingness to seek help from others (teacher, peers, TA) when working on academic problems	①	②	③	④	⑤

3.8 Please comment on how has this class CHANGED YOUR ATTITUDES toward this subject.

4	**As a result of your work in this class, what GAINS DID YOU MAKE in INTEGRATING the following?**					
4.1	Connecting key class ideas with other knowledge	①	②	③	④	⑤
4.2	Applying what I learned in this class in other situations	①	②	③	④	⑤
4.3	Using systematic reasoning in my approach to problems	①	②	③	④	⑤
4.4	Using a critical approach to analyzing data and arguments in my daily life	①	②	③	④	⑤

4.5 What will you CARRY WITH YOU into other classes or other aspects of your life?

		no help	A little help	Moderate help	Much help	Great help
5	**HOW MUCH did the following aspects of the class HELP YOUR LEARNING?**					
5.1	The instructional approach taken in this class	①	②	③	④	⑤
5.2	How the class topics, activities, reading and assignments fit together	①	②	③	④	⑤
5.3	The pace of the class	①	②	③	④	⑤
5.4	Please comment on how the INSTRUCTIONAL APPROACH to this class helped your learning.	①	②	③	④	⑤

5.5 How has this class CHANGED THE WAYS YOU LEARN/STUDY?

6	**HOW MUCH did each of the following aspects of the class HELP YOUR LEARNING?**					
6.1	Attending class	①	②	③	④	⑤
6.2	Participating in discussions during class	①	②	③	④	⑤
6.3	Listening to discussions during class	①	②	③	④	⑤
6.4	Participating in group work during class	①	②	③	④	⑤
6.5	Please comment on how the CLASS ACTIVITIES helped your learning.	①	②	③	④	⑤

6.6 Please comment on HOW OFTEN YOU PARTICIPATED in class discussions and HOW THE ATMOSPHERE IN THE CLASSROOM ENCOURAGED OR DISCOURAGED your participation

7	**HOW MUCH did each of the following aspects of the class HELP YOUR LEARNING?**					
7.1	The number and spacing of tests	①	②	③	④	⑤
7.2	The fit between class content and tests	①	②	③	④	⑤
7.3	The mental stretch required by tests	①	②	③	④	⑤
7.4	The way the grading system helped me understand what I needed to work on	①	②	③	④	⑤
7.5	The feedback on my work received during and after tutorials	①	②	③	④	⑤

7.6 Please comment on how the GRADED ACTIVITIES AND TESTS helped your learning.

		no help	A little help	Moderate help	Much help	Great help
8	**HOW MUCH did each of the following aspects of the class HELP YOUR LEARNING?**					
8.1	The primary textbook	①	②	③	④	⑤
8.2	The activities	①	②	③	④	⑤
8.3	The course website/Blackboard	①	②	③	④	⑤
8.4	Posted mini lectures	①	②	③	④	⑤
8.5	Posted Pencasts	①	②	③	④	⑤
8.6	Pencast solutions of Homework problems	①	②	③	④	⑤
8.7	Clickers during the lecture	①	②	③	④	⑤

8.8 Please comment on how the RESOURCES in this class helped your learning

9	**HOW MUCH did each of the following aspects of the class HELP YOUR LEARNING?**					
9.1	Explanation of how the class activities, reading and assignments related to each other	①	②	③	④	⑤
9.2	Explanation given by instructor on why the class was organized into groups	①	②	③	④	⑤
9.3	Explanation of why the class focused on the topics presented	①	②	③	④	⑤

9.4 Please comment on HOW the INFORMATION YOU RECEIVED about the class helped your learning.

10	**HOW MUCH did each of the following aspects of the class HELP YOUR LEARNING?**					
10.1	Interacting with the instructor during class	①	②	③	④	⑤
10.2	Interacting with the instructor during office hours.	①	②	③	④	⑤
10.3	Working with peers during class	①	②	③	④	⑤
10.4	Working with peers outside of class	①	②	③	④	⑤
10.5	Working with a tutor outside of class	①	②	③	④	⑤

10.6 Please comment on how the SUPPORT YOU RECEIVED FROM OTHERS helped your learning in this class.

Appendix D

Questions for the follow-up interview of SCDT

Interview Protocol

I) Student's consent

Students will be asked to fill out a permission form.

II) Interview

A. When everyone has finished the student's consent sheet, the interview will begin by:

1. To start the interview, why don't we introduce ourselves, state your majors and what your future goals are?

B. Topic one - group work; concept test and group problems:

2. Tell me what it was like to work in groups on the Stereochemistry concept diagnostic test.

3. How did the answering of questions like this as a group affect your understanding of the chemical concepts being studied?

   possible probing question - How did the small group learning (POGIL) benefit you?

C. Topic two – in-class activity sheets, critical thinking questions and tests:

4. Here is an example of an activity-sheet you have already taken in Chem102. What reasons would you use for deciding to answer this question?

5. What reasons would you use for deciding not to answer this critical thinking question?

6. What are the advantages of embedding graphs, pictures in critical thinking questions for in-class activity- sheets? Do these help you solve problems / explore concepts?

7. What are the disadvantages of having critical thinking questions on activity sheets?

8. What other recommendations could you provide to improve the use of critical thinking questions on activity sheets?

9. Here is an example of a critical thinking question found on a Chem102 test this semester. Explain the thought processes you would use to answer this question.

10. What study methods would be most helpful to enable you to answer this question?

D. Learning chemistry

11. How would you describe what needs to occur while people are learning chemistry?

12. How do critical thinking questions fit into the process of learning chemistry?

13. How does small group interaction or team work fit into the process of learning chemistry?

14. Does anyone have any further comments

15. How do you feel about using clickers in this course?

Thank you for taking the time to provide us the feedback

Questions for the Individual student interviews

1. Course in General: Small Group work: Learning, understanding, explaining and thinking

1.1 What is your major?

1.2 How do you feel about your chemistry course?

1.3 Do you feel that small group learning has strengthened your understanding of concepts in this course?

1.4 Do you think that mini-lectures have helped you to explore the concepts?

1.5 Do you think that the in-class small group activities are challenging?

1.6 Do you think the in-class group activities have helped you develop your critical/logical thinking? *(making decisions based on information, analysing, comparing, synthesizing, and reasoning?)*

1.7 Do you think that in-class group activities and argumentative discussions have provided opportunities to improve your written and oral skills in this course?

1.8 Are these small group discussions / in-class activities stressful and frustrating?

1.9 Do you think that the in-class group activities are more beneficial than traditional lectures?

1.10 Do you think the in-class group discussions have helped you prepare well for the tests?

1.11 Have these in-class small group discussions / activities helped you improve your test scores?

1.12 Do you think that participation in small group in-class activities have helped you gain confidence in this course?

2. Skills

2.1 Do you think that in-class activities and small group discussion have helped you improve your problem-solving skills?

3. Resources

3.1 How do you feel about using clickers in this course?

3.2 When do you find the clicker questions to be more effective?

3.3 Why do you think the professor is using clickers in this course?

3.4 Have you used clickers in any of other courses here?

3.5 Can you compare the way the clickers were used in your chemistry course to how they were used in these other courses?

3.6 Do you think Pencasting of homework solutions offered help in retaining your knowledge?

Appendix E

Faculty of Science and Engineering
Department of Chemistry

Curtin University

7039 Chemistry 101

Semester 1, 2011

Unit study package number:	7039
Mode of study:	Internal
Tuition pattern summary:	Lecture: 3 x 1 hour weekly Tutorial: 1 x 1 hour weekly commencing week 2 Laboratory: 1 x 3 hour weekly commencing week 2
Credit value:	25.0
Pre-requisite units:	WACE Chemistry 3A/3B or equivalent
Co-requisite units:	None
Anti-requisite units:	None
Additional Requirements:	None
Result type:	Grade/Mark
Approved incidental fees:	All fee information can be obtained through the Fees Centre. Visit http://fees.curtin.edu.au for details.

Unit Coordinator:

Name:	Dr Daniel Southam
Phone:	08 9266 7265
Email:	D.Southam@curtin.edu.au
Building : Room:	500.3124
Consultation times:	By appointment

Teaching Staff:

Name:	Prof Mark Buntine	A/Prof Simon Lewis	Dr Stuart Bailey
Phone:	08 9266 7265	08 9266 2484	08 9266 7808
Email:	M.Buntine@curtin.edu.au	S.Lewis@curtin.edu.au	S.Bailey@curtin.edu.au
Building : Room:	500.2101	500.4122	500.4116
Consultation times:		By appointment	

Administrative contact:

Name:	Alicia Harrison
Phone:	08 9266 7265
Email:	firstyearchem@curtin.edu.au
Building : Room:	500.2101

Learning Management System: FLECS - Blackboard (http://oasis.curtin.edu.au)

Syllabus

This unit is designed for students who have passed WACE Chemistry 3A/3B or equivalent. If you have not previously studied chemistry you should not take this unit. Chemistry 101 applies atomic theories to the concept of bonding enabling prediction of properties within matter. Topics covered include: principles of quantitative analysis; sub- atomic structure, quantum numbers, spectroscopy and nuclear chemistry; thermodynamics; bonding theories; molecular and ionic equilibria; coordination chemistry.

Introduction

Chemistry 101 is designed for students who have passed WACE Chemistry 3A/3B or equivalent and aims to provide an introduction to the study of matter. There are six lecture modules:

- Module A: Atomic theory and nuclear chemistry (Daniel Southam)
- Module B: Bonding (Daniel Southam)
- Module C: Coordination chemistry (Daniel Southam)
- Module D: Principles of analytical chemistry (Simon Lewis)
- Module E: Thermodynamics (Mark Buntine)
- Module F: Equilibria (Stuart Bailey)

There is also a comprehensive laboratory program with experiments involving:

- Quantitative analysis
- Qualitative identification of inorganic compounds
- Transition metal complexes
- pH and buffers
- Thermochemistry

Unit Learning Outcomes

On successful completion of this unit students can:

		Graduate Attributes addressed:
1.	Critically evaluate atomic theories and apply them to predict bonding within and properties of matter	
2.	Calculate the physical reactivity and energetics of matter	
3.	Employ the principles of quantitation to determine uncertainty in measurement.	
4.	Apply molecular-centric logical skills to discipline-specific problem solving	
5.	Employ experimental and analytical skills in the correct and safe use of laboratory equipment, individually and within a group.	

Curtin's Graduate Attributes

Apply discipline knowledge

Thinking skills (use analytical skills to solve problems)

Information skills (confidence to investigate new ideas)

Communication skills

Technology skills

Learning how to learn (apply principles learnt to new situations)

International perspective (value the perspectives of others)

Cultural understanding (value the perspectives of others)

Professional skills (work independently and as a team) (plan own work)

Find out more about Curtin's Graduate attributes at the Office of Teaching & Learning website: http://otl.curtin.edu.au

Learning Activities

Lectures

Lectures provide the fundamental basis of your knowledge in this unit. Attendance at lectures will give you guidance on the topics covered and provide you with examples of application of the theory. The lectures are designed to be interactive, and students are encouraged to attend prepared to participate.

In some lectures we will be using an “active learning” style of teaching that mixes

You must purchase the following personal protective equipment, which must be worn at all times during the laboratory sessions. You will be denied access if you are not wearing these items and receive zero for that laboratory:

- **Laboratory coat**
- **Safety glasses**, containing colourless transparent lenses. Prescription or sunglasses are not acceptable. The wearing of contact lenses is discouraged.
- **Enclosed shoes** should also be worn at all times, covering your toes, forefoot and heel. Thongs, sandals and slip-on shoes will not be permitted.

You should also purchase a metal or plastic spatula (available from Chemistry Club at cost price, see noticeboards in Building 500).

Other Resources

Students intending to do 2nd and 3rd year chemistry may wish to purchase the following items:

- Aylward & Findlay, *SI Chemical Data*, (any edition), John Wiley and Sons.

Calculators

Students may only use a handheld battery operated non-programmable scientific calculator in all tests and examinations. The Hewlett Packard HP10s is recommended, but any model of the above type may be used. Any other types, including graphics calculators, are not permitted.

Assessment

Assessment Schedule

Task	Value (%)	Comprising	Date due	Unit Learning Outcome(s) assessed
Tutorials	10%	10 x 1% assessment items marked on an A - D scale	Weekly at your tutorial	1, 2, 3, 4
Laboratories	20%	10 x 3 hour laboratories marked to a total of 100	Weekly at your laboratory	1, 2, 3, 4, 5
Mid-semester tests	20%	2 x 45 minute equally weighted tests. One administered in the AC Lab, one paper-based.	Test 1: Week commencing 11 April Test 2: Week commencing 9 May	1, 2, 3, 4
Final examination	50%	One 2.5 hour final written examination.	Examination period (TBA)	1, 2, 3, 4, 5

Detailed information on assessment tasks

1. Tutorials

The tutorial program for this unit is a collaborative environment where you can get help with questions set by the lecturers. Each week there will be a short tutorial exercise that you must submit at the end of the session. You can get help with completing these questions during the tutorial from the tutors. All students are encouraged to bring problems to the tutors for assistance and guidance.

Each week a short assessment will be marked by your tutors to give you feedback on your progress. These will be graded on participation and performance with a single mark given on an A – D scale. If there's some discrepancy between the two grades your tutor will help you to improve either or both aspects.

Grade	**Participation** Observing the tutorial I noted that the student was...	**Performance** Assessing the submitted work I found that...
A	...actively engaged in the exercise displaying teamwork and leadership.	...a **completely** full attempt with **completely** correct and logical answers to the questions posed was displayed.
B	...engaged in the exercise displaying some teamwork.	...a **mostly** full attempt with **many** correct and logical answers to the questions posed was displayed.
C	...completing the exercise without teamwork.	...a **partial** attempt with **some** correct and logical answers to the questions posed was displayed.
D	...not participating in the group.	**...little or no** attempt with **few** correct answers to the questions posed was displayed.
X	...absent from the tutorial.	...no work was submitted.

2. Laboratories

Laboratories will be assessed out of ten (10) marks each according to the assessment criteria given with each experiment.

In every laboratory session your demonstrator may deduct up to 20% of the available marks from your mark based on their observations of your laboratory conduct, hygiene and cleanliness.

For safety reasons, students must follow the instructions of all staff at all times. Persistent failure to follow instructions may result in removal from the laboratory and a mark of zero (0) being recorded.

3. Mid-semester test

The mid-semester test will examine concepts covered up to and including the teaching week immediately prior to the test.

Test 1 will be an online test to be taken in the Assessment Centre Laboratory on Level 5 in the library (Building 105) from 11 April onwards (not the weekend). You must book for this test by following the links to "Assessment Centre Bookings" in OASIS. You must book for a session prior to attending and no extensions will be granted for full sessions due to late bookings.

Test 2 will be an written multiple choice test to be taken in your scheduled tutorial in the week commencing 9 May. You must attend your tutorial at this time to sit this test. No further tests will be offered.

In both tests you will be provided with a formula sheet, periodic table and blank paper for rough calculations, but you should bring your own calculator. Students will be permitted only one non-programmable scientific calculator in both tests.

4. Final examination

The exam will consist of three sections; a multiple-choice section and two written sections. You must obtain at least 40% in each written section to gain a pass in this unit.

This exam will assess materials covered in the lectures, laboratories, tutorials and online quizzes. Students will be permitted only one non-programmable scientific calculator in the exam. This exam will be held in the normal exam period.

Fair assessment through moderation

Moderation describes a quality assurance process to ensure that assessments are appropriate to the learning outcomes, and that student work is consistently evaluated by assessors. Minimum standards for the moderation of assessment are described in the Assessment Manual, available from http://policies.curtin.edu.au/policies/teachingandlearning.cfm.

Late Assessment Policy

This ensures that the requirements for submission of assignments and other work to be assessed are fair, transparent, equitable, and that penalties are consistently applied.

1. All assessments which students are required to submit will have a **due date and time** specified on the Unit Outline.
2. Accepting late submission of assignments or other work will be determined by the unit coordinator or Head of School and will be specified on the Unit Outline.
3. If late submission of assignments or other work is **not** accepted, students will receive a penalty of 100% after the due date and time ie a zero mark for the late assessment.
4. If late submission of assignments or other work **is** accepted, students will be penalised by ten percent per working day for a late assessment submission (eg a mark equivalent to 10% of the total allocated for the assessment will be deducted from the marked value for every day that the assessment is late). This means that an assignment worth 20 will have two marks deducted per working day late. Hence if it was handed in three working days late and marked as 12/20, the student would receive 6/20. An assessment **more than seven working days overdue will not be marked**. Work submitted after this time (due date plus seven days) may result in a Fail – Incomplete (F-IN) grade being awarded for the unit.

Late submissions of assessment for this unit **will not** be accepted after the due date.

Pass requirements

To gain a pass in this unit students must:

- obtain at least 40% of the available marks in both written sections of the final examination,
- satisfactorily complete 80% of the available laboratories,
- gain at least 50% of the overall mark.

Failure to satisfy all criteria will result in a failing grade being applied, even if the overall mark is greater than 50%.

Laboratory exemptions

Students who have previously failed this unit may request an exemption from the laboratory. The following guidelines apply to the granting of exemptions from laboratory courses in first year:

- The granting of an exemption is a privilege and not a right and is at the discretion of the unit coordinator.
- An exemption may be granted to a student repeating a failed unit if the lab assessment for the failed unit is 60% or above.
- An exemption will not be granted if there is an unsatisfactory record of missed or late submissions.
- An exemption is only valid once and cannot be carried over to subsequent years.
- No exemption will be granted if the unit has been failed more than once.

All requests for exemptions must be made by completing an "Request for laboratory exemption" form available from FLECS-Blackboard under "Unit Information" or the reception, Building 500, Level 2 (Room 2101).

Plagiarism

Plagiarism occurs when work or property of another person is presented as one's own, without appropriate acknowledgement or referencing. Plagiarism is a serious offence. For more information refer to http://academicintegrity.curtin.edu.au.

Plagiarism Monitoring

Work submitted may be subjected to a plagiarism detection process, which may include the use of systems such as 'Turnitin'. For further information see http://academicintegrity.curtin.edu.au/students/turnitin.cfm.

Additional information

Enrolment:

It is your responsibility to ensure that your enrolment is correct - you can check your enrolment through the eStudent option on OASIS, where you can also print an Enrolment Advice.

Supplementary/Deferred Exams:

Supplementary and deferred examinations granted by the Department of Chemistry will be held in the week commencing 11 July 2011. Notification to students will be made after the Board of Examiners meeting via the Official Communications Channel (OCC) in OASIS. It is the student's responsibility to check their OASIS account for official Curtin correspondence on a weekly basis. If your results show that you have been awarded a supplementary or deferred exam you should immediately check your OASIS email for details.

Student Rights and Responsibilities

It is the responsibility of every student to be aware of all relevant legislation and policies and procedures relating to his or her rights and responsibilities as a student. These include:

- the Student Charter
- the University's Guiding Ethical Principles
- the University's policy and statements on plagiarism and academic integrity
- copyright principles and responsibilities
- the University's policies on appropriate use of software and computer facilities

Information on all these things is available through the University's "Student Rights and Responsibilities" website at: http://students.curtin.edu.au/rights.

Student appeals: http://students.curtin.edu.au/rights/appeals/index.cfm

---

Recent unit changes

We welcome feedback as one way to keep improving this unit. Students are encouraged to give unit feedback through **eVALUate**, Curtin's online student feedback system (see http://evaluate.curtin.edu.au/info/index.cfm). Recent changes to this unit include:

1. Increasing the frequency of tutorials from fortnightly to weekly.
2. Changes to the type and mode of online assessments.
3. Improvements to the laboratory program
4. Increase in the use of active learning in-lecture activities

7040 Chemistry 102

Semester 2, 2011

Unit study package number:	7040
Mode of study:	Internal
Tuition pattern summary:	3 x 1 hour lectures weekly 1 x 3 hour laboratory weekly commencing week 2 1 x 1 hour tutorial weekly commencing week 2
Credit value:	25 credit points
Pre-requisite units:	None
Co-requisite units:	None
Anti-requisite units:	None
Additional Requirements:	None
Result type:	Grade/Mark
Approved incidental fees:	All fee information can be obtained through the Fees Centre. Visit fees.curtin.edu.au for details.
Scheduled times and Venues:	see http://timetable.student.curtin.edu.au for scheduled times and venues

Unit Coordinator and Lecturer:	Name:	Dr Daniel Southam
	Phone:	08 9266 7265
	Email:	firstyearchem@curtin.edu.au
	Building : Room:	500.3124
	Consultation times:	Contact Alicia Harrison

Lecturers:	Name:	A/Prof Mauro Mocerino	Prof Mark Buntine	Dr Stuart Bailey
	Phone:	08 9266 3125	08 9266 7265	08 9266 7808
	Email:	M.Mocerino@curtin.edu.au	M.Buntine@curtin.edu.au	S.Bailey@curtin.edu.au
	Building : Room:	500.4115	500.2101	500.4116
	Consultation:	By appointment	By appointment	By appointment

Administrative contact:	Name:	Alicia Harrison
	Phone:	08 9266 7265
	Email:	firstyearchem@curtin.edu.au
	Building : Room:	500.2101

Learning Management System: FLECS - Blackboard (oasis.curtin.edu.au)

Acknowledgement of Country

We respectfully acknowledge the Indigenous Elders, custodians, their descendants and kin of this land past and present.

Syllabus

This unit is designed for students who have passed WACE Chemistry 3A/3B or equivalent. If you have not previously studied chemistry you should not take this unit. General chemistry involving intermolecular forces, chemical kinetics and electrochemistry. Structure and bonding of organic compounds including isomers. Reactions and properties of aliphatic and aromatic hydrocarbons, and organic compounds containing common functional groups. Experiments involving purification and separation techniques, reactions of functional groups, reactions of hydrocarbons and industrially relevant analytical techniques.

Introduction

Chemistry 102 aims to provide an introduction to the study of matter in a series of seven modules:

- Module A: Instrumental Analytical Chemistry (3 lectures, Daniel Southam)
- Module B: Intermolecular forces (6 lectures, Mark Buntine)
- Module C: Redox (3 lectures, Stuart Bailey)
- Module D: Hydrocarbons (9 lectures, Mauro Mocerino)
- Module E: Kinetics (3 lectures, Mark Buntine)
- Module F: Substitution and elimination reactions (6 lectures, Mauro Mocerino)
- Module G: Carbonyl compounds and biologically important molecules (6 lectures, Mauro Mocerino)

Unit Learning Outcomes

On successful completion of this unit students can:

		Graduate Attributes addressed:
1.	Apply the basic principles of kinetics to solve problems in theoretical and practical contexts.	
2.	Identify common functional groups and describe their principle reactions, their mechanistic pathway and predict the products of such reactions.	
3.	Predict physicomechanical properties of matter from their intermolecular forces.	
4.	Use internationally recognised conventions in the communication of chemistry, including nomenclature, graphical and symbolic representation of molecules.	
5.	Efficiently and safely perform a range of laboratory procedures, including analysis, synthesis, isolation and purification.	

Curtin's Graduate Attributes

Apply discipline knowledge	Thinking skills (use analytical skills to solve problems)	Information skills (confidence to investigate new ideas)
Communication skills	Technology skills	Learning how to learn (apply principles learnt to new situations)
International perspective (value the perspectives of others)	Cultural understanding (value the perspectives of others)	Professional skills (work independently and as a team) (plan own work)

Find out more about Curtin's Graduate attributes at the Office of Teaching & Learning website: http://otl.curtin.edu.au

Learning Activities

Lectures

Lectures provide the fundamental basis of your knowledge in this unit. Attendance at lectures will give you guidance on the topics covered and provide you with examples of application of the theory. The lectures are designed to be interactive, and students are encouraged to attend prepared to participate. Attendance at and participation in lectures are integral to the likelihood of success in this unit.

Laboratories

Laboratory classes (commencing week 2) provide you with important skills in practical chemistry and develop good teamwork and communication. It's your responsibility to make sure you're familiar with the topic material required for successful completion of the exercise before the laboratory session. You should thoroughly read the laboratory notes for the exercises and complete any pre-laboratory questions before entering the lab.

Make sure you are present promptly at the beginning of the laboratory session, as vital health and safety information is provided at this time and failure to attend may place yourself or others at risk of injury. You should also ensure you are adequately attired for the laboratory by wearing a laboratory coat, safety glasses and enclosed shoes to each laboratory. You may be barred from entry or asked to leave the laboratory at any time for failure to follow health and safety advice or for incorrect attire.

Tutorials

The tutorial program comprises weekly "face-to-face" tutorials (commencing week 2). Your tutorial exercises are provided weekly, and assessed according to the attached schedule. The topics and assigned activities for the tutorial sessions will be posted on FLECS-Blackboard the week before the tutorial.

These classes will address concepts and skills critical for a thorough understanding of some of the more challenging aspects of chemistry that are not readily addressed elsewhere. Your tutorial assignments are to be submitted at the completion of each of the assessed tutorial sessions.

Referencing style

Students should use the Vancouver referencing style when preparing assignments. More information can be found on this style from the Library web site:
library.curtin.edu.au/research_and_information_skills/referencing

Learning Resources

Essential Texts

You will need to purchase the following resources in order to complete this unit:

- Blackman, Bottle, Schmid, Mocerino & Wille, *Chemistry*, John Wiley and Sons, 2007.
- *Chemistry 102: Laboratory Manual*, Curtin University, 2011 (also available to download from FLECS-Blackboard)

Personal Protective Equipment

You must have the following personal protective equipment to work in the laboratory:

- **Laboratory coat** of a type that fastens up the front, has long sleeves and comes to your knee.
- **Safety glasses** containing colourless transparent lenses. Prescription or sunglasses are not acceptable. The wearing of contact lenses is discouraged.
- **Enclosed shoes** should also be worn at all times, fully covering your toes, forefoot and heel. Thongs, sandals and slip-on shoes will not be permitted.

It is a legislative requirement that you must correctly wear a laboratory coat, safety glasses and fully enclosed shoes at all times in the laboratory. You will be denied access if you are not wearing these items and receive zero marks for that laboratory. If you remove these items in the laboratory you may be asked to leave and will receive zero marks for that laboratory. A limited number of laboratory coats and safety glasses only are available for hire in the teaching laboratories at your expense.

Calculators

Students may only use a handheld battery operated non-programmable scientific calculator in all tests and examinations. The Hewlett Packard HP10s is recommended, but any model of the above type may be used.

Any other types, including graphics calculators, are **not** permitted in all tests and the final examination. It is your responsibility to check the compliance of your calculator before any test or examination. If unacceptable devices are found on or about your person after the commencement of a test or examination, these may be taken as evidence of cheating and you risk disciplinary action in accordance with University policy.

Assessment

Assessment Schedule

Task	Value (%)	Comprising	Date due	Unit Learning Outcome(s) assessed
Tutorials	10%	10 x 1% assessment items marked on an A - D scale	Weekly at your tutorial	1, 2, 3, 4
Laboratories	20%	10 x 3 hour laboratories	Weekly at your laboratory, commencing week 2	1, 2, 3, 4, 5
Mid-semester tests	20%	2 x 40 minute equally weighted tests	At your tutorial: Test 1: Week commencing 22 August Test 2: Week commencing 26 September	1, 2, 3, 4
Final examination	50%	2.5 hour written examination	During examination period	1, 2, 3, 4, 5

Detailed information on assessment tasks

Tutorials

The tutorial program for this unit is a collaborative environment where you can get help with questions set by the lecturers. Each week there will be a short tutorial exercise that you must submit at the end of the session. You can get help with completing these questions during the tutorial from the tutors. All students are encouraged to bring problems to the tutors for assistance and guidance.

Each week a short assessment will be marked by your tutors to give you feedback on your progress. These will be graded on participation and performance with a single mark given on an A – D scale. If you do not attend and participate in the tutorial the maximum mark you will receive is a C.

Late tutorials will not be accepted. Exemption from tutorials due to illness is not permissible.

Laboratories

Each laboratory session will be assessed out of ten (10) marks according to the assessment criteria given with each experiment.

In every laboratory session your demonstrator may deduct up to 20% of the available marks from your mark based on their observations of your laboratory conduct, hygiene and cleanliness. You must follow their instructions at all times.

For safety reasons, students must follow the instructions of all teaching and technical staff at all times. Persistent failure to follow instructions may result in removal from the laboratory and a mark of zero (0) being recorded.

Mid-semester tests

Each of the two mid-semester tests will examine concepts indicated in the Program Calendar attached to this Unit Outline. They will each comprise a series of multiple choice questions containing a single fully correct answer. You should attend your scheduled tutorial. If you are unable to attend due to illness please contact the unit coordinator within 5 working days. Failure to do so within this timeframe will result in a mark of zero (0) being recorded.

In both tests you will be provided with a formula sheet, periodic table and blank paper for rough calculations, but you should bring your own calculator. Students will be permitted only one non-programmable scientific calculator in both tests.

Final examination

The exam will be a 2.5 hour final examination covering all lecture material. It will comprise one multiple choice and two short answer written sections. This exam will assess materials covered in the lectures, laboratories and tutorials. Students will be permitted only one non-programmable scientific calculator in the exam. This exam will be held in the end of semester examination period.

Fair assessment through moderation

Moderation describes a quality assurance process to ensure that assessments are appropriate to the learning outcomes, and that student work is evaluated consistently by assessors. Minimum standards for the moderation of assessment are described in the Assessment Manual, available from policies.curtin.edu.au/policies/teachingandlearning.cfm

Late Assessment Policy

This ensures that the requirements for submission of assignments and other work to be assessed are fair, transparent, equitable, and that penalties are consistently applied.

1. All assessments which students are required to submit will have a **due date and time** specified on the Unit Outline.
2. Accepting late submission of assignments or other work will be determined by the unit coordinator or Head of School and will be specified on the Unit Outline.
3. If late submission of assignments or other work is **not** accepted, students will receive a penalty of 100% after the due date and time ie a zero mark for the late assessment.
4. If late submission of assignments or other work **is** accepted, students will be penalised by ten percent per working day for a late assessment submission (eg a mark equivalent to 10% of the total allocated for the assessment will be deducted from the marked value for every day that the assessment is late). This means that an assignment worth 20 will have two marks deducted per working day late. Hence if it was handed in three working days late and marked as 12/20, the student would receive 6/20. An assessment **more than seven working days overdue will not be marked**. Work submitted after this time (due date plus seven days) may result in a Fail – Incomplete (F-IN) grade being awarded for the unit.

Late submission of assignments or other work will not be accepted in this unit.

Pass requirements

In addition to gaining at least 50% of the total marks, to gain a pass in Chemistry 102 you must meet the following requirements:

1. Complete at least least 80% (eight out of ten[1]) of the available experiments and gain at least 50% of the total laboratory marks.
2. Obtain at least 40% of the available marks in both written sections of the final examination.

Failure to meet both criteria will result in a Fail – Incomplete (F-IN) grade being applied, even if your total mark is greater than 50%.

Laboratory exemptions

Students who have previously failed this unit may request an exemption from the entire laboratory program. The following guidelines apply to the granting of exemptions from laboratory courses in first year:

- The granting of an exemption is a privilege and not a right and is at the discretion of the Unit Coordinator.
- An exemption may be granted to a student repeating a failed unit if the lab assessment for the failed unit is 60% or above.
- An exemption will not be granted if there is an unsatisfactory record of missed or late submissions.
- An exemption is only valid once and cannot be carried over to subsequent years.
- No exemption will be granted if the unit has been failed more than once.

All requests for exemptions must be made by completing a "Request for laboratory exemption" form available from FLECS-Blackboard under "Unit Information" or the reception, Building 500, Level 2 (Room 2101).

Plagiarism

Plagiarism occurs when work or property of another person is presented as one's own, without appropriate acknowledgement or referencing. Plagiarism is a serious offence. For more information refer to academicintegrity.curtin.edu.au

Plagiarism Monitoring

Work submitted may be subjected to a plagiarism detection process, which may include the use of systems such as 'Turnitin'. For further information see http://academicintegrity.curtin.edu.au/students/turnitin.cfm.

Additional information

Enrolment:

It is your responsibility to ensure that your enrolment is correct - you can check your enrolment through the eStudent option on OASIS, where you can also print an Enrolment Advice.

[1] Students who are absent from the laboratory due to illness, University business or participation in the Elite Athletes Program may be granted an exemption from an experiment at the discretion of the Unit Coordinator or the Head of the Department of Chemistry. If you were absent from the laboratory due to one of the aforementioned reasons you should complete an 'Absence from the Laboratory form' available from FLECS-Blackboard and attach the requisite documentary evidence. If approved, exemptions do not count toward the total number of laboratories for this pass requirement or the total laboratory mark. All requests for exemption must be received by Friday, 14 October 2011.

Supplementary/Deferred Exams:

Supplementary and deferred examinations granted by the appropriate Board of Examiners will be held in the week beginning 5 December 2011. It is your responsibility to ensure that you are available to sit an examination at any time in this week. This examination is a one-time offer and further deferred or supplementary examinations are not possible. Arrangements to suit individuals will not be made.

Notification to students will be made after the Board of Examiners meeting via the Official Communications Channel (OCC) in OASIS. It is the student's responsibility to check their OASIS account on a weekly basis for official Curtin correspondence. If your results show that you have been awarded a supplementary (X) or deferred (DA) examination you should immediately check your OCC for details.

Student Rights and Responsibilities

It is the responsibility of every student to be aware of all relevant legislation and policies and procedures relating to his or her rights and responsibilities as a student. These include:

- the Student Charter
- the University's Guiding Ethical Principles
- the University's policy and statements on plagiarism and academic integrity
- copyright principles and responsibilities
- the University's policies on appropriate use of software and computer facilities

Information on all these things is available through the University's "Student Rights and Responsibilities" website at: students.curtin.edu.au/rights.

Student appeals: http://students.curtin.edu.au/rights/appeals/index.cfm

Recent unit changes

We welcome feedback as one way to keep improving this unit. Students are encouraged to give unit feedback through **eVALUate**, Curtin's online student feedback system (see http://evaluate.curtin.edu.au/info/index.cfm).

Recent changes to this unit include:

1. Increasing the frequency of tutorials from fortnightly to weekly.
2. Increase in the use of active learning in-lecture activities
3. Changes to the type and mode of assessments.
4. Improvements to the laboratory programme

	http://evaluate.curtin.edu.au/info/dates.cfm

Appendix F

Program calendar

Week	Lecture 1 Wed @ 8	Lectures 2/3 Wed @ 2	Tutorial	Other	Laboratory
1 28-Feb	Module A: Atomic theory	Module D: Principles of analysis	No tutorial	Quiz 0 (Intro to WileyPLUS)	No lab
2 7-Mar	Module D: Principles of analysis	Module A: Atomic theory	Tutorial 1 (Module D)		Experiment 1: An introduction to the laboratory - Chemical Puzzles
3 14-Mar	Module A: Atomic theory	Module E: Thermodynamic s	Tutorial 2 (Module A)	Quiz 1 (A/D)	Experiment 2: Determination of acetic acid in vinegar
4 21-Mar	Module E: Thermodynamic s	Module A: Atomic theory	Tutorial 3 (Module A)		Experiment 24: Hard Soft Acid Base Theory
5 28-Mar	Module B: Bonding	Module E: Thermodynamic s	Tutorial 4 (Module E)	Quiz 2 (A/E)	
6 4-Apr	Module E: Thermodynamic s	Module B: Bonding	Tutorial 5 (Module E)		Experiment 16: Exploring Hess' Law using calorimetry
7 11-Apr	Module B: Bonding	Module F: Equilibria	Tutorial 6 (Module B)	Mid-sem Modules A, D, E (AC Lab)	Experiment 12: An introduction to coordination chemistry: simulation of gold extraction from its ores
8 18-Apr	Module F: Equilibria	Module B: Bonding	Tutorial 7 (Module F)		No lab
9 25-Apr	Tuition Free Week				
10 2-May	Module C: Coord Chem	Module F: Equilibria	Tutorial 8 (Module F)	Quiz 3 (B/E/F)	Experiment 18: Designing and making buffer solutions
11 9-May	Module F: Equilibria	Module C: Coord Chem	Mid-sem Modules B, C, F (In tutorial time)		Experiment 23: Coordination chemistry: synthesis of metal acac complexes
12 16-May	Module C: Coord Chem	Module F: Equilibria	Tutorial 9 (Module C)	Quiz 4 (C/F)	Experiment 2c: Titration stakes
13 23-May	Module F: Equilibria	Module C: Coord Chem	Tutorial 10 (Modules C & F)		Experiment 22: Posters
14 30-May	Study Week Week				
15 6-Jun	Exams				
16 13-Jun					

7039 Chemistry 101
Date published Monday, 21 February 2011
This unit is managed by Department of Chemistry

Page 8 of 8
CRICOS Provider Code
WA 00301J, NSW 02637B

Laboratory Program Calendar

Week	Begin Date	Laboratory Activity	
Orientation	**11 July**		
1.	**18 July**	No laboratory	
2.	**25 July**	Experiment 5a: Identification of components in a mixture by paper and thin layer chromatography	
3.	**1 August**	Experiment 6: Intermolecular forces - solubility of liquids	
4.	**8 August**	Experiment 7: Purification of benzoic acid by recrystallisation	
5.	**15 August**	Experiment 8: Preparation and reactions of cyclohexene	Analytical Chemistry Experiment 1**
6.	**22 August**		
7.	**29 August**	Experiment 9: Preparation and reactions of 4-nitroacetanilide	Analytical Chemistry Experiment 2**
8.	**5 September**		
9.	**12 September**		
10.	**19 September**	Experiment 10: Carboxylic acids and their derivatives – using mind maps to link concepts	Analytical Chemistry Experiment 3**
11.	**26 September**		
12.	**3 October**	Experiment 19: Kinetics of the iodine clock reaction	
13.	**10 October**	No laboratory	
14.	**17 October**	Study Week	
15.	**24 October**	Exams Week 1	
16.	**31 October**	Exams Week 2	

** Three instrumental analytical chemistry experiments will be conducted on rotation. Details will be provided on Blackboard. The experiments are:

- Experiment 17: Atomic absorption spectrometry
- Experiment 20: Vanillin in imitation vanilla essence
- Experiment 21: Gas chromatography

Appendix G

Time Required	
In class	*At home*
90 mins	60 mins

ACTIVITY 3: MOLECULAR GEOMETRY & SHAPE

Why?

Molecular electronic structures describe how atoms bond to form molecules through sharing valence electrons. To arrive at an electronic structure a calculation method is used to determine the number of electron domains. Molecules adopt a shape that minimises their energy. In many cases it is possible to predict the geometry and shape of a molecule simply by considering the repulsive energy of electron domains and some simple geometry. Being able to understand the shapes the bonds form allows us to describe the bonding environment, explain the electron distributions between atoms and predict intermolecular forces.

Learning Objectives

- ✓ Determine the number of electron domains for simple molecules.
- ✓ Predict using VSEPR the likely molecular geometry and shape for simple molecules.
- ✓ Predict the bond angles in simple molecules.

Resources

Blackman, Bottle, Schmid, Mocerino & Wille, *Chemistry*, Chapter 5.4–5.6, pp 165–189.

Model 3.1: Calculating the number of electron domains

An electron domain is any region about a central atom in a molecule where electron density is found. A single electron domain can consist of a pair of electrons in a single bond, four electrons in a double bond, six electrons in a triple bond or a non-bonding pair of electrons.

The procedure below is called the Central Atom Valence Electron (CAVE) method for determining the number of electron domains in covalent compounds. The procedure is described in four steps and the example of the sulfate anion (SO_4^{2-}) is used to illustrate each step.

		Example, sulfate anion SO_4^{2-}	
1	**Identify the central atom**		
	The central atom is either determined by the number of atoms present (ie H_2O, where O is central) or by the lowest electronegativity (ie in $ICIF^-$, where I is central)	*Sulfur is the central atom due to both number of atoms and electronegativity.*	
2	**Electron counting**		
	a) Count the number of electrons in the valence shell of the central atom	*a) Sulfur has six valence electrons*	*$+6e^-$*
	b) Count the number of electrons required by the outer atom(s) to gain a full valence shell	*b) Each oxygen requires two electrons, so eight in total*	*$+8e^-$*
	c) Add or subtract electrons for anions or cations (formal charge)	*c) Add two electrons for formal charge (2– = 2 x e^-)*	*$+2e^-$*
3	**Multiple bonds**		
	In outer positions some atoms have multiple bonds and the number of electrons must be adjusted: • double bonds subtract $2e^-$ per double bond for elements sulfur and oxygen • triple bonds subtract $4e^-$ per triple bond for nitrogen	*Each oxygen is in the outer position. Subtract $2e^-$ for each of the four oxygens*	*$-8e^-$*

4	Total electron domains		
	Total up the number of electrons and divide by two to give the number of electron domains. This should always be a whole number.	***There are four electron domains about sulfur in the sulfate anion.***	*8÷2 =* ***4***

Critical Thinking Questions

1. Examine Model 3.1 carefully:
   a) How do you determine the central atom in a molecule?

   b) How do you determine the number of valence electrons of an atom?

   c) Which three elements have multiple bonds when in the outer position?

   d) Why do we add electrons for negatively charged anions and subtract electrons for positively charged cations?

2. Consider the sulfur trioxide molecule, SO_3:
   a) How many valence electrons does sulfur have and how many more does it need to fill its valence shell?

   b) How many valence electrons does oxygen have and how many more does it need to fill its valence shell?

   c) How many electron domains are around the sulfur in sulfur trioxide (SO_3)?

Activity 3: Molecular geometry and shape

3. Consider the water molecule, H_2O.

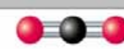
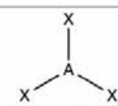
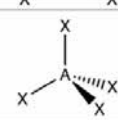
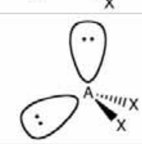
   a) Based on your knowledge of water, how many bonds exist about the central oxygen atom?

   b) Use the method in Model 3.1 to calculate the number of electron domains about oxygen in water.

   c) Compare your answers to parts a) and b) and rationalise the difference in terms of the number of non-bonding domains or lone pairs[1] present on oxygen in water.

Model 3.2: Determining geometry and shape

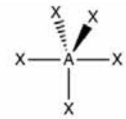
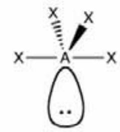
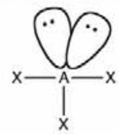
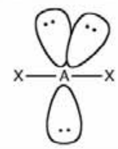
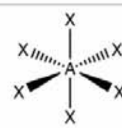
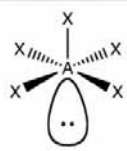
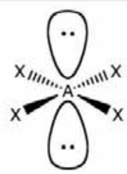
The VSEPR (valence shell electron pair repulsion) model predicts the geometries (total number of electron domains) and shapes (number of bonding electron domains) by considering the interelectron repulsions and placing the electron domains as far from each other as possible in three dimensional space to minimise energy.

Electron domains	Geometry	Lone Pairs	Shape	Line Diagram	Example	
2	linear	0	linear	X—A—X	CO_2	
3	trigonal planar	0	trigonal planar		BF_3	
		1	bent		NO_2^-	
4	tetrahedral	0	tetrahedral		CH_4	
		1	trigonal pyramidal		NH_3	
		2	bent		H_2O	

---

[1] Any electrons that do not participate in bonding are called non-bonding electron domains or lone pairs.

Activity 3: Molecular geometry and shape

Electron domains	Geometry	Lone Pairs	Shape	Line Diagram	Example
5	trigonal bipyramidal	0	trigonal bipyramidal		PCl_5 
		1	see-saw		SF_4 
		2	T-shaped		ClF_3 
		3	linear		I_3^- 
6	octahedral	0	octahedral		SF_6 
		1	square pyramidal		ClF_5 
		2	square planar		XeF_4 

Line diagrams are used to denote three dimensional molecular structures on the page. There are three ways bonding electron domains are represented:

- on the plane of page: (solid line)
- towards the reader: (wedge)
- away from the reader: (hashed line)

Lone pairs or non-bonding domains are denoted by a lobe with two dots inside or sometimes just two dots :.

Activity 3: Molecular geometry and shape

Critical Thinking Questions

4. According to Model 3.2 what single piece of information is required to determine geometry?

5. According to Model 3.2 what two pieces of information are required to determine shape?

6. Explaining your answer briefly and based on your answers to CTQs 4 and 5 do lone pairs contribute to:

   a) geometry?

   b) shape?

7. Based on your answers to all previous CTQs, what is the geometry and shape of:

   a) sulfate anion, SO_4^{2-}?

   b) sulfur trioxide, SO_3?

   c) water, H_2O?

8. Draw line diagrams for each of the molecules in CTQ7, recalling the rule about double bonds for terminal atoms. A double bond is represented in a line drawing by a double line ═══. For ionic species surround the line drawing with square brackets and place the formal charge outside, eg: $[SO_4]^{2-}$.

9. In previous studies you may have used Lewis diagrams and the octet rule to determine molecular shapes. Sulfur disobeys the octet rule and can hold up to 18 electrons in its valence shell. Explain this observation.

Activity 3: Molecular geometry and shape

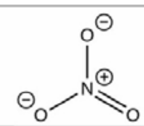
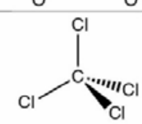
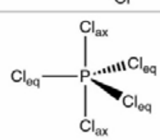
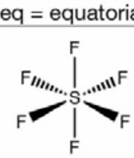
10. Based on the relative electronegativities of sulfur and oxygen, on which atom would the negative formal charge be more likely to be found in the sulfate anion?

11. From your answer to CTQ 10 propose a new line drawing including the positions of the two electrons with a ⊖ next to the atom carrying the formal charge.

    Remember that oxygen can only hold eight electrons in its valence shell. There are six potential variations on this structure. This is called resonance, where there is more than one possible structure, each of equal and lowest energy.

Model 3.3: Bond angle and electron domains

A bond angle is the angle made by three connected nuclei in a molecule. By convention, the bond angle can be any number between 0 and 180°. The table below illustrates bond angles and the number of bonding and non-bonding electron domains for some selected molecules.

Molecular formula	Line Structure	Bond angle	Central atom electron domains		Geometry / shape
			Bonding	Non-bonding	
$HCCH$	H—C≡C—H	$\angle HCC = 180°$	2	0	linear / linear
NO_3^-		$\angle ONO = 120°$	3	0	trigonal planar / trigonal planar
CCl_4		$\angle ClCCl = 109.45°$	4	0	tetrahedral / tetrahedral
PCl_5	 ax = axial eq = equatorial	$\angle Cl_{ax}PCl_{eq} = 90°$ $\angle Cl_{eq}PCl_{eq} = 120°$	5	0	trigonal bipyramidal / trigonal bipyramidal
SF_6		$\angle FSF = 90.0°$	6	0	octahedral / octahedral

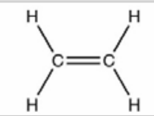
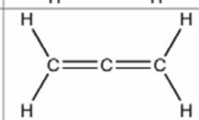
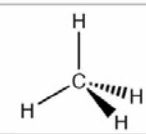
Activity 3: Molecular geometry and shape

Critical Thinking Questions

12. On the line diagrams in Model 3.3 draw the bond angles and circle the central atom in each case.
13. How are the number of bonding electron domains determined from the line structure?
14. How is the geometry determined from the number of bonding electron domains?
15. The bond angles in Model 3.3 can be grouped around four approximate values. What are they?
16. How is the bond angle determined from the geometry and/or shape?
17. In full and grammatically correct English sentences describe how the bond angle can be determined from the number of electron domains.
18. Using the same principles developed above describe how you could determine the bond angles for the molecule iodine heptafluoride, IF_7, which has seven bonding domains and a pentagonal bipyramidal geometry and shape. Sketch a line drawing of this molecule.

Activity 3: Molecular geometry and shape

Model 3.4: Bond angles and hydrocarbons

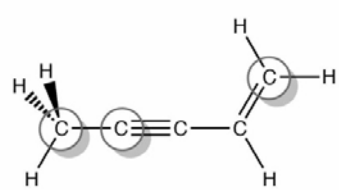
Molecular formula	Line Drawing	Bond angle	Central atom electron domains		Shape (about the central atom)
			Bonding	Non-bonding	
HCCH	H—C≡C—H	$\angle HCC = 180°$	2	0	linear
H_2CCH_2		$\angle HCH = 121.1°$	3	0	trigonal planar
H_2CCCH_2		$\angle CCC = 180°$	2	0	linear
		$\angle HCH = 121.1°$	3	0	trigonal planar
CH_4		$\angle HCH = 109.45°$	4	0	tetrahedral / tetrahedral

Critical Thinking Questions

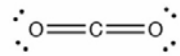
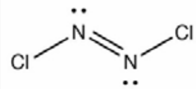
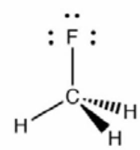
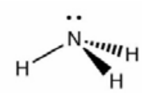
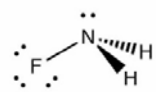
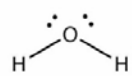
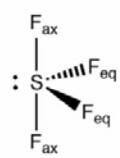
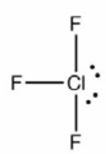
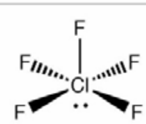
19. Does the presence or absence of a double bond contribute to shape? Explain your answer.

20. Does the presence or absence of a double bond contribute to bond angle? Explain your answer.

21. Based on your answers above, predict the bond angles for each of the circled carbon atoms in the molecule below.



Model 3.5: Deviation from ideal bond angles

Molecular formula	Line Structure	Bond angle	Central atom electron domains		Geometry / Shape
			Bonding	Non-bonding	
CO_2		$\angle OCO = 180°$	2	0	linear / linear
ClNNCl		$\angle ClNN = 117.4°$	2	1	trigonal planar / bent
CH_3F		$\angle HCH = 109.45°$ $\angle HCF = 109.45°$	4	0	tetrahedral / tetrahedral
NH_3		$\angle HNH = 107°$	3	1	tetrahedral / trigonal pyramidal
NH_2F		$\angle HNH = 106.95°$ $\angle HNF = 106.46°$	3	1	tetrahedral / trigonal pyramidal
H_2O		$\angle HOH = 104.5°$	2	2	tetrahedral / bent
SF_4		$\angle F_{ax}SF_{eq} = 87.8°$ $\angle F_{eq}SF_{eq} = 101.5°$	4	1	trigonal bipyramidal / see-saw
ClF_3		$\angle FClF = 87.5°$	3	2	trigonal bipyramidal / T-shaped
ClF_5		$\angle FClF = 86.0°$	5	1	octahedral / square pyramidal
XeF_4		$\angle FXeF = 90°$	4	2	octahedral / square planar

Critical Thinking Questions

22. Based on your answer to CTQs 15 and 16 calculate the deviation (in degrees) from the ideal bond angle(s) for each molecule given in Model 3.5. For example N_2Cl_2 has a deviation of –2.6°.

23. What feature(s) of the molecule lead to deviation away from the ideal angles determined in CTQs 15 and 16?

24. Where must the feature(s) discovered in CTQ23 be located for there to be a significant effect on the bond angle?

25. Estimate the magnitude of deviation for each feature determined in CTQ24 (in degrees).

26. Considering the geometries presented in Model 3.5 and using your findings from Model 3.3, explain why the bond angle in bent molecules is expected to be close to 117.5° or 104.5°. Your answer to CTQ25 will help.

Activity 3: Molecular geometry and shape

Information

Recall that the VSEPR (Valence Shell Electron Pair Repulsion) model attempts to minimise electron domain repulsion and thus gain a lower energy by placing the domains as far apart in three dimensional space as possible.

27. Based on your answers above which is greater: lone pair-bonding pair repulsion or bonding pair-bonding pair repulsion? Explain your answer briefly.

28. Would you expect lone pair-lone pair repulsion to be greater or less than lone pair-bonding pair repulsion? Explain your answer briefly.

29. Carefully examine the molecules SF_4 and ClF_5 and explain why the lone pairs are placed on an equatorial position as opposed to an axial position.

30. Use the same reasoning as CTQ29 to explain why the lone pairs are placed in the axial positions in the square planar compound XeF_4. What effect does this have on the bond angles?

Homework Problems

1. Use the VSEPR model to predict the geometry and shape of each of the following molecules. Sketch a line drawing in the box next to its number of electron domains and indicate resonance structures.

   O_3 I_3^- IF_6^+ SbF_5 $COCl_2$ SeO_3^{2-} SiF_4 KrF_4 SF_4 ICl_3 BrF_5

Electron domains	Line drawings
2	
3	
4	
5	
6	

Activity 3: Molecular geometry and shape

2. Sketch a line drawing of the geometry and shape of the following molecules and ions. Use the VSEPR methodology to derive this and show your working clearly.

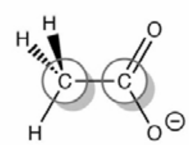
a)	CF_2Cl_2	c)	ClF_2^-	e)	SeF_4
b)	ClF_4^+	d)	PF_4^+	f)	$GaCl_3$

3. Both PF_3 and PF_5 are known compounds. NF_3 also exists, but NF_5 does not. Why is there no molecule with the formula NF_5?

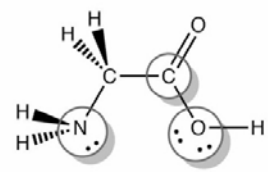
4. Determine the molecular geometry and shape of the nitrate anion, NO_3^-. Show all resonance structures clearly.

5. Predict the bond angles and shape for each atom circled in the line diagrams below.

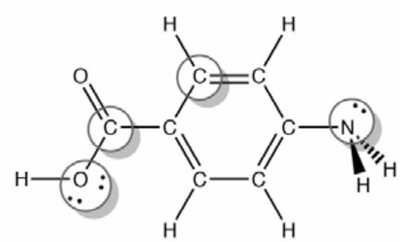
a) acetate ion



b) glycine (an amino acid)



c) paraaminobenzoic acid (PABA used in sunscreen)



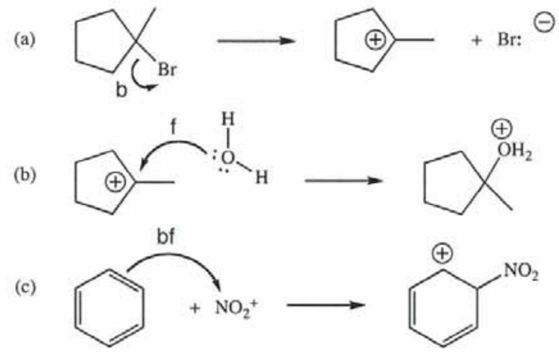
Appendix H

Team Element: .... *Chem 102 Activity F-3*

Revision: Curved-arrow Processes

To describe bond breaking and bond forming processes in mechanisms, chemists have developed a "curved arrow" notation. A curved arrow is used to show the movement of electrons and it is a form of "electron bookkeeping."

Model 1: Classifying curved-arrow processes



Q1. For the reactions above, indicate which arrows depict bond breaking (b) and bond forming (f) processes or both (bf)

(a) breaking, (b) forming, (c) both breaking and forming

Q2. For those arrows which depict the bond breaking process, do the electrons of the reacting species go from being unshared to shared between two atoms, or from shared to unshared?

go from shared to unshared

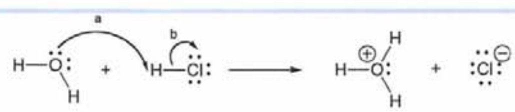
Q3. For those arrows which depict the bond forming process, do the electrons of the reacting species go from being unshared to shared between two atoms, or shared to unshared?

go from unshared to shared

Q4. Which of the equations in Model 1 are an example of electrons going from being shared between two atoms (say A and B) to being shared between two atoms (say A and C)?

Example (c) involving both bond breaking and bond forming

Model 2: Reaction of hydrogen chloride with water (revision from Activity D2)



Q5. Using the terms shared and unshared, explain what happened to the electrons in the H-Cl bond.

The electrons in the H–Cl bond go from being shared between the H and Cl atoms to being an unshared pair of electrons on the chloride ion.

Q6. Using the terms shared and unshared, explain where the electrons in the new O-H bond came from.

The electrons in the newly formed H–O bond (shared electrons) come from a pair of unshared electrons on the oxygen atom in water.

Q7. Why is the positive charge on the oxygen and not the hydrogen in the product H_3O^+?
The positive charge is on the oxygen atom in H_3O^+ because this atom has provided a pair of its unshared electrons to form the O–H bond. The electrons have gone from being unshared to being shared between the O and H.

Q8. Using your answers to questions 1-7, summarise the rules and conventions for using curved arrows in mechanisms by completing the statements below.

- **Curved arrows are used to show bond <u>forming</u> and bond <u>breaking</u> processes**
- **Curved arrows start at a pair of electrons (either an unshared pair, or a bond)**
- **Curved arrows end at a region of electron deficiency (+ of δ+) or to form an anion.**

Nucleophilic substitution

Box 1 – Possible substitution pathways

In the process of converting reactants into products, the R-X is broken and the R-Nu bond is formed. There are three theoretical mechanistic possibilities for this conversion.

1. break the R–X bond first, then form the R–Nu bond
2. form the R–Nu bond first, then break the R–X bond
3. form the R–Nu as the R–X bond is broken

The experimental evidence which follows will help you to discover which of these possibilities are the most likely mechanisms for these substitution reactions.

In trying to understand the mechanism of nucleophilic substitution reactions, chemists studied many reactions of alkyl halides and found that these reactions could be classified into two groups – Type A and Type B. Some experimental evidence is given below.

Experimental Evidence - Kinetics

Model 3: The effect of reactant concentration on reaction rate

Concentration of R-X (mol L^{-1})	Concentration of Nu^- (mol L^{-1})	Relative Reaction Rate	
		Type A	Type B
1	1	1	1
1	2	1	2
2	1	2	2
2	2	2	4
3	2	3	6

Q9. Consider the relative concentration and reaction rate values given in Model 3.

(a) How many molecules affect the reaction rate of Type A? What are they? **One, the RX**

(b) How many molecules affect the reaction rate of Type B? What are they? **Two, the RX and Nu^-.**

(c) Assign the terms *unimolecular* and *bimolecular* to Type A or Type B to describe the dependence of each reaction pathway on the concentration of reacting species.

Type A =unimolecular
Type B = bimolecular

Recall

A rate law is an equation relating the rate of a reaction to concentration. The rate of a reaction changes when you change the concentration of species in the rate determining step, so only species involved in this step appear in the rate law. (See Module E lecture notes)

Q10. (a) Based on your answers to Q4(a)-(c), which species are involved in the rate determining step for each pathway?

	Type A		Type B
Species:	**RX**	Species:	**RX and Nu^-**

(b) Complete the rate law equations for Type A and Type B reactions.

Type A: **Rate = k[RX]**
Type B: **Rate = k[RX][Nu^-]**

Organic chemists use the naming convention "S_Nx" to describe these kinds of reactions, where:

S is for substitution
$_N$ is for nucleophilic
x is the number of species involved in the rate determining step

Q11. Using this convention and your answers to Q10-11, give appropriate names to the Type A and Type B reactions in Model 3.

Type A = S_N1
Type B = S_N2

Model 4: Nucleophilic substitution reactions

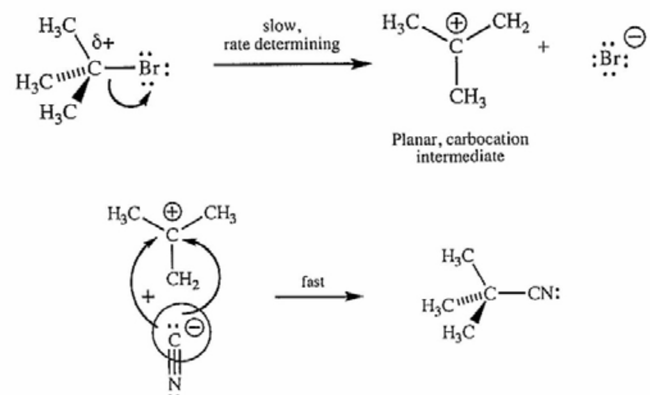
Consider the following nucleophilic substitution reactions:

$$\text{(i)}\quad (CH_3)_3C—Br \;+\; KCN \longrightarrow (CH_3)_3C—CN \;+\; KBr$$

$$\text{(ii)}\quad CH_3CH_2—Br \;+\; NaOH \longrightarrow CH_3CH_2—OH \;+\; NaBr$$

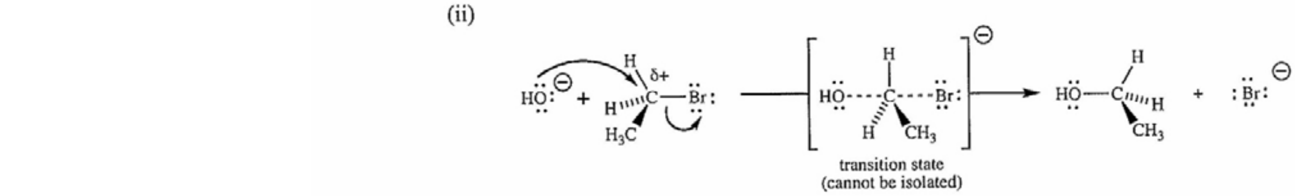
Experiments suggest that the mechanisms for these reactions are as shown below:

(i)



the nucleophile can approach from either side. Need to show only one curved arrow.

(ii)



Q12. (a) Put a circle around the nucleophile and add a δ^+ to the most electrophilic carbon atom in the alkyl halides in the reactions in Model 4.

(b) Use curved arrows to indicate the bond breaking and bond forming processes on the diagrams above.

Q13. Based on the rate laws you developed in Q10, classify the above reaction mechanisms as S_N1 or S_N2.

Reaction (i) is an example of an S_N**1** mechanism;

Reaction (ii) is an example of an S_N**2** mechanism

Q14. Consider the first reaction mechanism in Model 4.

(a) Complete the following statement:

In an S_N1 mechanism the rate determining step involves the formation of a **carbocation intermediate**

(b) Within your group describe the general stability trend (3°, 2°, 1° etc) of the species identified in part (a) above.

the stability of carbocations decreases from 3° > 2° > 1° (3° most stable, 1° least stable)

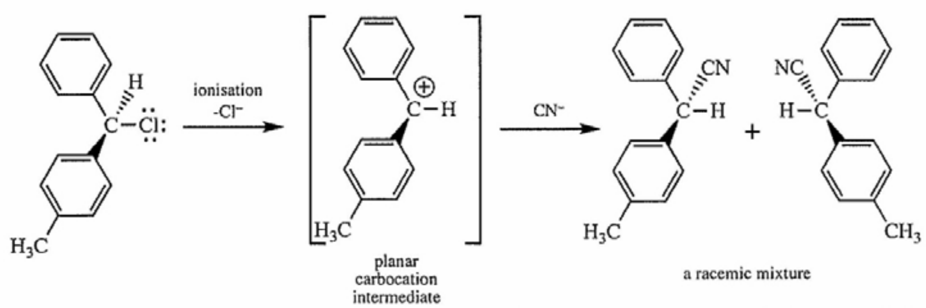
(c) Does it also explain the relative reactivities: R_3CX (3°) > R_2CHX (2°) > RCH_2X (1°) of alkyl halides in S_N1 mechanisms? Explain your answer.

Yes because the rate of a reaction is determined by the rate determining step In an S_N1 mechanism, the rate of reaction is dependent on the formation of the carbocation intermediate. The ease of formation of carbocations follows the order: 3° > 2° > 1°

Experimental Evidence - Stereochemistry

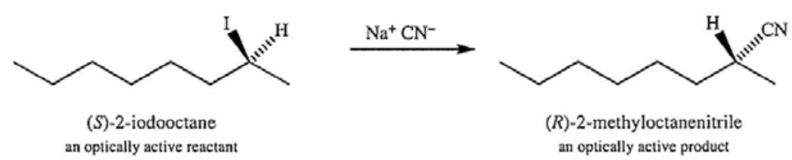
Q15. Experimental evidence shows that the S_N1 mechanism produces a racemic (50:50) mixture of products, while the S_N2 produces a product with inverted stereochemistry.

(a) Within your group, discuss how the S_N1 mechanism supports this evidence and complete the example below.



Reason: A racemic mixture of products is obtained because the carbocation is planar and the nucleophile can approach from either side (in this case as drawn from either above or below).

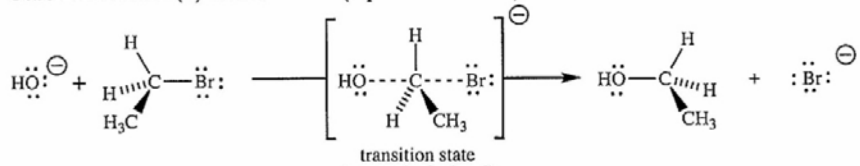
(b) Within your group, discuss how the S_N2 mechanism supports this evidence. Use the example below to explain your answer.



Reason: In an S_N2 mechanism, the incoming nucleophile approaches the electrophilic carbon atom from the opposite side to the leaving group. This causes the stereochemistry at that centre to be inverted. Therefore if a chiral alkyl halide is used a chiral product will be obtained.

Model 5: Experimental Evidence – Steric Effects

Consider reaction (ii) from Model 4 (reproduced below).



Study the diagrams below and discuss in your groups which alkyl bromide would react most readily by the mechanism shown in reaction (ii) above.

Figure 1: Space filling pictures of primary-tertiary carbon compounds.

Q16. In which alkyl bromide would you expect the formation of the C–OH bond by the mechanism in Model 5 to be easiest? Explain.

methyl bromide, because there is greatest access to the electrophilic carbon atom

Q17. In which alkyl bromide would you expect the formation of the C–OH bond by the mechanism in Model 5 to be hardest? Explain.

***tert*-butyl bromide, because there is least access to the electrophilic carbon atom**

Q18. Which alkyl bromide would react fastest by the mechanism in Model 5? Which would react slowest? Explain.

Methyl bromide is fastest and *tert*-butyl bromide would be slowest. Reason linked to the access to the electrophilic carbon atom.

Q19. Summarise below your group's the order of reactivity of the four alkyl halides by the mechanism described in Model 5.

Order of reactivity: methyl halides > 1° > 2° > 3°

Q20 Which mechanism (S_N1 or S_N2) would be most affected by steric hindrance, i.e. limited spatial accessibility due to bulky substrates? Explain your answer.

S_N2 as this mechanism requires the nucleophile to "push" the leaving group off the carbon atom. To do this good access to the electrophilic carbon atom is required.

Summary

Q21. Let us revisit the possible substitution pathways outlined at the beginning of this activity (see **Box 1** on page 3)

(a) Which of the three theoretical possibilities described in the box satisfies the experimental evidence for an S_N1 mechanism? **Explain your reasoning.**

Theoretical possibility number 1: break the R–X bond first, then form the R–Nu bond
Reason: this is the only option that involves only the alkyl halide in one of the steps. The rate law for an S_N1 mechanism only involves the alkyl halide.

(b) Which of the three theoretical possibilities described in the box satisfies the experimental evidence for an S_N2 mechanism? **Explain your reasoning.**

Theoretical possibility number 3: form the R–Nu as the R–X bond is broken

Reason: although both options 2 and 3 would satisfy the rate law for an S_N2 mechanism, option 3 does not require the formation of a pentavalent carbon atom. Option 3 also describes a one step process.

(c) Within your group, discuss what is the most important factor in determining if a reaction proceeds by an **S_N1 Mechanism**? Write your group's answer and reason in a grammatically correct sentence.

The principle fact determining whether a reaction proceeds via an S_N1 mechanism is the stability of the carbocation intermediate produced in the rate determining step. Therefore alkyl halides that can produce a stable carbocation intermediate are more likely to react by an S_N1 mechanism than those that cannot produce a stable carbocation.

Order of reactivity: 3° > 2° >> 1° >>methyl

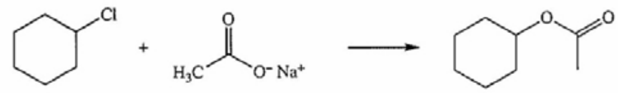
(d) Within your group, discuss what is the most important factor in determining if a reaction proceeds by an **S_N2 Mechanism**? Write your group's answer and reason in a grammatically correct sentence.

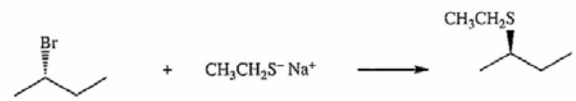
The principle fact determining whether a reaction proceeds via an S_N2 mechanism is the accessibility of the nucleophile to the electrophilic carbon atom of the alkyl halide. Therefore alkyl halides that have good access to the carbon atom bearing the leaving group are more likely to react by an S_N2 mechanism than those with a crowded electrophilic carbon atom.

Order of reactivity: methyl > 1° > 2° >> 3°

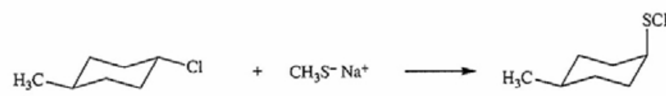
Homework

Complete the following S_N2 reactions:

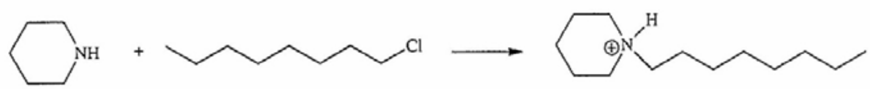
(a) 

(b) 

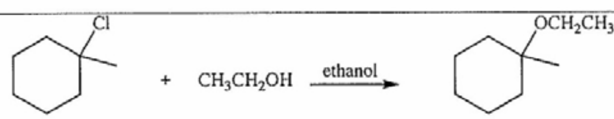
need to show inversion of stereochemistry

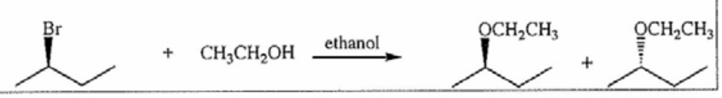
(c) 

need to show *trans* stereochemistry

(d) 

Draw the structural formula for the product(s) of each of the following S_N1 reactions.

(a) 

(b) 

Appendix I

The students were encouraged to think-aloud while answering the questions of delayed post-test of SCDT as a POGIL group. A Livescribe smart pen was used to record the conversations. The researcher has posed questions as and where necessary to keep track of their understanding of the concepts. Following is the transcript of the conversations between students and the researchers while answering the Item 2 of the delayed post-test of SCDT.

Item 2

S1: which of the following doesn't have an enantiomer?
S2: laughs…
R: OK
S1: actually, I do not know what an enantiomer is ….
R: it is not an enantiomer, if you know what makes a molecule super-imposable and non-superimposable, you can answer this?
(Smartphone screen is mimicked as a mirror) look at the molecule…. (directs the student to view the image of the molecule on the screen of the smartphone) are these same or different?
S1: they are different; an enantiomer is a different ….. thing.
S2: points towards, molecule C, does this one have?
S1: yes, because… carbon, hydrogen … that is different…… the carbon doesn't have four different groups (recognises that it is not chiral)
S2: yes
S1: one, two … three, (searches for different groups of atoms around carbon) doesn't have, so, that would?
S2: yes
R: Think about it; think about it…, does it have four different groups attached to the carbon?
S2: No
R: so, does this mean, it is the feature you are after
S2: did you get that (questions ' S1')
S1: yes
R: (prompting to view the mirror images through smartphone screen) do you think the image of molecule C is super-imposable or non-superimposable? Imagine, would the mirror image completely overlay the molecule C.
S2: superimposable …. Molecule 'C' does not have an enantiomer
R: (points towards molecule 'A') why this one is an enantiomer?
S2: …..
R: Is it confusing, you have said, molecule is 'C' can't have an enantiomer, because there are two methyl groups, hence, it is superimposable,
S2: This molecule 'A' is not superimposable on its mirror image (if you keep a mirror at its front), hence it will have an enantiomer
R: what reason can you give to your response?
S2: Number 2, it does not have a plane of symmetry.
R: OK, if you have chosen that, Is there any other best reason that you can give.
S2: pause
R: OK, that's alright. Can you identify achiral molecule from these?
S2: …..

R: OK, what is achiral molecule?
S1: ….
R: What do you call a molecule that is superimposable on its mirror image?
S2: achiral … that one (points towards molecule ‘C’)
S1: because the carbon is connected to four different groups, and there are two methyl groups, so it is superimposable on its mirror image. That one you need (selects reason 3)
Item 5
S1: What is the best way to describe the relationship between these two molecules?
S2: ….
S1: they are not superimposable
S2: no
S1: no
S2: OK
S1: because they got four units (referring to the groups of atoms around the carbon)
S2: ya
R: Why it is not superimposable?, as such it is not superimposable and the reason …. As you twist it around the carbon, what would happen? Can you make them superimposable?
S1: no
R: on their mirror images?
S1: wait… wait…wait a second… they are all messed around, they are all same here….
R: Just one turn, would those molecules are superimposable?
S1: This H goes there, this OH goes there, if you rotate around like this, the OH goes to here, the H goes to here, and the H goes here where the OH was here,
R: aha
S1: I would guess they are non-superimposable here
S2: ya.. ya.. its
S1: they are non-superimposable and they are also mirror images
S2: no.. no.. they are not mirror images, that one is not
R: Can I just point out one thing, you take one of the molecule as standard and try to manipulate with the second one. So, let us take this one (molecule ‘B’), what happens is, just make a turn, so the methyl goes up and OH goes down. So in that scenario, alright, visualise that, the OH going down, methyl going up, alright, and look at the images of the both the molecules,
S1: OK
R: Right, visualise…. How do they look like? You need to be a bit hypothetical. Right, that’s what the question is about. So when this comes up and this goes down, do they look same or different?
S2: ya…ya… if you rotate those, they are identical
R: alright, do you understand that..
S2: ya
R: with a simple rotation, the molecules are identical
S2: ya
S1: ya
R: are they similar visually or structurally?
S2: both
R: what is the best response to this item?
S2: they are identical (response ‘D’)

R: now, the reason…
S2: oh! Number three
R: check it out!
S1: four
S2: four
R: Any reason for that? You are talking about mirror images …. When you keep the mirror there …
S2: they are superimposable but not mirror images of the same.
S1: ya… ya….
R: alright…..

Appendix J

Curtin University

Science and Mathematics Education Centre

Information and call for volunteers in an education research project titled:

An Exploration of Process Oriented Guided Inquiry Learning in Undergraduate Chemistry Classes

As part of the research program for my PhD, being undertaken through Curtin University, I am conducting a research study of the course, CHEM 102 in Semester 2, 2012, to assist in determining the effectiveness of Process Oriented Guided Inquiry Learning in undergraduate chemistry classes.

It is hoped that the research will assist in gaining better understanding of the teaching and learning of chemistry, which can be used to improve learning outcomes in this area at both Curtin University and other institutions.

The Student Assessment of their Learning Gains (SALG) focuses exclusively on the degree to which CHEM 102 has enabled your learning. The purpose of this questionnaire is to gather information on how various components of CHEM 102 contributed to your learning.

Your involvement in the research is entirely voluntary. You have the right to withdraw at any stage without it affecting your rights or my responsibilities.

The information you provide will be kept separate from your personal details, and only myself and my supervisor will only have access to this.

This research has been reviewed and given approval by Curtin University Human Research Ethics Committee (Approval Number: **SMEC - 45 - 10**). If you would like further information about the study, please feel free to contact me on 0403 596 779- or by email: venkat.vishnumolakala@curtin.edu.au

Alternatively, you can contact my supervisor **Dr. David Treagust** on 9266 7924 or email d.f.treagust@curtin.edu.au

Thank you,

Ven Vishnu

Instructions:
Please fill in **one box only** for the following statements corresponding to the scale indicated by completely filling the circle ● with a **blue** or **black** ballpoint pen.

		no help	A little help	Moderate help	Much help	Great help
1	**HOW MUCH did the following aspects of the class HELP YOUR LEARNING?**					
1.1	Attending class	①	②	③	④	⑤
1.2	The pace of the class	①	②	③	④	⑤
1.3	Working with peers during class	①	②	③	④	⑤
1.4	Working with peers outside of class	①	②	③	④	⑤
1.5	Explanation of how the class activities, reading and assignments related to each other	①	②	③	④	⑤
1.6	Explanation given by instructor on why the class was organised into groups	①	②	③	④	⑤
1.7	Explanation of why the class focused on the topics presented	①	②	③	④	⑤
1.8	Connecting key class ideas with other knowledge	①	②	③	④	⑤
1.9	Small Group Activities in this class help my learning	①	②	③	④	⑤
1.10	Participating in discussions during class	①	②	③	④	⑤
1.11	Listening to discussions during class	①	②	③	④	⑤
1.12	Participating in group work during class	①	②	③	④	⑤
1.13	The number and spacing of tests	①	②	③	④	⑤
1.14	The way the grading system helped me understand what I needed to work on	①	②	③	④	⑤
1.15	The feedback on my work received during and after tutorials	①	②	③	④	⑤

1.16 Please comment on HOW the INFORMATION YOU RECEIVED about the class helped your learning.

1.17 Please comment on HOW OFTEN YOU PARTICIPATED in class discussions and HOW THE ATMOSPHERE IN THE CLASSROOM ENCOURAGED OR DISCOURAGED your participation

1.18 Please comment on how the GRADED ACTIVITIES AND TESTS helped your learning.

1.19 How has this class CHANGED THE WAYS YOU LEARN/STUDY?

1.20 Please comment on how the INSTRUCTIONAL APPROACH to this class helped your learning.

	2 As a result of your work in this class, what GAINS DID YOU MAKE in the following SKILLS?	No help	A little help	Moderate help	Much help	Great help
2.1	Identifying patterns in data	①	②	③	④	⑤
2.2	Recognising a sound argument and appropriate use of evidence	①	②	③	④	⑤
2.3	Developing a logical argument	①	②	③	④	⑤
2.4	Connecting key class ideas with other knowledge	①	②	③	④	⑤
2.5	Using systematic reasoning in my approach to problems	①	②	③	④	⑤
2.6	Applying what I learned in this class in other situations	①	②	③	④	⑤
2.7	Working effectively with others	①	②	③	④	⑤

2.8 Please comment on what SKILLS you have gained as a result of this class.

3 As a result of your work in this class, what GAINS DID YOU MAKE in the following?

3.1	Enthusiasm for the subject	①	②	③	④	⑤
3.2	Confidence that you understand the material	①	②	③	④	⑤
3.3	Confidence that you can do this subject area	①	②	③	④	⑤
3.4	Your comfort level in working with complex ideas	①	②	③	④	⑤

3.5 Please comment on how has this class CHANGED YOUR ATTITUDES toward this subject.

4 HOW MUCH did each of the following aspects of the class HELP YOUR LEARNING?

4.1	The primary textbook	①	②	③	④	⑤
4.2	The course website/Blackboard	①	②	③	④	⑤
4.3	Posted mini lectures	①	②	③	④	⑤
4.4	Posted Pencasts	①	②	③	④	⑤
4.5	Pencast solutions of Homework problems	①	②	③	④	⑤
4.6	Clickers during the lecture	①	②	③	④	⑤

4.7 Please comment on how the RESOURCES in this class helped your learning

Please turn over and complete the additional items on the last page

5	HOW MUCH did the following aspects of the class HELP YOUR LEARNING?	No help	A little help	Moderate help	Much help	Great help
5.1	The main concepts explored in this class	①	②	③	④	⑤
5.2	The relationships between the main concepts	①	②	③	④	⑤
5.3	The following concepts that have been explored in this class	①	②	③	④	⑤
5.4	Representing molecules with Lewis structures, condensed structures, skeletal structures, and three-dimensional ball and stick	①	②	③	④	⑤
5.5	Identifying functional groups in organic molecules	①	②	③	④	⑤
5.6	Applying curved arrow conventions to describe bond forming and bond breaking processes	①	②	③	④	⑤
5.7	Attractive forces between molecules and the effect on physical properties	①	②	③	④	⑤
5.8	The reactions of alkyl halides, nucleophilic substitution reactions	①	②	③	④	⑤
5.9	S_N1 and S_N2 reaction mechanisms	①	②	③	④	⑤
5.10	Distinguishing different types of isomers	①	②	③	④	⑤
5.11	Classifying compounds as chiral/achiral	①	②	③	④	⑤
5.12	Identifying stereocentres in molecules	①	②	③	④	⑤

5.13 Please comment on HOW YOUR UNDERSTANDING OF THE SUBJECT HAS CHANGED as a result of this class.

5.14 Please comment on how THE WAY THIS CLASS WAS TAUGHT helps you REMEMBER key ideas.

Thank you for your participation in this survey.

Appendix K

Standardized Regression Weights: (Group number 1 - Default model)

			Estimate
ProcessSkills	<---	ActiveLearning	.879
ConceptLearning	<---	ActiveLearning	.778
Resources	<---	ActiveLearning	.535
AL16	<---	ActiveLearning	.684
AL15	<---	ActiveLearning	.635
AL14	<---	ActiveLearning	.712
AL13	<---	ActiveLearning	.784
AL12	<---	ActiveLearning	.611
AL11	<---	ActiveLearning	.665
AL10	<---	ActiveLearning	.566
AL9	<---	ActiveLearning	.682
AL8	<---	ActiveLearning	.622
AL7	<---	ActiveLearning	.631
AL6	<---	ActiveLearning	.616
AL5	<---	ActiveLearning	.529
AL4	<---	ActiveLearning	.379
AL3	<---	ActiveLearning	.595
AL2	<---	ActiveLearning	.674
AL1	<---	ActiveLearning	.671
CL1	<---	ConceptLearning	.778
CL2	<---	ConceptLearning	.831
CL3	<---	ConceptLearning	.772
CL4	<---	ConceptLearning	.713
CL5	<---	ConceptLearning	.674
CL6	<---	ConceptLearning	.590
CL7	<---	ConceptLearning	.761
RES1	<---	Resources	.762
RES2	<---	Resources	.958
RES3	<---	Resources	.756
RES4	<---	Resources	.583
PS3	<---	ProcessSkills	.882
PS2	<---	ProcessSkills	.902
PS1	<---	ProcessSkills	.824

Squared Multiple Correlations: (Group number 1 - Default model)

	Estimate
ActiveLearning	.000
ProcessSkills	.772
Resources	.287
ConceptLearning	.605
PS1	.679
PS2	.813
PS3	.778
RES4	.340
RES3	.572
RES2	.917
RES1	.580
CL7	.579
CL6	.348
CL5	.454
CL4	.508
CL3	.596
CL2	.691
CL1	.606
AL1	.451
AL2	.455
AL3	.354
AL4	.143
AL5	.280
AL6	.379
AL7	.398
AL8	.387
AL9	.465
AL10	.321
AL11	.442
AL12	.374
AL13	.614
AL14	.507
AL15	.403
AL16	.468