THE UNIVERSITY OF HULL

Researching the Development of Problem-Solving Skills in Undergraduate Students and the Effect of Cognitive Factors on Performance

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by

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Abstract

Solving problems is the motivating force behind many scientific endeavours. A student's ability to solve problems is a key to their academic success. Problem-solving skills developed during a degree course are of significant value to graduate employers and therefore need to be valued significantly by educators and learners. This thesis describes the investigation into the factors that influence undergraduate chemistry students' abilities to develop the problem-solving skills they require for success in their undergraduate studies and beyond.

Quantitative data was gathered from chemistry undergraduates for three cognitive variables thought to influence academic performance. Context-rich open-ended problems were developed in order to assess students' ability to solve more complex problems. Performance data was gathered from open-ended problem-solving sessions alongside performance data from assessments within a chemistry degree course, including final degree scores. The quantitative data was used to identify any relationships between the students' cognitive abilities and academic performance.

Qualitative research investigated the variety of approaches students take towards solving open-ended problems and also gathered data on students' attitudes towards and experiences of the use of context-rich open-ended problems.

The results show that chemistry students' mental capacities and disembedding abilities have an impact upon their ability to solve complex open-ended problems. The skills required to solve complex open-ended problems were identified as being different skills to those required to solve the algorithmic problems found to be common elements of assessments used within undergraduate chemistry degrees.

The qualitative research revealed details of students' approaches to open-ended problem-solving and a shift in attitudes towards a more positive view of such activities.

Approaches to problem-solving were identified as novice, transitional and expert. Students were also found to be able to reflect upon their learning experiences. They enjoyed the experiences and saw the value of them despite finding them challenging.

The implications of the findings are discussed and recommendations for further work are made.

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1.0 Introduction

1.1 The case for skills development

Employers, educators and funding bodies have stressed the importance of the development of a wide range of subject-specific and transferable skills during university courses (Coldstream, 1997). A number of reports based upon consultations with graduate employers stressed the employers' wishes to obtain independent, self-reliant and innovative graduates who can think outside the box and bring about transformations in the ways in which an organisation operates (Dearing, 1995, Harvey, *et al*., 1997).

Employers seek graduates with a range of transferable skills (Dearing, 1995, Finer, 1996, Mason, 1998). Graduates that are numerate, able to work well with others and communicate effectively are in demand more than ever in today's fast-paced world. Globally, employers have identified the main areas requiring improvement as: reading comprehension, memory; concentration; oral communication skills; written communication skills; creative thinking; planning; problem analysis; problem-solving; motivation; analytical thinking; prioritising; time management; assimilation of information; getting started (procrastination) (Buzan, 2003). A number of investigations within higher education have revealed similar findings. The programme specification template made recommendations as to how new or existing degree programmes should be developed to meet the needs of today's employers and prospective students (QAA, 2000).

As a result of the QAA report, programme specifications are now written that identify the intended outcomes of degree programmes in terms of:

- the knowledge and understanding to be gained from undertaking the degree programme;
- the key skills required and developed during the degree programme, i.e.

numeracy, the use of information technology, communication and learning how to learn;

- the cognitive skills developed during the degree programme, such as the ability to critically analyse the subject matter and understand methodologies;
- subject specific skills acquired, such as laboratory skills.

Prospective students now use the information from the programme specifications to make informed decisions about their education by choosing a programme best suited to their learning style and aspirations. Programme specifications are also used by employers to ascertain the suitability of prospective employees by referring to the skill sets developed by certain degree programmes. The institutions delivering degree programmes use the programme specifications to show that the intended outcomes are demonstrable as well as achievable and gain feedback from students and recent graduates as to how well their needs were met and learning outcomes reached (QAA, 2000).

The subject benchmark statement for chemistry details subject specific programme specifications (QAA, 2007). The statement lists a number of aims for degree programmes in chemistry, including:

- Involving students in a learning experience that is satisfying and intellectually stimulating, that promotes an appreciation of the applications of chemistry and instils a sense of enthusiasm for chemistry.
- Allowing students to develop the ability to apply their knowledge and skills to the solution of practical and theoretical problems.
- Development of transferable skills that are of value to chemistry graduates, regardless of their chosen career path.

The benchmark statement details specific subject knowledge that students should acquire within a chemistry programme. Also listed in detail are the skills and abilities chemistry students are expected to develop. The statement stresses the importance of *"chemistry-related cognitive abilities and skills"* including:

- Demonstrable knowledge and understanding of scientific facts, concepts, principles and theories.
- Ability in qualitative and quantitative problem-solving by the application of such knowledge and understanding to both familiar and unfamiliar situations.
- Skills in communicating scientific information effectively to a range of audiences either orally or in writing.

The statement lists a number of transferrable skills including:

- Communication skills
- Problem-solving skills
- Computation skills and numeracy
- Information retrieval skills
- IT skills
- Interpersonal skills
- Time-management and organisational skills

A number of investigations and reviews have been completed by various government departments and industry councils into the skills required by employers across the UK. The Leitch Review of Skills was tasked with considering the UK's long-term skills requirements (HM Treasury, 2006). The review predicted that by 2020 the UK's skills base will be behind those of many similarly developed countries. The review states that the country needs to increase significantly the skill levels of the employable population for a number of reasons. These include the need to remain economically competitive within increasingly global markets, to raise rates of employment, to avoid increases in social inequality, deprivation and child poverty. *"The best form of welfare will be to ensure people can find their next job."* (HM Treasury, 2006). In order to meet these needs the review recommends: a focus on developing economically valuable skills, making sure those skills are demand-led, meeting the needs of employers, making sure that the measures taken to increase skills are adaptable and respond to the changing demands of the market. Further recommendations included: increasing investment in skills training in order to promote greater access and participation, in addition to increasing employer engagement with training programmes.

The report entitled *World Class Skills: Implementing the Leitch Review of Skills in England* emphasised the importance of implementing the recommendations put forward in the Leitch Review (Department for Innovation Universities and Skills, 2007). The main points of the report were:

- Improved skills and qualifications lead to jobs, improved career prospects and greater financial stability for individuals and their families.
- Greater social mobility was identified as an important product of improved skills.
- Within the wider community better skills provide an escape route from the low achievements and ambitions of previous generations.
- Employers will benefit from having a more highly skilled workforce through higher productivity, profitability and increased competitiveness.

The report stresses the importance of changing the culture in this country towards one that values employers who take responsibility for improving the skills and qualifications of their employees. Such changes in attitudes and behaviours will lead to increased productivity and profitability for employers and will benefit employees and their families as well as the wider community. In response to these changes in attitude, suppliers of education and training need to be increasingly responsive to the needs of employers and learners.

Research by the CBI shows that almost a third of employers (30%) are dissatisfied with their graduates' employability skills. Skills such as team working, communication and problem-solving were identified as requiring significant improvement. Employers are also dissatisfied with graduates' attitude to work (25%), self-management (33%), business awareness (44%) and foreign language skills (49%) (CBI/Pertemps, 2006).

In 2008, The Council for Industry and Higher Education surveyed 233 employers. The companies surveyed ranged from small businesses (less than 100 employees) to large organisations (more than 1000 employees). The survey asked employers to comment on the employability skills of their graduate employees (Archer and Davison, 2008).

- 86% of employers consider good communication skills to be important, yet many were dissatisfied with their graduates' abilities to express themselves effectively.
- 'Soft' skills such as team working are also considered vital, more important than most 'hard' skills, although numeracy and literacy skills are considered essential by 70% of employers.
- 65% of international employers indicated that having overseas professional work experience makes graduates more employable.

Table 1 indicates the results of a survey of employers into which attributes they considered most important in their prospective employees. A greater majority of employers clearly consider soft skills more important than hard or technical skills.

Table 1: Top ten most important skills and capabilities when recruiting new graduates (Archer and Davison, 2008)

Skill/Capability	*Percentage of employers*
Communication skills	86%
Team-working skills	85%
Integrity	83%
Intellectual ability	81%
Confidence	80%
Character/personality	75%
Planning & organisational skills	74%
Literacy	71%
Numeracy	68%
Analysis & decision-making skills	67%

Table 2 shows the skills employers are most satisfied with. Many of these skills however, are considered much less important. For example, communication skills, considered the most important skills, only ranked 16th in terms of employer satisfaction.

Table 2: Top ten capabilities employers are most satisfied with and their importance ranking (Archer and Davison, 2008)

Skill/Capability	*Satisfaction Rank*	*Importance Rank*
IT skills	1	14
A postgraduate qualification	2	33
Good degree classification	3	15
Qualification from an institution with a good reputation	4	26
Intellectual ability	5	4
Character/personality	6	6
Team-working skills	7	2
Relevant course of study	8	20
Integrity	9	3
Cultural fit with your company	10	19

A report published by Universities UK and The Confederation of British Industry listed a set of employability skills identified from a survey of British employers (UUK/CBI, 2009). Employability skills were defined as *"A set of attributes, skills and knowledge that all labour market participants should possess to ensure they have the capability of being effective in the workplace – to the benefit of themselves, their employer and the wider economy."*

The list of skills includes:

- Self-management – a willingness to accept responsibility, be flexible, resilient, self-starting and appropriately assertive. The ability to manage time effectively and a readiness to improve own performance based on feedback/reflective learning.
- Team working – the ability to co-operate with and respect others, negotiating/persuading skills, contributing to discussions, and awareness of interdependence with others.
- Business and customer awareness – a basic understanding of the key factors for business success – e.g. the importance of innovation and taking calculated risks – and the need to provide customer satisfaction and promote customer loyalty.
- Problem-solving – critical analysis of situations to reach appropriate solutions through creative thinking.
- Communication and literacy – the ability to produce clear, structured written work and the development of effective oral communication skills including listening and questioning.
- Application of numeracy – manipulation of numbers, general mathematical awareness and its application in practical contexts (e.g. measuring, weighing, estimating and applying formulae).
- Application of information technology – basic IT skills, including competence with word processors, spreadsheets, file management and the use of internet search engines.

All of these attributes must be founded on a positive attitude, a readiness to take part, contribute and be open to new ideas as well as a drive to make these happen. Also frequently mentioned by both employers and universities is entrepreneurship or an ability to demonstrate an innovative approach, creativity, collaboration and risk taking. An individual with these attributes can make a huge difference to any business (UUK/CBI, 2009).

The "STEM choices" report emphasises the need to encourage people to consider a career in STEM (science, technology, engineering and mathematics) subjects (Department for Children Schools and Families, 2009). The report states that the UK labour market has seen an increasing demand for higher skilled professionals. In 1960, unskilled or semi-skilled employment accounted for eight million or 33% of the labour market. This figure has gradually decreased to the point where in 2007 the Treasury forecast that by 2020 only 600,000 or 2% of the labour market would be in unskilled or semi-skilled jobs. The demand for people with STEM skills is further increased by greater demand for medical and alternative energy technologies due to an ageing population and climate change respectively. Between 1997 and 2007 there was a 15% decline in the number of students graduating in STEM subjects, yet the CBI predicts that by 2014 the UK will need an extra 730,000 people with STEM qualifications compared to 2007 (Department for Innovation Universities and Skills, 2009).

The Cogent Sector Skills Council represents a range of science-based industries including, Nuclear, Pharmaceuticals, Industrial Biotechnology, Plastics, Composites, Oil, Gas and Petroleum (Cogent Sector Skills Council, 2009). The workforce within such industries, make up 20% of UK manufacturing turnover which is in the region of £170bn per year. This requires an annual recruitment of up to 4000 graduates. 45% of these recruits graduate in STEM subjects. The *Technically Higher* skills strategy focuses *"on the development and delivery of science, innovation, intellectual and capital knowledge"*. Cogent aims to achieve this by researching the skills needs of employers. This will lead to development and delivery of suitable skills training as well as employer led work-based degree programmes. Increasing the participation of employment councils and government departments will help further these aims. In the current economic climate, new graduates need to be equipped with the intellectual and personal skills required to succeed in a rapidly changing professional and cultural environment. With a reorganisation of funding, priority is being given to STEM subjects and prioritised further by production of graduates with skills in the required areas (Hubble, 2010).

Chemistry graduates from nine UK universities were surveyed two and a half years after leaving university (Hanson and Overton, 2010). Each respondent was asked to complete a questionnaire designed to determine which areas of knowledge and skills developed in the degree programmes had been of most use since graduation and how well they had been developed. Many respondents identified that their scientific knowledge had been well developed during the degree programme. However, they had found that, since graduation, some of this knowledge was of less use in their employment. Conversely, many of the respondents reported a deficit in generic skills. They felt that their degree programme had not sufficiently developed many of the skills now required of them in their employment.

These skills included planning and design of experiments, interpretation of experimental data, numeracy and computational skills, report writing skills, oral presentation skills, information retrieval skills, problem-solving skills, team-working skills, time management and organisational skills, and independent learning ability required for continuing professional development. The report recommended that future revision of degree programmes should include opportunities to develop generic skills and that: *"Undergraduates should be advised about the range of skills new graduates require. Presentations by recent alumni may be one of the best ways to put over this message."*

In order to facilitate a more effective transition into the world of work upon graduation, students need to have acquired a number of generic skills including critical thinking and the ability to tackle unfamiliar and/or open-ended problems (Belt *et al.*, 2005). The ability to apply their knowledge to the situations that their future employers will present them with is essential (Heaton *et al.*, 2006). Complex, open-ended problem-solving activities, such as those tackled through problem-based learning have been demonstrated to develop this wide range of transferable skills (Duch *et al.*, 2001).

The work detailed thus far provides a compelling case for significant investment in and development of higher education courses that achieve the many requirements of all interested parties. Numerous academic studies have been undertaken in the fields of science education and education in general, some of which will be reviewed in this chapter. Much of the work has been underpinned by theories of the development of intellect and behaviour in children proposed by Jean Piaget in the last century.

1.2 Models of intellectual development

1.2.1 Piaget's genetic epistemology

Piaget studied the cognitive development of children in order to understand how humans acquire knowledge and develop intellectually (Piaget, 1972). Piaget's work has had a strong influence on more recent educational theories. He proposed that without the right level of psychological development children are incapable of undertaking certain tasks. These levels of psychological development, however, do not progress smoothly. During their formative years, children experience periods of transition characterised by significant shifts in understanding and capabilities. These transition periods were said to take place at 18 months, 7 years and 11-12 years old. As a result of Piaget's work, school curricula were developed on the understanding that children are incapable of relating to the world in certain ways until these transitions have taken place. Piaget identified four developmental stages (Piaget and Inhelder, 1969). Each stage is characterised by an increasingly complex view of the self and the surrounding environment (see table 3).

Table 3: Stages of cognitive development (Piaget and Inhelder, 1969, Piaget, 1972)

Stage	***Characterised by***
Sensori-motor *(Birth-2 yrs)*	Differentiation of self from objects. Awareness of self as agent of action. Awareness of the permanent existence of objects.
Pre-operational *(2-7 years)*	Use of language to describe objects. Egocentric thinking and simple classification.
Concrete operational *(7-11 years)*	Logical thought about objects and events. Classification is more discerning and conservation occurs.
Formal operational *(11 years and up)*	Ability to think logically and systematically. Concerns of a more hypothetical and ideological nature.

These stages have been found to be too rigid (Huitt and Hummel, 2003): many children manage concrete operations earlier than suggested, and some people never attain formal operations (or at least are not called upon to use them). *"Only 35% of high school graduates in industrialized countries obtain formal operations; many people do not think formally during adulthood"* (Huitt and Hummel, 2003). Piaget identified a number of processes that an individual undertakes whilst moving through the stages of development. These are shown in table 4:

Table 4: Piaget's key concepts (Piaget and Inhelder, 1969, Piaget, 1972)

Concept	***Explanation***
Adaptation	Adapting to the environment through assimilation and accommodation.
Assimilation	Acquiring knowledge that fits with what is already known.
Accommodation	Developing new ideas that accommodate new information.
Equilibration	Obtaining a balance between assimilation and accommodation.
Classification	Grouping objects together based on common features.
Class Inclusion	Understanding that classes of objects are also sub-sets of a larger class.
Conservation	Classification remains the same even when an object is changed.
Decentration	Move away from one system of classification to another
Egocentrism	Believing that you are the centre of the universe. An early stage of psychological development.
Operation	The process of mentally working something out.
Schema	The mental representation of a set of related perceptions and ideas
Stage	A period in a child's development in which he or she is capable of understanding some things but not others.

Schemata are hypothetical constructs inferred by Piaget from his experimental observations. These mental structures have no physical form and are not observable. A schema is used by an individual to facilitate adaptation to stimuli (Wadsworth, 1996).

Schemata can be thought of as concepts or categories. A useful analogy might be that of a database. As new stimuli are encountered and knowledge is acquired, categories are created and/or modified and loaded with data. The learning process constantly requires the database to be updated as new categories are created and old ones are modified. As an individual grows and learns, the revision of this database changes to reflect reality more closely. Adaptation proceeds by assimilation and accommodation. These complementary processes act as the mechanisms by which learners acquire experience and knowledge about themselves and their environment. If presented with new stimuli that have commonalities with existing knowledge, the new stimuli are easily understood and new knowledge is acquired. The new knowledge is easily assimilated into the existing schemata. It is akin to adding new data to a database that fits into one or more of the existing categories. Assimilation results in a quantitative change in the internal structures (schemata). Accommodation must take place in order to grasp new concepts. The internal structure of the mind must change in order to accommodate data that does not belong in any of the existing categories. A new category must be added to the database. Accommodation results in a qualitative change in the internal structures (schemata).

Equilibration must take place in order to achieve a balance between assimilation and accommodation. If an individual almost always assimilated stimuli and very rarely accommodated they would end up with a small number of very large schemata. Conversely, if accommodation occurred at the expense of assimilation an individual would end up with a large number of small schemata. Piaget termed either of these extremes a state of disequilibrium. The driving force of equilibration is to move from a state of disequilibrium towards equilibrium. This is achieved by an ongoing process of assimilation and accommodation. Upon encountering a new stimulus, a child will attempt to assimilate that into existing schemata. If this cannot be achieved, existing schemata will be modified or new schemata will be created and accommodation occurs and equilibrium is momentarily reached (Wadsworth, 1996). In looking at assimilation and accommodation from the child's point of view, Piaget found accommodation no more problematic than assimilation. The schemata of adulthood are built upon the schemata of childhood. In reaching adulthood, ways of understanding the world have been acquired. These methods of understanding the world have proved successful in that they have facilitated an individual's survival. Assimilating new information and ideas, which fit with this world-view, is not problematic. The problem arises with the increasing difficulty with which new ideas and views are accommodated. Such problems would inevitably lead to disequilibrium and equilibration would become increasingly difficult. The ability to continue learning and development throughout adulthood is therefore as important as ever.

"For educators the basic implication is clear. If an objective of education is to enhance children's acquisition of knowledge, educational methods must be based on active exploration." (Wadsworth, 1996).

1.2.2 The Perry scheme of intellectual development

According to Perry there are nine "positions" on the "journey" to intellectual (and moral) development (Perry, 1970). These positions were categorised through the study of college students' and describe their attitudes towards knowledge, their courses of study, their teachers and their own roles in the learning process. The nine positions, grouped into four categories, are:

A. Dualism/Received Knowledge: Knowledge is black and white. There are right/wrong answers to every problem, *"engraved on Golden Tablets in the sky, known to Authorities"* (Rapaport, 1984)

1. Basic Duality:

All problems are solvable: therefore, the student's task is to learn the Right

Solutions *i.e.* the discipline/teacher has all the solutions and the job of the student is to memorise and repeat them.

2. Full Dualism:

Some Authorities (literature, philosophy) disagree; others (science, mathematics) agree. *”Therefore, there are Right Solutions, but some teachers' views of the Tablets are obscured"*. The student perceives their task as *"learning the Right Solutions and ignoring the others!"* (Rapaport, 1984) At this level, students begin to see that some problems seem to have more than one answer (usually when faced with alternative opinions or disagreement among teachers) but they still believe that one of them must be right, a case of following the right authority. Students enter higher education at this stage (Rapaport 1984).

Dualistic students prefer structured classes and view them as providing the right answers; they want facts and formulas and have an aversion to theories or abstract models, open-ended questions, or active or cooperative learning. Conflicts between teacher and text or between two teachers are seen threateningly as conflicts among authorities.

B. Multiplicity/Subjective Knowledge: *"There are conflicting answers; therefore, one must trust one's inner voice, not external Authority."* (Rapaport, 1984)

3. Early Multiplicity:

A wider dualism of problems: those whose solutions are known and those whose solutions are not yet known. For the latter, the teacher's role is seen as providing methods of finding the right answers, rather than as giving the right answers directly. The student then perceives their task as learning how to find the Right Solutions.

4. Late Multiplicity:

As the student progresses chronologically or cognitively, the second kind of problem is seen as being the more common one. It is then perceived that teachers do not have the right answers for every problem and some problems are unsolvable, that *"everyone has a right to his own opinion. No one is wrong!"* (Rapaport, 1984)

Open-ended questions and cooperative learning are tolerated, but not if they have too much of an effect on grades. Students start resolving issues using supporting evidence rather than relying completely on what authorities say, but preconceptions and prejudices are seen as acceptable evidence and once a solution is reached they are rarely inclined to look at alternatives. The teacher is then perceived as a facilitator, teaching how to think or in some cases as irrelevant. "*At this point, some students become alienated, and either retreat to an earlier ("safer") position ("I think I'll study maths, not literature, because there are clear answers and not as much uncertainty") or else escape (drop out). ("I can't stand college; all they want is right answers" or "I can't stand college; no one gives you the right answers")"* (Rapaport, 1984).

C. Relativism/Procedural Knowledge: *"There are disciplinary reasoning methods; connected knowledge: empathetic. Vs. separated knowledge: objective analysis"* (Rapaport, 1984)

5. Contextual Relativism:

Students have begun to realise that teachers are not always looking for the right solutions, but for supported solutions. Students view knowledge and values as depending on perspective and context. They learn to evaluate solutions and these solutions are not necessarily absolutes or objectively based. Using real evidence to reach and support conclusions becomes habitual.

6. Pre-Commitment:

The student sees the need for making choices, making commitments to a solution, to a course of action based on critical evaluation and often in the absence of certainty and external authority.

D. Commitment/Constructed Knowledge: *"Integration of knowledge learned from others with personal experience and reflection."* (Rapaport, 1984)

7. Commitment:

The student makes a commitment in personal direction and values.

8. Challenges to Commitment:

The student experiences implications of commitment, its consequences and attempts to resolve the conflicts by balancing commitments already made.

9. Post-Commitment:

In acknowledging that some conflicts may never be fully resolved the student comes to terms with the continuing struggle, and realises commitment is a never-ending process and that one must retrace this whole journey over and over. The student can be at different stages at the same time with respect to different subjects.

In terms of applying this knowledge to the classroom Rapaport stated, "*There is evidence that a student at position x will not understand, will literally not be able to make any sense out of instruction, aimed at position x + 2 or beyond. Conversely, students at higher levels are bored by instruction, aimed at lower levels"* (Rapaport, 1984). Course design should appeal to and not alienate students at various positions (Cornfield and Knefelkamp, 1979). Providing *"an appropriate balance of challenge and support"* by occasionally posing problems a level or two above the students' current position can aid progression through the Perry positions (Felder, 1997). Assigning open-ended problems in context with marks less dependent upon the outcomes, especially early on in the course, will allow students to develop the higher order cognitive skills, such as critical thinking, required for the progression through the Perry positions. Working in small groups will expose students to multiplicity and help them to model the required cognitive skills (Culver and Hackos, 1982, Pavelich and Moore, 1996).

1.2.3 Constructivist epistemology

"In Piaget's theory, there is no objective reality as such. There is, of course, a real world to be known, but every individual's knowledge of that world is always under construction and never fully constructed." (Wadsworth, 1996). The constructivist view of knowledge developed from Piaget's work says that *"knowledge is constructed in the mind of the learner"* (Bodner, 1986). A more detailed explanation is, *"learners construct understanding. They do not simply mirror and reflect what they are told or what they read. Learners look for meaning and will try to find regularity and order in the events of the world even in the absence of full or complete information"* (von Glasersfeld, 1984). This view of knowledge calls for more of a dialogue between student and teacher for many reasons. A teacher aware of constructivist epistemology will question students' answers, whether they are right or wrong, in order to make students justify their answers and encourage them to reflect on their learning. This approach will also allow a teacher to assess their students' level of understanding and tailor subsequent instruction that accommodates their students' learning requirements (Bodner, 1986). If students are to learn meaningfully, they must *"choose to relate new knowledge to relevant concepts and propositions they already know. In rote learning, new knowledge may be acquired simply by verbatim memorisation, arbitrarily incorporated into a person's knowledge without interacting with what is already there"* (Ausubel, Novak et al. 1978). This calls for presentation of material in an order that may not be the most logical order in the mind of an expert who has already constructed this knowledge (Einstein and Infeld, 1938). During a lecture course, students will rarely know where that will take them in a few weeks or months. Without an awareness of the learning objectives of a lecture course students can easily lose focus, revert to rote learning and concentrate on merely knowing enough to

successfully complete an assessment (Bodner, 1986).

"The most important single factor influencing learning is what the learner already knows" (Ausubel *et al.*, 1978, Entwistle and Entwistle, 1992). This being the case, if what a learner already knows is a misunderstanding or misconception, it will be more difficult to ensure the correct understanding or conception. Many of these misconceptions are resistant to instruction (Bodner 1986). Research has shown that students both bring with them and take away many misunderstandings and misconceptions from science courses (Osborne and Cosgrove, 1983, Bodner, 1986, Nurrenbern and Pickering, 1987, Andersson, 1990, Sawrey, 1990, Bodner and Domin, 1991, Gabel, 1999). This can be attributed to the traditional mode of teaching, often termed objectivism, consisting mainly of assessing whether students can merely memorise and reproduce isolated facts. Objective testing can often de-skill students, particularly linguistically, where students will learn just the scientific facts in order to perform well in assessments (Danili and Reid, 2006). This kind of surface approach to learning is often at the expense of acquiring certain higher order cognitive skills (Marton and Säljö, 1976, Entwistle, 1981, Biggs, 1987, Ramsden, 1992, Biggs, 1993, Overton, 2001). Bruner suggested three principles that should be used to guide instruction of students (Bruner, 1973).

1. *"Instruction must be concerned with the experiences and contexts that make the student willing and able to learn (readiness).*
2. *Instruction must be structured so that it can be easily grasped by the student (spiral organization).*
3. *Instruction should be designed to facilitate extrapolation and or fill in the gaps (going beyond the information given)."*

1.2.4 Multiple intelligences (MI) theory

In taking a broader view on the nature of intelligence Gardner initially identified seven components of intelligence through anthropological, neurophysiological and cultural studies (Gardner, 1983). An eighth intelligence was later added in a revised theory (Gardner, 1999). Every human possesses each of these eight intelligences. However, some intelligences may be more highly developed in an individual than others and thus the predominant intelligence/intelligences will determine a person's character and the way/ways in which they can learn and best express themselves (Gardner, 1983, Gardner, 1999).

1. Verbal/Linguistic intelligence: is the ability to be: receptive and productive in the use of words and language; skilful and creative with the understanding and use of language.

2. Logical/mathematical intelligence: is the ability to: reason using logic and numbers; recognise patterns; see and work with abstract concepts.

3. Musical/rhythmical intelligence: is the ability to: interpret and create music; distinguish subtle sounds in music and the environment; discriminate between different speech patterns and accents.

4. Spatial/visual intelligence: is the ability to: perceive images; perceive proportion and perspective; visualise objects in three-dimensional space.

5. Bodily/kinaesthetic intelligence: is the ability to: control bodily movements and handle physical objects skilfully; communicate using body language; learn by haptic experiences.

6. Interpersonal intelligence: is the ability to: understand and communicate with others; facilitate relationships and group processes.

7. Intrapersonal intelligence: is the ability to: introspect and know oneself; recognise one's strengths and weaknesses.

8. Naturalistic intelligence: is the ability to: recognise and classify natural phenomena.

Gardener has encouraged alternative approaches to teaching in order to tap into and make the best use of these multiple intelligences (Gardner, 1993). Kornhaber states that *"the theory validates educators' everyday experience: students think and learn in many different ways"* (Kornhaber, 2001). This has led many educators to develop new approaches that may better meet the various needs of students. The traditional concern of education has been to attend to just the first two intelligences. It was a case of opting for depth over breadth. Kornhaber's research has found that in places where M.I. theory has been applied improvements have been made in test results (Kornhaber, 2001).

1.3 The information processing model

The information processing model (see figure 1) describes how we process information and effect learning (Johnstone, 1993). Successful learning requires the efficient integration of the functions of the perception filter, the working memory space and long-term memory.

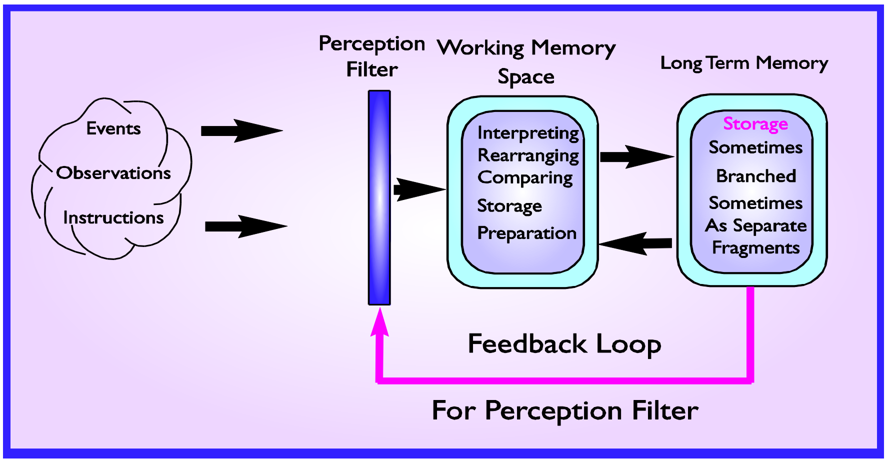

Figure 1: The information processing model

The perception filter is used to select task relevant information and eliminate irrelevant information. Working memory is a temporary storage space used to process new information alongside information retrieved from long-term memory (Baddeley, 1986). Long-term memory is where knowledge is stored and concepts develop. The operation of the perception filter is strongly influenced by the contents of long-term memory. Information in long-term memory can be either branched (interconnected) or in separate fragments. This affects how efficiently information is retrieved from long-term memory for use in working memory and how effectively the perception filter works (Johnstone *et al.*, 1994). The size of the working memory space coupled with previously held knowledge in long-term memory is therefore a major determining factor for successful learning and problem-solving (Johnstone and El-Banna, 1986, Johnstone, 1993a, Johnstone, 1997). *"It is recommended that educators consider models of information processing and adjust teaching practices accordingly"* (St Clair-Thompson *et al.*, 2010).

1.3.1 The perception filter and field dependence/field independence

Individuals with an effective perception filter, i.e. the ability to separate relevant information from irrelevant and ignore the irrelevant information, are termed field independent. This ability is also often referred to as disembedding ability. Field Dependence/Independence is a determining factor in academic achievement. Science education research has consistently shown that field independent students are more successful at problem-solving, (Niaz, 1987a, Johnstone *et al.*, 1993), and perform better in assessments (Tinajero and Paramo, 1998, Danili and Reid, 2004, 2006). Tests of field independence are useful for predicting academic performance (Tinajero and Paramo, 1998, Sternberg and Zhang, 2001). A task used widely to assess field dependence/field independence is the Group Embedded Figures Test (GEFT) (Witkin *et al.*, 1971). The GEFT consists of 20 sets of complex patterns. Embedded within each complex pattern is a simple figure. The task is to recognise the simple figure within the complex pattern. See Figure 2 below.

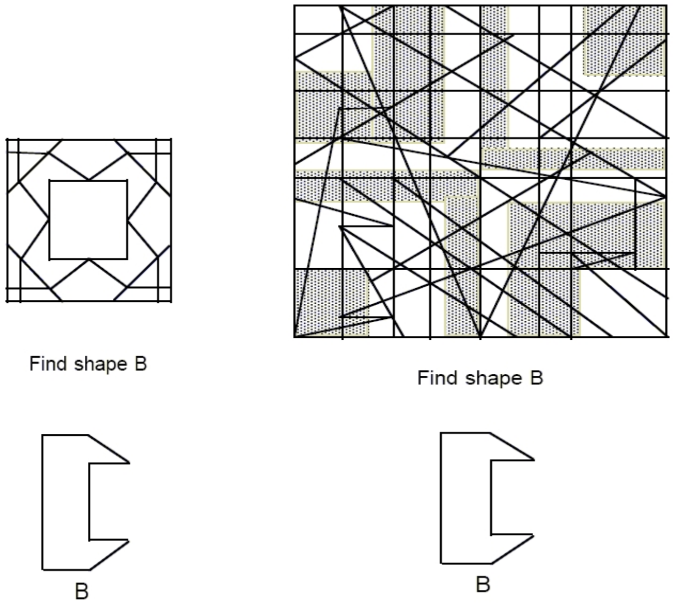

Figure 2: Examples of GEFT tasks

1.3.2 Working memory

Working memory is thought to have a fixed capacity that can hold only a limited number of pieces of information. This was described by Miller who found that working memory can only hold seven pieces of information, plus or minus two pieces of information (Miller, 1956). Attempting to work with larger amounts of information will overload the working memory and lead to ineffective learning and difficulty in completing assessment tasks. This effect is known as cognitive overload. In order to reduce the risk of cognitive overload the amount of information to be processed needs to be reduced. This is achieved by what is known as chunking (Miller, 1956). Chunking is a strategy used to make more efficient use of working memory. Chunking enables large amounts of information to be collapsed into a smaller number of chunks. For example, most people would not try to remember a mobile phone number (such as 07545688394) as eleven pieces of information but would break it down into chunks (such as 075....456...etc.). In reducing the number of chunks the working memory space also has a greater capacity for processing as well as storage. Chunking occurs with greater familiarity with the information. Experts chunk information constantly whereas novices may not have yet learned the same strategies. Without the effective use of chunking the working memory quickly reaches its capacity and cognitive overload occurs. Educators can help avoid cognitive overload by careful design of teaching activities such as problem-solving. Strategies include presenting required prior knowledge before presenting problems, removing 'noise' from the problems by scaffolding learning, by breaking down problems into smaller steps, and by using 'fading' which moves students gradually from worked examples to solving problems (Paas, *et al*., 2003).

The effect of limited working memory space of individuals can also be minimised by working in groups (Reid and Yang, 2002). Many studies have concluded that co-operative problem-solving has led to greater success (Johnson and Johnson, 1975, Tingle and Good, 1990, Basili and Sanford, 1991, Kempa and Ayob, 1991, Kempa and Ayob, 1995, Qin, *et al*., 1995, Wood, 2006, Kelly and Finlayson, 2007). Such group work can also help overcome misconceptions by sharing information and exchanging experiences and ideas (Basili and Sanford, 1991). Tingle and Good studied 178 high school students in chemistry and provided further evidence that students were able to teach each other by using models and analogies and asking questions during group discussion. Success in problem-solving may increase as a result of this (Tingle and Good, 1990).

Frequently used tests for working memory capacity are the forwards and backwards digit span tests (Wechsler, 1955). The tests involve memorising progressively longer sequences of single digits that have been read out. The forwards digit span test requires writing the digit sequences out in the order they have been read. The backwards digit span test requires the sequences to be mentally reversed and then written out in reverse order (St Clair-Thompson and Botton, 2009, St Clair-Thompson *et al.*, 2010).

1.3.3 M-Capacity

Science education research has often referred to a concept called mental capacity (Johnstone and El-Banna, 1986, Niaz, 1988a, 1989a, Niaz and Logie, 1993, Tsaparlis, 2005). Mental capacity is a product of the theory of constructive operators which suggests that cognitive performance is codetermined by hardware operators and schemes (Pascual-Leone 1970, Pascual-Leone 1987). Hardware operators are resources used during the processing of information, also referred to as mental attention. Schemes are task-relevant procedures, derived from Piaget's theory of cognitive development. M-Capacity is defined as the mental-attentional energy available for a particular task and has often been referred to as being interchangeable with working memory (Pascual-Leone *et al.*, 1978). M-capacity can be broken down into structural M-capacity (M_s), the total available M-capacity and functional M-capacity (M_f), the amount of M-capacity that is actually used. For those with high processing capability M_f is said to be close to M_s and those with low processing capability M_f is much lower than M_s. An individual is likely to be successful in problem-solving if the demand of a task is less than or equal to their functional mental capacity. Conversely, an individual is unlikely to be successful if the demand of a problem is greater than their mental capacity (Johnstone, 1984, Johnstone and El-Banna, 1986, Niaz, 1988, Niaz, 1989, Tsaparlis and Angelopoulos, 2000). One way an individual can overcome this limitation is to develop strategies that effectively reduce the demands of the task (Tsaparlis and Angelopoulos, 2000). The test for M-Capacity is the Figural Intersection Test (FIT) (Pascual-Leone and Burtis, 1974). The task is to identify the common point of intersection in the complex figure on the left hand side of the test paper from the shapes that appear individually on the right hand side. The FIT consists of 36 tasks of varying degrees of difficulty. See figure 3.

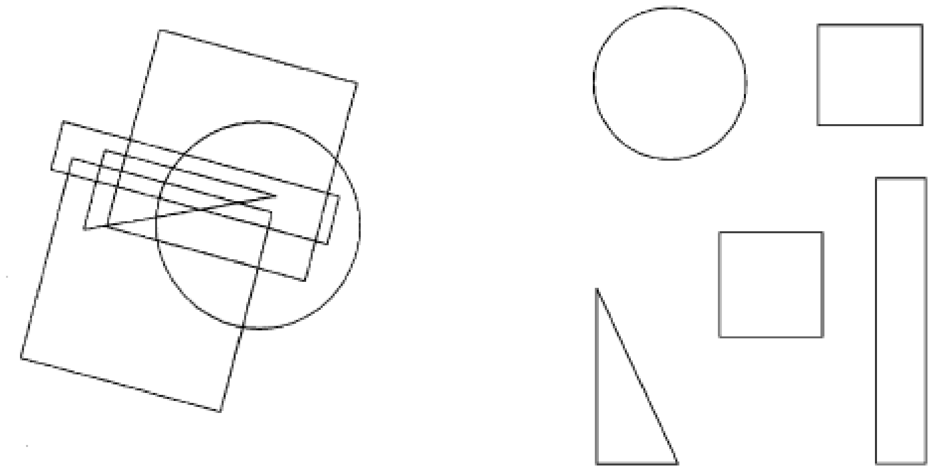

Figure 3: Example of a FIT task

Significant correlations have been found between scores on the digits backwards test and the figural intersection test (Johnstone and El-Banna, 1986, Vaquero *et al.*, 1996). Performance on both tests has been used as a predictor of problem-solving ability in science. Studies have investigated, organic synthesis problems (Tsaparlis, 1994, Tsaparlis and Angelopoulos, 2000), chemical equilibrium problems (Tsaparlis *et al.*, 1998), conceptual problems (BouJaoude *et al.*, 2004), non-algorithmic problems (Tsaparlis, 2005) and overall exam success in chemistry (Johnstone and El-Banna, 1986, Danili and Reid, 2004).

1.4 Context-based learning

Framing learning activities within a real-life context has been the subject of academic research for many years. Students take a variety of approaches to their learning. These approaches have been studied and have fallen broadly into two categories (Marton and Säljö, 1976). Deep processing occurs when students understand the meaning of what they are learning, and is associated with high scores on tests of their knowledge. Surface processing occurs when students merely memorise what they are studying, and is associated with poor test scores. Students who see the interconnections and links between different knowledge areas gained the highest scores in examinations which tested that knowledge and were more able to retrieve and use the information they have learned. This approach has been called elaborated learning (Coles, 1990). According to Coles, context is essential for elaborated learning. For elaborated learning to occur students will benefit from being able to relate what they now need to know to past experiences and prior knowledge (Coles, 1988). Recall of information is more likely when the learner has multiple routes of access to the stored information (Broadbent, 1976).*"The greater the network of knowledge and multiplicity of linkages between stored information, the more likely will be its retrieval and use"*. In cases where students are given an appropriate context they report *'things coming together'* (Coles, 1990). Context provides a motivating force for the student by which the student develops a wish to know more (wants rather than needs to learn something). Often, in the absence of context students are unsure about what they should be doing with the information given. This process can include private study, essay writing, problem-solving in groups, preparing and presenting a paper or case, computer-assisted learning, and examination revision (Rogers, 1960).

Johnstone identified the three levels of knowledge used within chemistry teaching and learning: the macroscopic, the sub-microscopic and the symbolic (Johnstone, 1991). See figure 4. Past research studies indicate that students' difficulty with the sub-microscopic level allows many scientific misconceptions to develop (Nakhleh 1993, Garnett and Hacking, 1995). Much chemistry instruction in universities focuses on the sub-microscopic and the symbolic levels, leaving out the macro or descriptive side of things and in the process stripping the facts of any real-life context and relevance to the outside world. Traditional teaching methods begin with symbolisms in order to reach an understanding of the sub-microscopic and only then move on to providing descriptive viewpoints, i.e. real-life contexts (Johnstone, 1991). Research has shown that beginning with the macro level is a more effective way to lead into the sub-microscopic and representational levels of knowledge and provides a frame of reference for the learning of the subject matter.

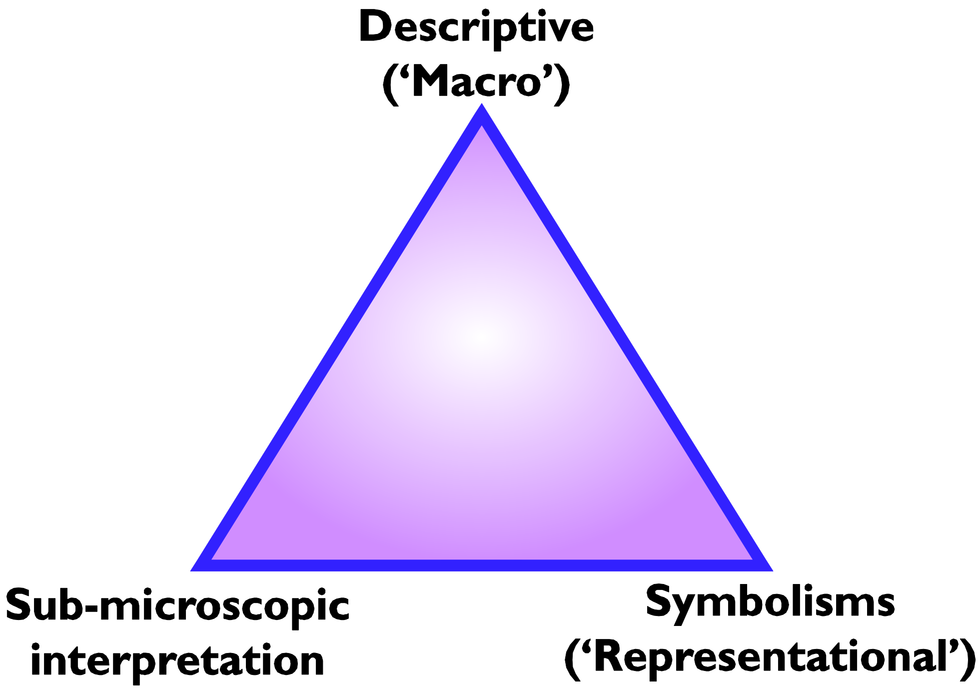

Figure 4: The Johnstone chemistry triangle (Johnstone, 1991)

Nelson (2002) proposed a similar approach to teaching and learning. Early instruction should focus on *"level one: the macroscopic or bulk level"* and only proceed onto learning topics at *"level two: the atomic and molecular level"* when students were familiar with the chemistry at the previous level. Familiarity with level two should be attained before topics at *"Level three: the electronic and nuclear level"* are taught.

The use of context to teach sciences has been the subject of much research. Solving chemistry problems requires a good knowledge of chemistry (Frazer, 1982). However, problem-solving in many cases has been unsuccessful even when students possessed most of the requisite knowledge (Sumfelth, 1988, Shaibu, 1992, Adigwe, 1993, Lee *et al.*, 1996). Students with basic knowledge of chemical terms did not recognize the relationships between concepts and therefore were unable to apply their knowledge (Sumfelth, 1988). Many context-based courses have been evaluated including those involving: discipline-related activities (Bailey, 1997); discipline independent courses (Wyeth, 1997); problem-based case studies in chemistry (Garratt and Mattinson, 1987, Pontin *et al.*, 1993). Studies within the sub-disciplines of chemistry: organic (Bennett and Cornely, 2001), inorganic (Breslin and Sanudo-Wilhelmy, 2001), and physical chemistry (Holman and Pilling, 2004, Belt *et al.*, 2005) and subjects allied to chemistry such as biochemistry (Cornely, 1998) and environmental science (Cheng, 1995, Breslin and Sanudo-Wilhelmy, 2001) have also been described. Problem-based approaches in laboratory work are also gaining in popularity (McGarvey, 2004, Kelly and Finlayson, 2009). The development of context-based science curricula and courses have been the focus of a number of studies in both school and university education (Bennett and Lubben, 2006, Gilbert, 2006, Fensham, 2009, Gilbert *et al.*, 2010, King, 2012, Broman and Parchmann, 2014, Stuckey and Eilks, 2014). The use of context to motivate and facilitate learning has led to problem-based learning becoming an increasingly popular method of teaching and learning in higher education, particularly within the scientific disciplines. The use of context to motivate and facilitate learning has led to problem-based learning becoming an increasingly popular method of teaching and learning in higher education, particularly within the scientific disciplines.

1.5 Problem-based learning (PBL)

Gabel and Bunce proposed that the factors affecting students' success in problem-solving are threefold: the type of problem and the underlying concepts of the problem; the learner characteristics, including cognitive styles, developmental levels and knowledge base; and learning environment factors, including problem-solving strategies or methods, individual or group activity (Gabel and Bunce, 1994). The principle of problem-based learning is to stimulate students to learn by presenting them with a real-life problem that they wish to solve (Margetson, 1998). Rather than just giving them the content and saying, *"learn this,"* questions are asked before all the information is given. Using previously acquired knowledge, acquiring new knowledge and learning new skills, students are expected to solve the problem. Providing limited stimulus material, the tutor guides and facilitates the learning process and encourages critical thinking. The work is often undertaken in groups. Problem-based learning allows students to learn how they learn. *"It has been shown that the most effective learning takes place when the students are actively involved and acquire the knowledge within the context it is to be used in."* (Margetson, 1998). Margetson also highlights the value of the learning process of inquiry, which he sees as lacking in subject-based learning where only the products of inquiry are given. He suggests that knowledge and skills acquired in context are of much greater value (Margetson, 1998). The general competences normally acquired from PBL are:

- Adapting to and participating in change.
- Dealing with problems, making reasoned decisions in unfamiliar situations.
- Reasoning critically and creatively.
- Adopting a more universal or holistic approach.
- Practicing empathy, appreciating the other person's point of view.
- Ability to collaborate productively in groups or teams.
- Identification of strengths and weaknesses and undertaking appropriate remediation,

The conditions for effective adult learning, amongst others, must include:

- a multidisciplinary approach whereby students will learn aspects of more than one discipline/subject due to the nature of the context;
- a cumulative learning process where progressively more complex and challenging goals and problems are set;
- an emphasis on the understanding of what has been learnt through reflection, feedback and chances to apply the acquired skills in practice (Engel, 1998).

Subject-based learning places an emphasis on content; an expert is seen as someone who knows a lot of content. Problem-based learning requires the knowledge of that content but not necessarily the expertise. In some cases using PBL, it is the problems that select the subject matter; its relevance is not prejudged as in subject-based learning (Margetson, 1998). A problem-based study in analytical and applied chemistry was found to develop a number of scientific and transferable skills that included: knowledge of multiple disciplines and application of that knowledge to analytical techniques; information handling and problem-solving skills and communication and teamwork. *"A problem-based approach can produce students who are well-motivated, independent learners, effective problem-solvers and who have a broad range of interpersonal and professional skills"* (Belt *et al.*, 2002). A study using undergraduate chemistry students compared the effectiveness of IT-enhanced problem-based learning to traditional problem-solving assignments (Barak and Dori, 2005). The students in the experimental group (IT-enhanced PBL) performed significantly better in tests and demonstrated greater understanding than those students in the control group (traditional problem-solving). Other problem-based approaches in chemistry have also been found to develop scientific knowledge and skills effectively (Heaton *et al.*, 2006, Gürses *et al.*, 2007, Kelly and Finlayson, 2007, McDonnell *et al.*, 2007, Kelly and Finlayson, 2009). Kirschner *et al* (2006), reported that teaching methodologies that provided minimal guidance for students were not working. According to the authors, instruction informed by constructivist, discovery, problem-based, experiential, and inquiry-based approaches does not take into account students' cognitive limitations and will therefore fail. *"these approaches ignore both the structures that constitute human cognitive architecture and evidence from empirical studies over the past half century that consistently indicate that minimally guided instruction is less effective and less efficient than instructional approaches that place a strong emphasis on guidance of the student learning process."* (Kirschner et al., 2006). In response to this publication Hmelo-Silver *et al* (2007) state that approaches such as problem-based and inquiry learning are not minimally guided forms of instruction. Problem-based and inquiry learning *"employ scaffolding extensively thereby reducing the cognitive load and allowing students to learn in complex domains"* (Hmelo-Silver *et al.*, 2007).

1.6 Problem-solving

"Whenever there is a gap between where you are now and where you want to be and you don't know how to find a way to cross that gap, you have a problem" (Hayes, 1981). Problem-solving is something encountered in all aspects of life. It is a skill that makes a large part of a graduate's employment (Reid and Yang, 2002b). Students should be better prepared with problem-solving skills when they reach the workplace. Facilitating the development of problem-solving skills has been the subject of much research into science education (American Association for the Advancement of Science (AAAS), 1993, Zoller, 1999b, National Research Council (NRC), 2003, Barak and Dori, 2005, Walsh *et al.*, 2007, Cheung, 2009, Kelly and Finlayson, 2009, Walsh, 2009, Cartrette and Bodner, 2010, Stamovlasis, 2010, Sandi-Urena *et al.*, 2011, St Clair-Thompson *et al.*, 2012). The types of problems set in examinations or assessments in higher education chemistry are largely algorithmic (Kempa and Nicholls, 1983, Bennett, 2004, 2008, Pappa and Tsaparlis, 2011).Algorithmic problems use mainly lower order cognitive skills whereas more open-ended problems call upon higher order cognitive skills. Problems requiring the application of higher order cognitive skills demand more than just knowledge to reach a solution. Knowledge or known theory must be applied in unfamiliar contexts using such skills as analysis, connection making, synthesis and critical thinking (Nakhleh, 1993, Tsaparlis, 2005, St Clair-Thompson *et al.*, 2012). Johnstone classified types of problem according to, the amount of data given, the familiarity of the methods and the openness of the outcome (Johnstone, 1993). Type 1 problems require the recall of algorithms and application of the problem to that algorithm (see table 5). Type 8 problems are the most

open-ended; they require the production of new data and the development of novel methods of working in order to reach a solution. This classification does not necessarily represent a hierarchy, in order of difficulty, just different types of problems. The more open-ended problems are more like the problems that are dealt with regularly in the workplace and academic research (Johnstone, 1993).

Table 5: Johnstone's classification of problems (Johnstone, 1993b)

Type	***Data***	***Methods***	***Outcomes***	***Skills Bonus***
1	Given	Familiar	Given	Recall of algorithms
2	Given	Unfamiliar	Given	Looking for parallels to known methods
3	Incomplete	Familiar	Given	Analysis of problem to decide what further data are required
4	Incomplete	Unfamiliar	Given	Weighing up possible methods and then deciding on the data required
5	Given	Familiar	Open	Decision making about appropriate goals. Exploration of knowledge networks.
6	Given	Unfamiliar	Open	Decisions about goals and appropriate methods. Exploration of knowledge and technique networks.
7	Incomplete	Familiar	Open	Once goals have been specified by the student, these data are seen to be incomplete.
8	Incomplete	Unfamiliar	Open	Suggestions of goals and methods to get there; consequent need for additional data. All of the above.

Inevitably, the introduction of problem-solving as a new and unfamiliar way of learning will encounter resistance at first. This can be attributed to the problems of assimilation and accommodation identified by Piaget (Piaget, 1972). *"Everyone reverts to concrete operational thought when they encounter something new"* (Herron, 1978). This also relates to Perry's scheme when there are challenges to commitment and a retreat to a "safer" position (Rapaport, 1984). Setting more challenging problems, will enable the development of higher order cognitive skills and allow students to overcome those challenges and solve more open-ended problems. This approach will help student's progression through the stages of intellectual development.

A number of studies within science education have attempted to assess how cognitive variables such as working memory, M-capacity and field dependence effect success in academic endeavours such as problem-solving, acquiring conceptual knowledge, examinations and project work. Using a selection of chemistry problems with varying M-demand, Niaz found that field independent students with high M-capacities were more likely to be successful at solving those problems (Niaz, 1987b). Individual M-capacities had less of an influence on problems of a lower M-demand. A suggested teaching strategy was to present students with problems of lower M-demand at first and work towards problems with higher M-demand. Thus, by the time students encountered more demanding problems they will have acquired more effective strategies for solving them (Niaz, 1987b, 1988b, 1989b). Tinajero and Paramo reviewed the impact of field dependence-independence on academic achievement in a number of subject areas (Tinajero and Paramo, 1998). They found that, in the large majority of studies, field independent students outperformed field dependent students (Tinajero and Paramo, 1997, 1998). Many studies into students' problem-solving ability have tested and compared multiple cognitive variables with achievement (Niaz and Logie, 1993, Tsaparlis *et al.*, 1998, Tsaparlis and Angelopoulos, 2000, BouJaoude *et al.*, 2004, Danili and Reid, 2004, Tsaparlis, 2005, Danili and Reid, 2006, Sands and Overton, 2010, Tsitsipis *et al.*, 2010). Tsaparlis et al reported that high school chemistry students' (17-18 yrs) ability to solve algorithmic problems correlated significantly with working memory capacity, M-capacity and field dependence/independence (Tsaparlis *et al.*, 1998). Students with working memory capacities of six and above, M-capacities of six and above and a field independent cognitive style performed much better than other students. Danili and Reid also found significant correlations between chemistry test results of high school students (15-16 yrs) and working memory capacity and field dependence/independence (Danili and Reid, 2004).

This research was followed up by the use of a new instructional approach and an investigation of its effects upon test results. The new approach was carefully designed to reduce demand on working memory by presenting the material in steps, using models, changing the order of instruction, reducing the need for note-taking and building on prior knowledge. This approach was found to have a significant impact. The students taught using the new approach improved their academic performance significantly compared to a control group of students who had been taught using the usual method of instruction (Danili and Reid, 2004). Tsaparlis reported similar findings working with first-year chemistry undergraduates tackling non-algorithmic problems (Tsaparlis, 2005). Weak correlations were found with working memory capacity and problem-solving scores but stronger correlations were found with M-capacity and field-independence. St Clair-Thompson et al compared a number of cognitive variables of chemistry undergraduates (first, second and third years) with performance in both algorithmic and open-ended problem-solving tasks (St Clair-Thompson *et al.*, 2012). Significant correlations were found for open-ended problem-solving with working memory and M-capacity. No such correlations occurred for algorithmic problem-solving.

1.7 Phenomenography

In order to develop an effective method of teaching a particular phenomenon it is necessary to identify the routes by which an individual reaches an understanding of that phenomenon (Marton, 1992). *"Changes in a person's understanding constitute the most important form of human learning."* When these routes are identified, learning resources can be adapted and tailored to students' needs in order to enable them to reach a greater understanding of what they are learning. According to Marton, there are two ways to approach research into learning. A first order perspective looks at the world and makes statements about it. A second order perspective looks at people's experience of the world and describes those (Marton, 1981). In order to study our understanding of certain phenomena, Marton developed a research method called phenomenography. Phenomenography takes a second order perspective and aims to categorise people's experiences of phenomena by means of qualitative analysis of the responses to those phenomena. The important factor is the relationship between the phenomenon and an individual's experience of it (Marton, 1992).

In putting forward a case for the use of phenomenography as a research method, Marton considered that finding out *"the different ways in which people experience, interpret, understand, apprehend, perceive or conceptualize various aspects of reality"* was not only interesting in itself but had plenty of potential to further educational research. In addition, descriptions gained from a second-order perspective cannot be derived from descriptions gained from a first-order perspective, making an alternative research methodology a necessity. Different people will experience a given phenomenon in different ways. Marton asserted that groups of people understand phenomena in a limited number of ways. The aim of phenomenography is to identify the multiple conceptions that a group of people have for a particular phenomenon.

Of primary interest is the variation in conceptions within a group, rather than any individual's experience. Within a phenomenographic study, any conceptions of a phenomenon are not judged "correct" or "incorrect" and the conceptions of the researcher are not studied or described. Instead, the emphasis is placed upon the conceptions of a particular group of people (Marton, 1994). The results of a phenomenographic study, often called the "outcome space," are "categories of description" of the various conceptions of the phenomenon being studied. Phenomenography, however, does not stop at merely identifying these conceptions. The distribution of various conceptions throughout the group is then studied, as is the underlying meaning of the conceptions and relationships between them. Examining how conceptions of one aspect of the world relate to conceptions of another aspect is of value especially when you consider that such conceptions represent ways of dealing with the world. As some ways of dealing with phenomena are more productive than others, the descriptive categories can also be arranged hierarchically, creating an outcome space that contains an ordered and related set of categories of description (Marton and Booth, 1997).

A typical phenomenographic study starts with a research question, for example: "What are chemistry students' conceptions of the mole?" (Lybeck *et al.*, 1988); "What are chemistry students' conceptions of solubility?" (Ebenezer and Erickson, 1996); "What are students' conceptions of acceleration?" (Dall'Alba *et al.*, 1993); "How do physics students approach problem-solving?" (Walsh *et al.*, 2007). Subjects of the study, take part in open, deep interviews, which are often recorded. The interviews are described as open in that they are relatively unstructured. Although the interviewer will have a set of questions prepared, any departures are followed up. Deep refers to the fact that the interview questions will proceed until the interviewee has nothing more to say and both parties are satisfied that the subject of discussion has been exhausted and a mutual understanding is reached (Bodner and Orgill, 2007).

Once a group of participants are interviewed, the recordings are transcribed and the transcripts are analysed. The analysis of the transcripts begins by identifying points of interest and relevance with respect to the research question. Once such points of interest are identified per individual they are compared across the group and any similarities and differences are discerned. This process is repeated a number of times with the categories of description being revised and refined until definitions of the categories are reached. Further participants are then interviewed and their transcripts analysed. Interviews take place until no new ways of experiencing the phenomenon are revealed and a final set of the categories of description are reached (Marton, 1986, Dall'Alba, 1994, Akerlind, 2005). The outcome space finally takes shape once the relationships between the categories of description are considered and described in a hierarchical order (Marton, 1994). Walsh *et al* (2007) studied the problem-solving approaches used by introductory physics undergraduates. The aim was to determine how the problem-solving approaches of novices differed to those of experts. The 22 students participating in the study displayed four different approaches.

1) Scientific approach (Involved a qualitative analysis of the situation followed by a systematic attempt to reach a solution based upon that qualitative analysis with references to the concepts involved. The final step was an evaluation of the solution.)
2) Plug-and-chug (Involved an analysis of the situation based upon the required formulae or variables, using these data in a trial and error manner in order to reach a solution, which was rarely evaluated.)
3) Memory-based approach (Involved analysis of the situation based upon previous examples, attempting to fit the given variables into those examples. The concepts are thought of as variables and no evaluation of a solution takes place.)
4) No clear approach (Involved analysis based upon the given variables, which are used in a random manner, again, no evaluation of a solution takes place.)

The students who adopted a scientific approach were able to adopt the plug-and-chug approach when tackling less complex problems but plug-and-chug students were unable to adopt the scientific approach (Walsh *et al.*, 2007). The researchers observed that the majority of introductory students did not approach the problems qualitatively. Those students that applied a scientific approach to problem-solving were more likely to be successful. As part of the study, an instructor was asked to attempt the same problems as the students. The expert problem-solver was observed to tackle the problems in a much more systematic way. The instructor approached the problems using the concepts rather than equations or the given variables and always used diagrams in reaching a solution. The students categorised as using a scientific approach were the only students who came close to using an approach similar to that of the instructor. Only two of the student participants in the study used a scientific approach and these two students did not use that approach for every problem they attempted. The categories of description produced in this study had similarities to another study carried out in the United States (Tuminaro 2004). Both sets of researchers believe that the findings of their work should lead to interventions in the way students are instructed in physics as well as further research in these areas.

A Hungarian study (Toth and Ludanyi, 2007) combined a phenomenographic approach with knowledge space theory to examine students' descriptions of the atom. The participants of the study were chemistry students from 7th to 11th grades and their responses were compared to those of a similar study carried out in the United States using 9th to 11th graders in physical science classes (Unal and Zollman, 1999). The descriptions of the atom fell into six categories: 'No response'; 'I don't know'; 'Units of matter'; 'Constituents of atoms'; 'Model of atoms'; and 'Other'. Three of these categories: 'Units of matter' (U); 'Constituents of atoms'(C); and 'Model of atoms' (M); were analysed further.

The three categories could be combined in seven different approaches (U, C, M, U+C, U+M, C+M and U+C+M) and each possible combination was detected in the students' responses. Both the Hungarian and American studies found the highest categories to be U, C+M and U+C+M, and these were found not to change significantly from grade to grade. Further analysis showed that throughout their progression through the school grades the students' knowledge structures changed with instruction and became more complex but in general returned to their original states by the end of their studies. The authors recommend that instructors should be providing students with more sophisticated definitions of the atom as they progress through the grades in order to allow students' understanding of the concepts to develop.

A recent study investigated physics students' understanding of the quantum mechanical concepts of wave-particle duality and the Heisenberg uncertainty principle (Ayene *et al.*, 2011). The researchers chose these particular concepts as the focus of their research because the transition from classical mechanics to quantum mechanics is often a difficult one and identifying the nature of any misconceptions would assist in the development of future learning resources. Previous studies at other institutions had also investigated students' understanding of these concepts, identifying them as difficult concepts to learn but essential for progression within a physics degree (Johnston *et al.*, 1998, Mannila *et al.*, 2002). The participants in the investigation were twenty-five second year students, who had previously completed a Modern Physics course (in their first year) and a Quantum Mechanics I course (in their second year). The students were selected based on their first year final grades, 14 having achieved a grade C, 7 a grade B and 4 a grade A. Following analysis of the interview transcripts, the categories of description were determined.

The concept of wave-particle duality fell into three categories, namely, (1) classical description, (2) mixed classical-quantum description, and (3) quasiquantum description. Students' conceptions of the uncertainty principle were described in four different categories, (1) uncertainty as an extrinsic property of measurement, (2) uncertainty principle as measurement error or uncertainty, (3) uncertainty as measurement disturbance, and (4) uncertainty as a quantum mechanics uncertainty principle. Only 16% (4) of the participants provided a quasiquantum description of wave particle duality. While a quasiquantum description does not demonstrate a full understanding of the concept, it is very close. The first two categories of classical description and mixed classical-quantum description comprised 80% (20) of the respondents. Similarly, with respect to the concept of Heisenberg's uncertainty principle, 88% (22) of the students fell into the first three categories of description, (i.e. uncertainty as an extrinsic property of measurement, uncertainty principle as measurement error or uncertainty and uncertainty as measurement disturbance) which were seen as insufficient descriptions of the concept. The students who fell into the final category, 12% (3), described uncertainty as a quantum mechanics uncertainty principle but were perceived to be merely reciting definitions memorised from textbooks. In view of their findings, the researchers concluded that the majority of their students had failed to reach a sufficient understanding of quantum mechanical concepts, which they attributed to traditional teaching methods favouring inconsistent learning and failing to provide proper understanding. These findings were consistent with those of previous studies (Johnston *et al.*, 1998, Ireson, 1999, Mannila *et al.*, 2002, Olsen, 2002, McKagan *et al.*, 2008). The consensus is that quantum mechanical concepts are poorly understood and that many of the misconceptions are rooted in students' inability to move away from a classical physics world-view.

"Highly formalized traditional teaching methods lead to a rather fragmentary ''shallow learning.'' In light of the conceptual difficulties identified in this study and in previous studies, it is deemed important to go beyond traditional instruction to allow students to develop a deeper conceptual understanding of quantum mechanics" (Ayene *et al.*, 2011). Ayene suggests that courses need to be designed that develop understanding of these concepts. This could be done by introducing *"students to the full range of differences for studying the properties of particles and waves within the contexts of classical and quantum physics"* and by presenting course content in the form of experiments and computer simulations that promote discussion within lectures or tutorials.

1.8 Attitudes towards learning

Related to the findings of phenomenographic studies are those which probe students' attitudes towards learning. *"If university teachers are asked, what is the most important student characteristic associated with successful studies, they usually mention traits such* *as attitude, motivation, and genuine interest"* (Berg, 2005). Much of the work done in assessing student attitudes originates from Perry's work (Perry, 1970). Moore found that very few students reach the higher Perry levels, (7-9), concerned with elaboration of identity and commitment (Moore, 1994). Through pre and post course attitude questionnaires Berg found several students displayed significant changes in attitude towards learning chemistry, both positive and negative (Berg, 2005). The questionnaires consisted of paired statements representing opposing viewpoints of the attitude object. For example, *"all one has to do in science is to memorise things"* would be opposed by *"understanding science is the key part of science study"* and the responses to these questions would be Strongly Agree, Agree, Undecided, Agree, Strongly Agree. Such questionnaires avoid the potential ambiguity that can arise from Likert-type questionnaires (Likert, 1932, Perry, 1970). For example, using a Likert-type format a statement like *“Learning all the material covered in lectures should be enough to pass the course”* could prompt the response *"disagree"* from two students holding very different views. *“I strongly disagree since you should know much more”* and *“I strongly disagree since it is enough to know part of what has been covered in lectures.”* In the Berg study the students with the largest shifts in attitude, positive and negative, were interviewed in order to determine the reasons behind these shifts (Berg 2005). Interview questions explored the students’ background, their experience of their first semester at university and any further thoughts on the discussion of those topics. The study found students with a positive attitude shift displayed more motivated behaviour and students with a negative attitude displayed the opposite.

1.9 The aims of this PhD project

Considering the need to enable the development of various transferable skills in undergraduate students (Dearing, 1995, Finer, 1996, Coldstream, 1997, Harvey *et al.*, 1997, Mason, 1998, QAA, 2000a, CBI/Pertemps, 2006, HM Treasury, 2006, Department for Innovation Universities and Skills, 2007, QAA, 2007, Archer and Davison, 2008, Cogent Sector Skills Council, 2009, Department for Children Schools and Families, 2009, Department for Innovation Universities and Skills, 2009, UUK/CBI, 2009, Hanson and Overton, 2010, Hubble, 2010) this project aimed to investigate how students could develop some of these skills and determine some of the factors influencing skills development. Using the information processing model (Johnstone, 1997) as a template for learning, the project aimed to investigate how three cognitive factors, working memory capacity, M-capacity and field-dependence/independence, influence the academic performance of chemistry undergraduates. Particular attention was paid to performance in problem-solving activities. The main aims of the project were:

- To investigate whether there is a correlation between the three cognitive factors and the academic performance of chemistry undergraduates, particularly performance in problem-solving.
- To investigate students' attitudes towards the use of context-rich open-ended problems.
- To investigate the strategies used by undergraduate students to solve context-rich open-ended problems.
- To identify the implications of the research findings with respect to chemistry education.

2.0 Methodology

2.1 Problem development: reasons and context

Several context-based open-ended problems were developed for use in the research. It was intended that the problems would:

- Be non-algorithmic, open-ended problems that have no single correct answer, requiring students to identify the required data and develop a strategy in order to reach a solution (Johnstone, 1993).
- Be designed to promote the development of higher order cognitive skills such as critical reading, problem solving, critical thinking, decision making, evaluation, etc. (Overton, 2001).
- Begin with a real life context that may interest the student and provide a greater motivation to reach the solution (Ramsden, 1984, Coles, 1990).

Suitable problems needed to fulfil the above criteria and be able to fit in with the time constraints of teaching periods. A set of context-based open-ended problems considered to fulfil the aims above was produced. The problems were designed to enable individuals or small groups to reach a solution in 20-30 minutes. This set of problems can be found in appendix 1, problems 1 - 15. Some, but not all, of these problems were later used with chemistry undergraduates. These problems were designed to facilitate the development of skills such as critical thinking, decision making etc, and used a real-life context. Such problems, however, are unlikely to be encountered in postgraduate research or graduate employment. Drawing on experience of problems encountered in an analytical chemistry laboratory and in consultation with the departmental industrial liaison officer, a further set of problems were produced. This set of problems can be found in appendix 1, problems 16 - 20. These problems were based on real examples of work being carried out in industry today. Within the context of an industrial laboratory, people working with these problems would have the requisite specialist knowledge and technology to be able to reach a solution. Therefore, the undergraduate students would be asked to develop a strategy or a plan of action that they would be able to carry out if they had the resources and technology available. The students' answers to the problems would be assessed on the coherence of their strategy.

2.2 Assessment of Problem Demand

The intellectual demands of the problems were evaluated. Each solution was broken down into the number of steps required to reach a solution which gave an indication of the M-Demand of the problem (Niaz, 1989). The number of steps ranged from 9 to 15. The M-demand of chemistry problems has been assessed in a number of previous studies (Niaz, 1987b, 1988b, Niaz, 1989a, Niaz and Logie, 1993, Tsaparlis, 1994, Tsaparlis, 1998, Tsaparlis *et al.*, 1998, Tsaparlis and Angelopoulos, 2000, Stamovlasis and Tsaparlis, 2005, Tsaparlis, 2005). Many of these publications have reported that a student will only be successful in solving a problem if their M-capacity is greater than or equal to the M-demand of the problem. A number of publications have reported on the assessment of M-demand of problems but have often not shown how they have arrived at such figures. Niaz stated that, *"In practice it has proved very difficult to assess the M-demand of a task independently of the performance of a given subject on that task."* (Niaz and Logie, 1993). The majority of these studies have been undertaken with pre-university students. At these levels of education, problems and exercises are less demanding and much more algorithmic in nature than the problems developed in this project. The problems in this project were designed to enable students to tackle open-ended problems and develop problem-solving skills. Because the problems were presented with incomplete data, required a method to be developed and had a number of possible solutions, they required different approaches than algorithmic problems. Although the M-demand score of a problem gives a quantitative indicator of difficulty it is not necessarily helpful in the cases of these problems. For example, if two students tackle the same problem in two different ways, both students may have used a different number of steps to reach a solution and therefore had a different load on their working memory.

One problem used in the research was: "You've got home after a hard day's study and you're starving. You search the freezer and find a chicken curry with rice. How much energy is required to heat the frozen curry?"

One possible solution to this problem is:

1. Assume 500g of Curry.
2. Assume the mass to be heated is 500g of ice.
3. Assume the temperature of the frozen curry is ≈ -20°C.
4. Assume hot food needs to be ≈ 70°C to be suitable for consumption.
5. Estimate Specific Heat Capacity of ice ≈ 2 kJ kg^{-1} K^{-1}
6. Energy required for ΔT -20°C to 0°C ≈ (2 × 20 × 0.5) ≈ 20kJ
7. Estimate Specific Latent Heat of fusion of ice at 0 ºC, ≈ 300 kJ kg^{-1}
8. Energy required for fusion at 0°C ≈ (300 × 0.5) ≈ 150kJ
9. Estimate Specific Heat Capacity of Water ≈ 4 kJ kg^{-1} K^{-1}
10. Energy required for ΔT 0°C to 70°C ≈ (4 × 70 × 0.5) ≈140 kJ
11. Total energy required = 20 + 150 + 140 ≈ <u>310kJ</u>

Another possible solution to this problem is:

1. Assume use of a microwave oven to heat the Curry.
2. Estimate the microwave oven used has a power rating of 800W.
3. Estimate the time the microwave oven takes to heat the curry is 5 minutes.
4. 5 minutes = 300 seconds.
5. Assume the microwave oven operates on full power.
6. Energy required ≈ 800 × 300 ≈ 240000J ≈ <u>240kJ</u>

These are just two possible ways of solving the problem. If judged in terms of M-demand the first solution would be of higher demand than the second solution. Therefore, the same problem could have different cognitive demands depending upon the approach taken.

Johnstone classified problems in a more qualitative way, see table 5 (Johnstone, 1991). Some of the problems used in this project contained more of the required data than others but all were presented with incomplete data. The goal of each problem was clearly given, so the main task was to develop a strategy to solve the problem, decide which data was required and then work out the answer following the strategy and using the estimates and assumptions made. According to Johnstone's classification, all of the open-ended problems developed for use in this research were of type 4.

2.3 Tests for cognitive variables

Assessing the students' cognitive variables would enable the identification of any relationships between students' cognitive abilities and their academic performances, particularly problem solving (Niaz and Logie, 1993, Tsaparlis *et al.*, 1998, Tsaparlis and Angelopoulos, 2000, BouJaoude *et al.*, 2004, Danili and Reid, 2004, Tsaparlis, 2005, Danili and Reid, 2006). Three cognitive variables were measured.

2.3.1 Working Memory

The tests used for measuring working memory capacity were the forwards and backwards digit span test (Wechsler, 1955). The tests and instructions can be found in appendix 3. The forward digit span test consists of 14 sequences of digits to be read out by the test administrator and written out on the test paper provided. Each sequence has to be held in working memory and written down only when the administrator has read the last digit of the sequence. The sequences ranged from three to nine digits long with two sequences at each length. The backwards digit span test consists of 14 sequences of digits as in the forwards test. Each sequence has to be held and processed in working memory and written down in reverse order, from left to right, when the administrator has read the last digit of the sequence. The sequences ranged from two to eight digits long with two sequences at each length.

A student's working memory is given by the highest span at which both sequences are written down correctly from the backwards test. The maximum score is eight. Working memory can then be categorised as high, medium or low. See table 6.

Table 6: Categorisation of backwards digit span test scores

Score	≤5	=6	≥7
Category	Low	Medium	High

2.3.2 M-Capacity

The test for M-Capacity consists of the Figural Intersection Test (FIT) (Pascual-Leone and Burtis, 1974). The FIT consists of 36 tasks of varying degrees of difficulty (see figure 5). Twenty minutes are allowed for the test. A mark is awarded for each point of intersection that is correctly identified with a maximum score of 36. The number of correct items is then reduced to an M-capacity score. See table 7.

Table 7: Categorisation of Figural Intersection Test scores

Score	≤4	5-9	10-15	16-20	21-25	26-30	31-35	36
M-Level	1	2	3	4	5	6	7	8
Category	Low				Medium		High	

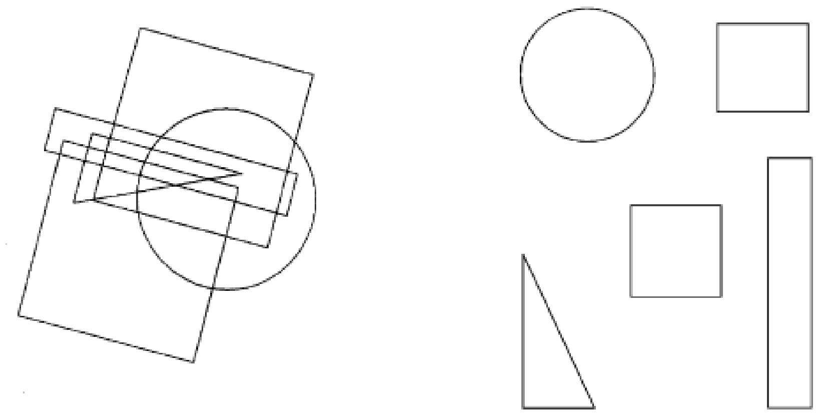

Figure 5: An example of a FIT task.

2.3.3 Field Dependence/Field Independence

The task for Field Dependence/Field Independence is the Group Embedded Figures Test (GEFT) (Witkin *et al.*, 1971). The GEFT consists of 20 tasks (see figure 6). For each embedded figure correctly identified one mark is given. Twenty minutes are given for the test and a score out of 20 is obtained for each student. The scores can then be categorised as Field Dependent, Field Medium and Field Independent. See table 8.

Table 8: Categorisation of Group Embedded Figures Test scores

Score	≤7	8-13	≥14
Category	Field Dependent	Field Medium	Field Independent

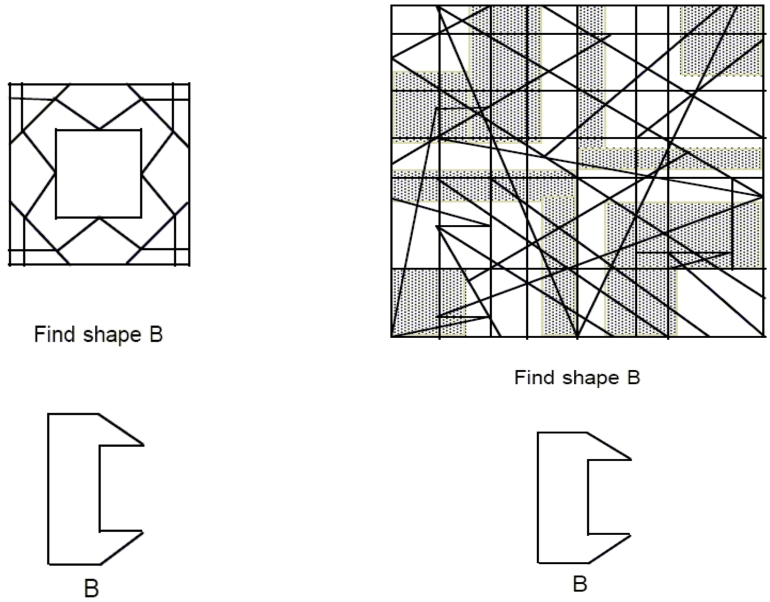

Figure 6: Examples of GEFT tasks

2.3.4 Administration of tests for cognitive variables

Over the course of three years, the three tests were administered to groups of chemistry undergraduates. Most of the students tested were University of Hull chemistry undergraduates. One cohort of chemistry undergraduates at the University of Birmingham was also tested. Table 9 shows the numbers of participants.

Table 9: Test Participants

	Tasks		
Group	**BDS**	**FIT**	**GEFT**
Hull	226	222	232
Birmingham	47	51	50
All Students	273	273	282

2.4 Attitude questionnaires

An attitude questionnaire was designed to assess the students' attitude, to chemistry in general, problem solving and the use of context. The questionnaire used statement pairs representing opposing viewpoints of the attitude object (Perry, 1970). See appendix 4. During each testing session, the students completed a pre-questionnaire. This questionnaire was used to assess the students' attitudes towards aspects of their study before they participated in the problem solving sessions. At the end of the problem solving sessions, students completed the same attitude questionnaire to identify any changes of attitude. The post-questionnaire responses were compared with the responses from the pre-questionnaire and any overall changes in attitude were quantified.

2.5 The problem-solving sessions

At the start of each session the intentions of the exercises were explained and the following guidelines were given to the students.

- There are not necessarily any right or wrong ways to solve these problems.
- Not everyone will work out the problem the same way and arrive at the same answer.
- Write down all working, all estimates and assumptions, all thoughts and any information you ask for.
- Marks will be given for the process and initiative (i.e. ability to make assumptions and estimates, knowing what information you need) more than getting an answer.
- Use of calculators is not allowed.
- Some data can be given but only if requested.
- The questions were designed to help students: develop critical thinking, reasoning, find out if they could extract relevant information and see how they perform in these against their cognitive abilities, identified by the test results.
- After each problem there will be time for feedback and discussion about solutions and better/different problem solving strategies. This feedback will hopefully help with

further attempts.

The students were given about 20 minutes on each problem or until the majority of the class reached a solution. The scripts for each problem were then collected from each student for marking.

2.5.1 Year 3: University of Hull

Year 3 students were given the problems 1, 4 and 7 (from appendix 1) to be attempted individually. Every cohort of year 3 students tackled problems 1 and 4, but only one cohort tackled problem 7. The numbers of participants are indicated in table 10.

Table 10: Year 3 University of Hull problem-solving participants

N		
1	*4*	*7*
149	148	34

2.5.2 Year 2: University of Hull and University of Birmingham

Field dependence/independence has been shown to have a significant effect upon academic achievement (Tinajero and Paramo, 1998, Sternberg and Zhang, 2001). Performance in the group embedded figures test produces three categories, field dependent, field medium, and field independent. Year 2 students were divided into groups according to these categories and asked to solve problems 5, 10 and 13 (from appendix 1) in groups. Within a group of students, working together, the working memory capacities of the individuals would be combined and may not then be considered as a limiting factor. The group problem solving exercises could determine the impact of field dependence/independence upon problem solving ability. Table 11 indicates the numbers of year 2 participants. The students were also given problem 12 (From appendix 1) to work on individually. See table 11.

Table 11: Year 2 problem-solving participants

N	***Problem numbers***			
University	*5*	*10*	*12*	*13*
Birmingham	54	54	20	54
Hull	145	142	132	146
Total	199	196	152	200

2.6 Assessment of performance in problem-solving sessions

Each of the requirements for successfully solving problems were identified and marks out of ten were split and allocated to each requirement as illustrated in figure 7. For example, to solve a problem successfully a student would have to identify the relevant information contained in the question and disregard any irrelevant information. This would then be followed by identifying any missing data and making sensible estimates and/or assumptions. The student would then have to apply known methods and/or develop new ones before identifying the goals, working towards them and checking the goals once they have been reached. Each problem is assigned a mark out of 10 according to the marking scheme below.

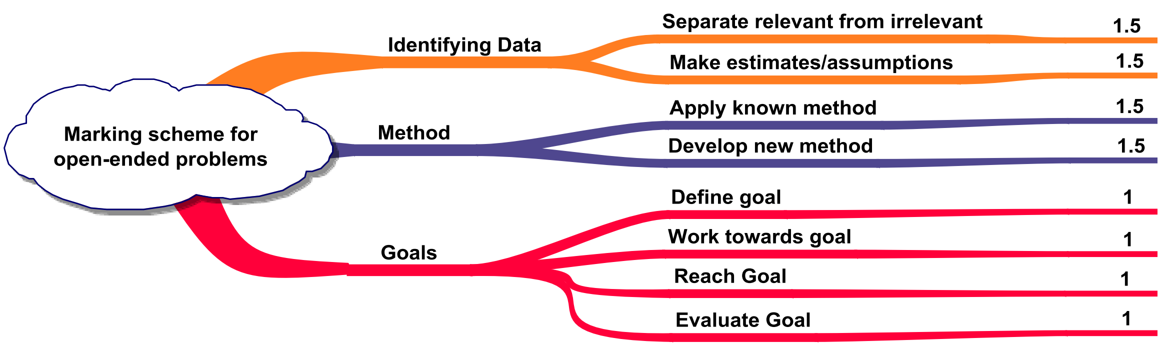

Figure 7: Marking scheme for open-ended problems

2.7 Algorithmic problem-solving and degree marks

Past exam scripts were obtained for Hull chemistry students who had taken part in the research. Six purely algorithmic problems were identified and the marks for individual problems were collected. Degree marks were also obtained as well as average marks for each year of the degree course. This data was analysed in order to identify any relationships with cognitive abilities and performance in open-ended problem solving.

2.8 Qualitative research

2.8.1 End of module questionnaire

The open-ended problem-solving sessions usually made up part of a module and took place towards the end of any particular module. As usual, students were asked to complete a questionnaire asking for their evaluation of the module. The following question was added to that questionnaire in order to gain some specific feedback about the open-ended problems.

- Please tell us how the problem solving activities you have tackled over the past two weeks has compared to problem solving you have done previously, Were they easier, more difficult, more interesting, less interesting etc.?

2.8.2 Interviews

After analysis of the problem solving scripts and the pre and post questionnaires, six year 2 students were interviewed in order to gain more insight into their experience of open-ended problem-solving. The interviews were conducted on a one-to-one basis with a neutral interviewer. The following questions were used:

1. How did the problems compare to problems that you've done before on your course?
2. Did you find them more or less challenging than conventional problems? Why?
3. Did you find them more or less enjoyable than conventional problems? Why?
4. In groups, how did you go about tackling a difficult problem?
5. Was it more or less challenging tackling them individually compared to in a group? Why?
6. What skills do you think these problems help you develop?
7. Would these skills be useful in your future career?

8. Would you be prepared to have a go at more problems to help us with this research?

The responses to these questions were recorded and transcribed. The transcripts were then analysed, noting any common themes.

2.8.3 Study of approaches to open-ended problem-solving

This study was intended to provide some insight into how chemistry students approach open-ended problems. Previous studies have enabled the identification of categories of approaches that students bring to their learning experience (Dall'Alba *et al.*, 1993, Ebenezer and Erickson, 1996, Walsh *et al.*, 2007). Fifteen students volunteered to take part in the research. Hour-long sessions were arranged for each student. The following three problems were selected for use in this study.

1. You've got home after a hard day's study and you're starving. You search the freezer and find a chicken curry with rice. How much energy is required to heat the frozen curry?
2. Many commercial hair restorers claim to stimulate hair growth. Human hair is composed mainly of the protein α-keratin. Assuming the protein is made up of amino acid units estimate the rate of incorporation of amino acid units per follicle per second.
3. On November 13 2005 an explosion at a chemical plant in Jilin City in north eastern China released 100 tonnes of benzene and nitrobenzene into the Songhua River. Two weeks later, nearly 700 miles downstream, the spill flowed into the Amur River flowing through the Russian city of Khabarovsk. The Chinese and Russian authorities used activated carbon in water treatment facilities to stop the contaminants getting into the municipal water supplies. Quantities of carbon were also dumped into the river. Below is a table giving the specifications of activated carbon typically used for water treatment. What mass of activated carbon would be required to completely eliminate the pollutants from the water in the affected areas?

Grade	*Filtracarb FY5*	*Filtracarb CC65/1240*
Surface area BETN2(m^2/g)	1150	1050
CTC (%)	55	65
Bulk density (g/cm^3)	0.49	0.45
Hardness (%)	99	90
Iodine n° (mg/g)	1100	1050

The participants were given a brief explanation of the aims of the study and then asked to attempt the problems. The students were encouraged to use a think aloud protocol to express their ideas and methods for solving each problem. Each session was recorded using a digital audio recorder. The participants were also given paper to write down their solutions to each problem. The role of the facilitator was to ask the participants to explain what they were doing and explain their problem-solving strategy without giving away any information that would help the participant reach a solution. In order to study whether students were able to make sensible estimations and carry out approximate calculations the participants were not allowed to use a calculator or look up additional information. To solve the problems, the students would have produce a strategy, make estimations and assumptions and carry out simple calculations. The recordings and scripts were analysed by making notes on each student's approach to problem solving. Common themes in the students' strategies and approaches were identified. The analysis produced a set of categories that described how a group of chemistry students approach open-ended problem-solving. A second researcher performed the same analysis and each set of categories was compared before producing a final set of categories describing the students' approaches to problem-solving.

3.0 Results

The quantitative data collected during the research was processed and analysed using SPSS. Of the 349 chemistry students that participated in the research 273 completed the digit span tests, 273 completed the figural intersection test and 282 completed the group embedded figures test. The majority of the statistical analysis involved comparing academic performance data with the data obtained from the four tests. This meant that no matter how much performance data was gathered for each student, it would only be of use if a particular student had also completed the tests. Testing sessions and problem-solving sessions needed to take place within the course timetable to avoid any extra workload for the students. As a result, problem-solving sessions often took place much longer after the testing sessions than desired, in some cases the following academic year. This meant that, for various reasons, some students who had taken part in the testing sessions were absent for the problem-solving sessions and some students who had taken part in the problem-solving sessions had not completed the tests. Access to students and, therefore, access to data relating to student performance was one of the most significant limiting factors of this research.

3.1 Cognitive Data

The quantitative data collected were used to investigate if any relationships existed between the data and any implications those relationships may have for teaching and learning in higher education. Each of the cognitive tests revealed scores with non-normal distributions. The fact that the data was skewed to higher scores could be due to lower achievers on these tests being selected out at earlier levels of education. This meant that the most suitable statistical analysis for correlations was Spearman's Rho. Table 12 shows the statistical analysis of the relationships between the three cognitive variables under investigation. The forward digit span test (FDS) has a maximum score of nine. The backwards digit span test (BDS) has a maximum score of eight. These two tests indicate the size of an individual's working memory capacity. The figural intersection test (FIT) has a maximum score of 36 and is an indication of M-capacity. The group embedded figures test (GEFT) has a maximum score of 20 and is used to categorise the extent of an individual's field dependence.

Table 12: Correlation coefficients for cognitive tests scores

		FDS		
BDS	Spearman	0.45^{**}		
	N	272	**BDS**	
FIT	Spearman	-0.07	0.00	
	N	266	267	**FIT**
GEFT	Spearman	0.00	0.07	0.40^{**}
	N	269	270	269

Correlations are significant for 2-tailed test at $^{**}p<0.01$

For these data, there are two significant correlations. A Spearman's rho correlation coefficient of 0.45 between the forward and backwards digit span tests (FDS v BDS) shows a weak to moderate positive correlation. This suggests that the two tasks, although similar in nature, are using slightly different cognitive resources. The forward digit span test is thought to use mainly the storage component of working memory with minimal processing. The backwards digit span test also requires storage but the reversal of the digit sequences requires more processing. These differences could account for the value of the correlation coefficient (St Clair-Thompson, 2009, St Clair-Thompson and Botton, 2009, St Clair-Thompson *et al.*, 2010). Scores for FIT and GEFT show a significant correlation coefficient of 0.40, indicating a weak positive correlation between the two variables. This would suggest that these two cognitive variables have elements in common. This is a typical value for such correlations (Morra, 2002). Both tests require an element of storage and a little processing. Both tests also require a focus on relevant information and an avoidance of distracters although this requirement is a greater within the GEFT. There appears to be no correlation between either of the digit span tests and both the FIT and GEFT. This could indicate that no relationship exists between these variables. One possible explanation for this is that the administration of the digit span tests as paper and pen tests makes it easy for participants to "cheat". i.e. write digit sequences for the backwards digit span test from right to left, in the order that the sequences were read out, rather that mentally reverse the sequence and write it down left to right as per the test instructions. Instances of such practices would invalidate some of the test scores and skew the results for the sample as a whole. There are now computer-based digit span tests that overcome this problem by ensuring that digits are recorded in the required order (St Clair-Thompson *et al.*, 2012). Another possible explanation for the lack of correlations between the digit span tests and the FIT and GEFT is that adults are much less challenged by the digit span tests than children. There is evidence to indicate that, whilst the digit span tests measure working memory in children, the tests only measure short-term memory in adults. The limits of short-term memory will have much less of an impact upon learning in general for an adult, as adults have usually developed strategies that can overcome those limits (St Clair-Thompson, 2009).

3.2 Open-ended problem-solving

Students were arranged into groups of four or five, according to their category of field dependence, (see table 8) to attempt some open-ended problems. Table 13 gives the correlation coefficients between the cognitive variables and the group problem-solving scores. The data were analysed using the scores from each problem (5, 10 and 13 in appendix 1) as well as an average score for the group problem-solving activity (GPS AVG). The group problem-solving average scores produce a significant weak positive correlation with the GEFT scores. This shows that, within this sample, field independent students working together are more proficient problem-solvers than their field dependent counterparts. Although the students were not grouped together according to their M-capacities there is a weak correlation between M-capacity and group problem-solving.

This is probably because scores for the two tests correlate weakly with each other and the students were, therefore, likely to have also been grouped together according to their category of M-capacity. The significance of these data is limited in that it is based upon the analysis of results from only three open-ended problems.

Table 13: Correlation coefficients for open-ended problem-solving ability in groups

Problem	**Type**	**FIT**	**GEFT**
5	Spearman	0.18*	0.37**
	N	174	175
10	Spearman	0.21**	0.08
	N	175	176
13	Spearman	0.21**	0.19*
	N	175	176
GPS AVG	Spearman	0.28**	0.26**
	N	175	176

Correlations are significant for 2-tailed test at *$p<0.05$ and **$p<0.01$

The scatter plot of group problem-solving score against GEFT scores (figure 8) shows that only groups of field medium and field independent (scoring 8-13 and ≥14 respectively) students were able to gain the highest marks (>7/10) for the open-ended problems.

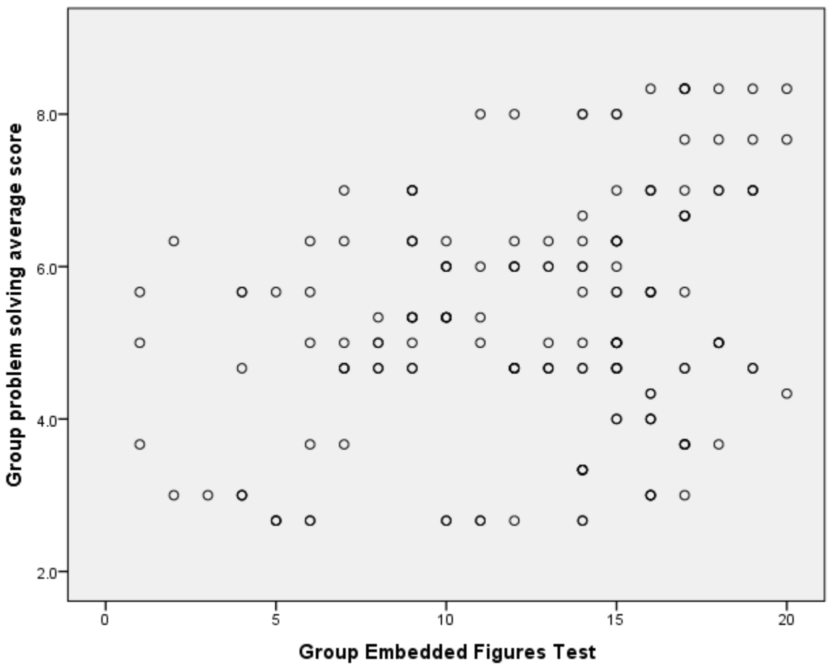

Figure 8: Plot of group embedded figures test scores versus group problem-solving average score

The scatter plot of figural intersection test scores versus group problem-solving average scores (figure 9) shows that the only students showing proficiency at open-ended problem-solving were those with FIT scores greater than 20.

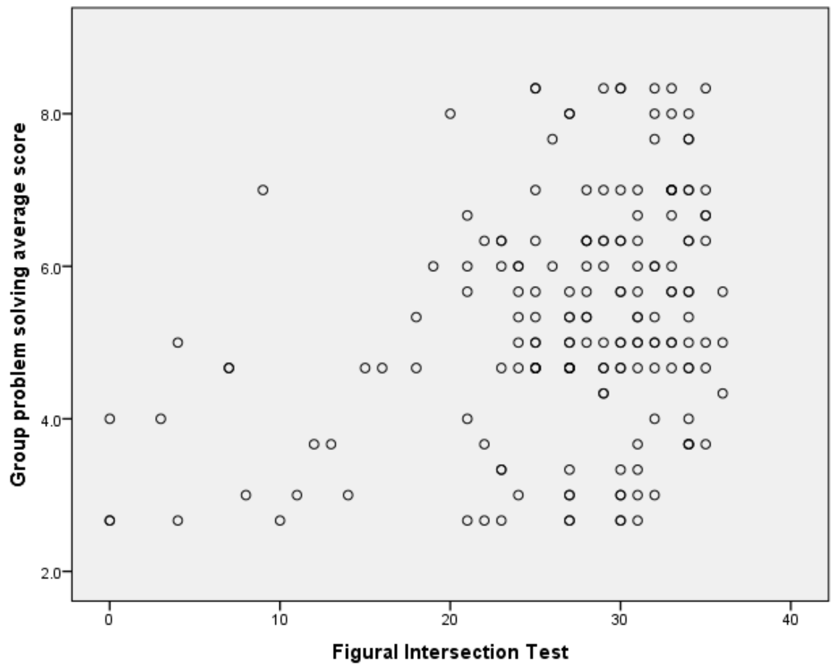

Figure 9: Plot of figural intersection test scores versus group problem-solving average score

Table 14 details the correlation coefficients from the test scores and the scores from the problems that were attempted individually. The data was analysed using the scores from each of the problems (1, 4, 7 and 12 in appendix 1) and an average individual problem-solving score (IPS Avg). Weak significant positive correlations between problem 12 scores and FIT and GEFT scores give correlation coefficients of 0.24 and 0.28 respectively. The influence of the data from just this problem could account for the very weak but significant correlation that appears between the individual problem-solving average scores and the group embedded figures test. This suggests that, both M-capacity and field dependence may be factors influencing students' ability to solve open-ended problems. There appeared to be no correlations for the FDS and BDS scores with IPS average scores. Once again the significance of these data is limited by the small number of problems used to assess student's ability in solving open-ended problems and the relatively small number of participants.

Table 14: Correlation coefficients of cognitive variables and individual open-ended problem-solving ability

Problems	Type	FDS	BDS	FIT	GEFT
1	Spearman	-0.06	.11	-0.05	0.17
	N	123	124	125	130
4	Spearman	0.06	0.17	0.08	0.02
	N	121	122	122	128
7	Spearman	0.10	0.20	0.07	-0.19
	N	27	28	28	32
12	Spearman	0.10	0.10	0.24**	0.28**
	N	134	134	136	137
IPS Avg	Spearman	0.06	0.11	0.08	0.22**
	N	205	206	207	214

Correlations are significant for 2-tailed test at *p<0.05 and **p<0.01

Figure 10 shows the weak correlation obtained for individual problem-solving and GEFT scores. However, it is apparent that the higher problem-solving scores are generally obtained by students with higher GEFT scores.

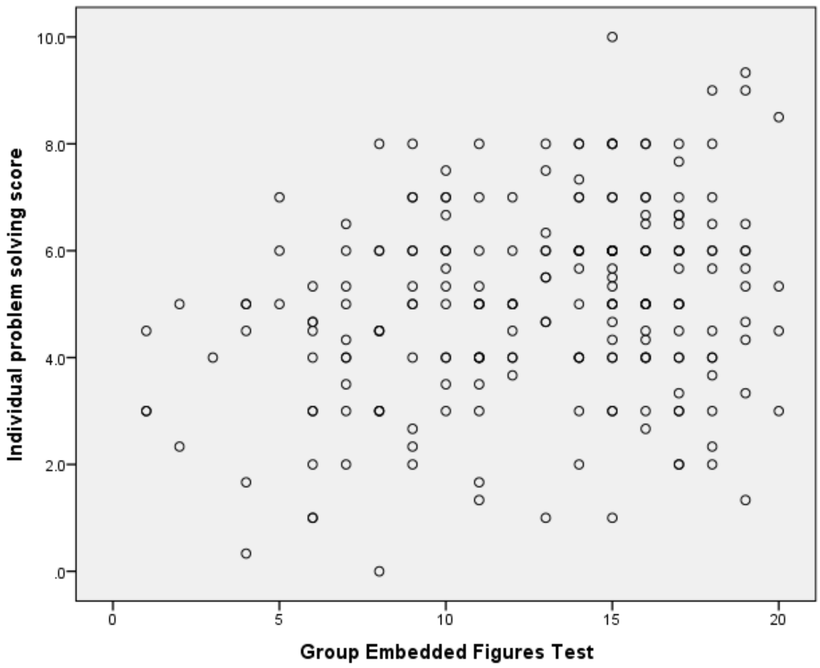

Figure 10: Plot of GEFT scores versus individual problem-solving average score

When the GEFT scores are categorised as field dependent, field medium and field independent a trend is more apparent (see figure 11). Field medium students are performing better than their field dependent counterparts (both the lowest and the highest scores are greater) and field independent students show further improvement in their performance.

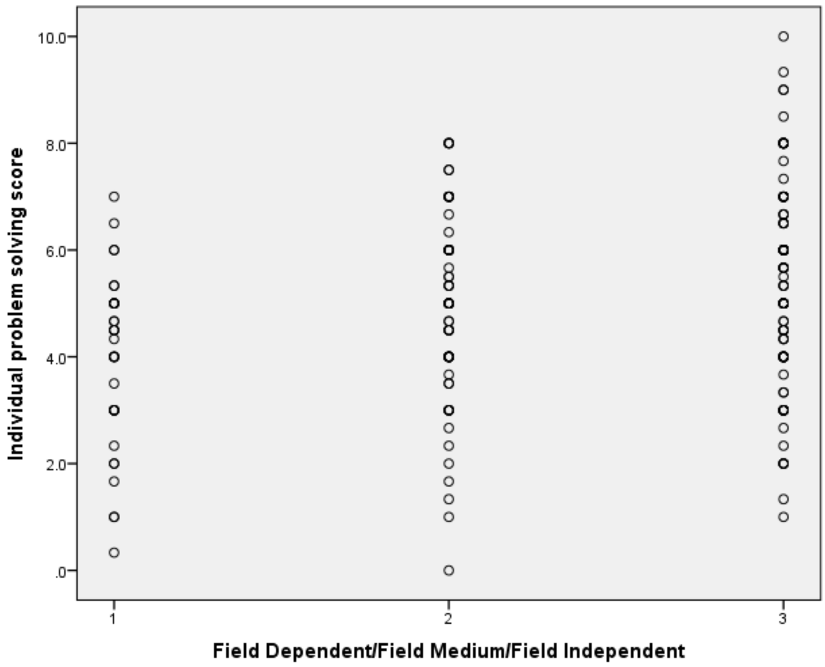

Figure 11: Plot of field dependence categories versus individual problem-solving average score

Although the statistical analysis yielded no significant correlations between FIT scores and IPS scores, the scatter plot of M-Capacity versus IPS average score, figure 12, shows that the only students to gain marks higher than 40% had an M-capacity of five or more. This appears to show a threshold beyond which only students above a certain M-capacity are proficient problem-solvers.

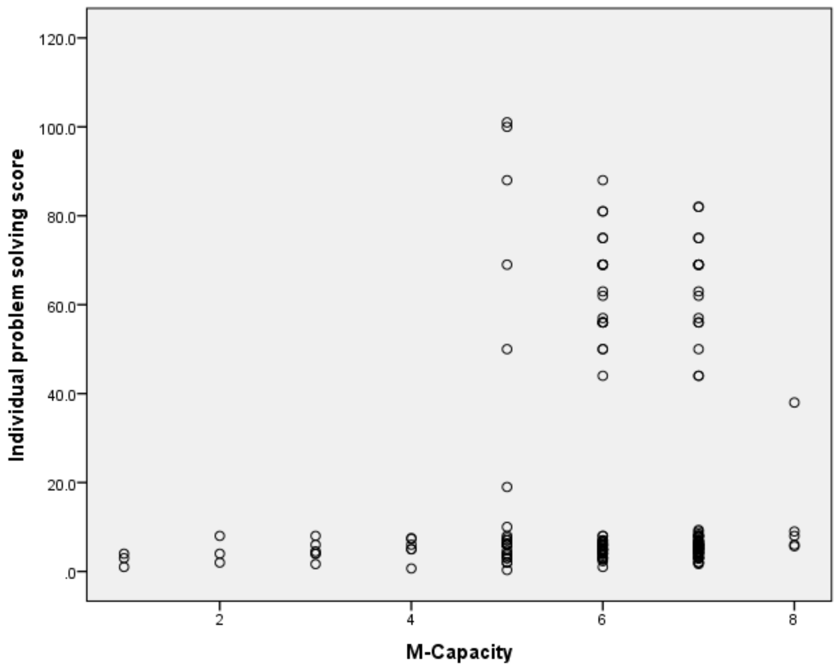

Figure 12: Plot of M-Capacity versus individual problem-solving average score

3.3 Algorithmic problem-solving

The data for algorithmic problem-solving ability was obtained from individual problems in exam papers. Marks for six problems were obtained for one cohort of students (N=43), and an average mark for algorithmic problem-solving was calculated (ALG Avg). The marks from the algorithmic problems yielded only one significant correlation (table 15). The FIT scores produced a correlation coefficient of 0.37 when compared to the algorithmic problems (ALG Avg). The weaker significance may be due to the low number of participants (N=35). This suggests that M-capacity may have some influence upon algorithmic problem-solving ability. The low number of algorithmic scores obtained per student (6) is a significant limit for these data.

Table 15: Correlation coefficients for cognitive ability and algorithmic problem-solving ability

	Type	FDS	BDS	FIT	GEFT
ALG Avg	Spearman	0.18	0.24	0.37*	0.29
	N	40	40	35	41

Correlations are significant for 2-tailed test at $^*p<0.05$

3.4 Degree Classification

Marks for each year of the chemistry degree course, and the degree marks as a whole, were compared with cognitive scores. Table 16 shows two weak correlation coefficients, both with weak significance factors ($p<0.05$). The limited number of participants could account for the lack of more significant correlations.

Table 16: Correlation coefficients for cognitive ability and degree performance

	Type	FDS	BDS	FIT	GEFT
Yr 1 %	Spearman	0.12	0.16	0.08	0.02
	N	135	135	131	140
Yr 2 %	Spearman	0.13	0.14	0.12	-0.03
	N	136	137	133	141
Yr 3 %	Spearman	0.09	0.20*	0.17	-0.04
	N	136	137	133	141
Degree %	Spearman	0.13	0.20*	0.16	0.01
	N	139	140	136	146

Correlations are significant for 2-tailed test at $^*p<0.05$

When both the group and individual problem-solving scores (GPS Avg and IPS

Avg) are compared with year and degree scores (Yr 1%, Yr 2 %, Yr 3 %, Yr 4 %, Degree %) there are no significant correlations relating to group problem-solving (Table 17). Individual open-ended problem-solving scores correlate weakly with degree scores. The correlation coefficient of 0.25 for (IPS Avg) verses (Degree %) suggests that degree scores improve as individual open-ended problem-solving ability improves. A significant limit to these data is again the number of participants.

Table 17: Correlation coefficients for open-ended problem-solving ability and degree performance

	Type	Yr 1%	Yr 2 %	Yr 3 %	Degree %
GPS Avg	Spearman	0.19	0.11	0.10	0.15
	N	78	78	77	77
IPS Avg	Spearman	0.24^{**}	0.25^{**}	0.20^{*}	0.25^{**}
	N	146	148	148	153

Correlations are significant for 2-tailed test at *p<0.05 and **p<0.01

Table 18 shows the correlations for the average scores for the algorithmic problems (ALG Avg) with degree marks and intermediate year marks as a percentage (Degree %; Yr 1%; Yr 2 %; Yr 3 %; Yr 4 %). Correlation coefficients of 0.74, 0.87 and 0.80 for each year and a value of 0.84 for the final degree marks indicate strong positive correlations between degree marks and algorithmic problem-solving scores. The plot of algorithmic scores verses degree scores (figure 13) clearly indicates a strong relationship between the two variables. Once again these data are limited by the small number of participants.

Table 18: Correlation coefficients for algorithmic problem-solving ability and degree performance

	Type	Yr 1%	Yr 2 %	Yr 3 %	Degree %
ALG Avg	Spearman	0.74^{**}	0.87^{**}	0.80^{**}	0.84^{**}
	N	39	39	39	39

Correlations are significant for 2-tailed test at **p<0.01

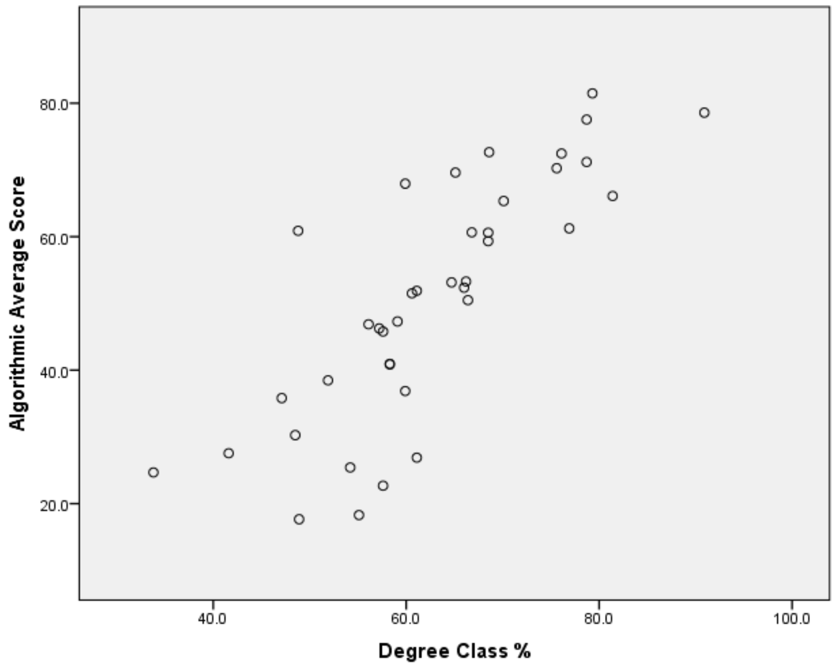

Figure 13: Plot of degree class as a percentage versus algorithmic problem-solving average

There were no significant correlations between both the group and individual problem-solving scores and the algorithmic problem-solving scores (Table 19). This suggests that algorithmic problem-solving abilities and open-ended problem-solving abilities use different skills. Figure 14 shows the plot of individual open-ended problem-solving average scores versus algorithmic problem-solving average scores. In the bottom right hand corner of the plot, there are four students, representing 7% of the sample, who show proficiency in solving algorithmic problems, scoring greater than 40%. These students, however, were less successful in solving open-ended problems. In the top left hand corner of the plot, eight students, representing 13% of the sample, were successful in solving open-ended problems, scoring greater than 40%. These students, however, were less successful in solving algorithmic problems.

Table 19: Correlation coefficients for algorithmic problem-solving ability and open-ended problem-solving ability

	Type	ALG Avg
GPS Avg	Spearman	0.03
	N	60
IPS Avg	Spearman	0.04
	N	61

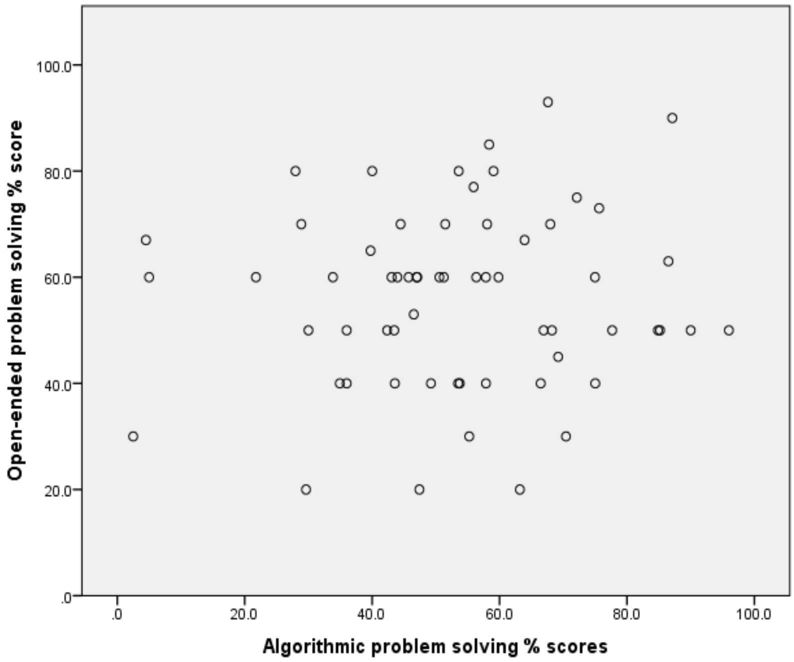

Figure 14: Plot of individual open-ended problem-solving average versus algorithmic problem-solving average

3.5 Chemistry students' attitudes

The questions on the attitudes questionnaires were designed to indicate positive or negative attitudes to problem-solving (see appendix 4). The number of responses that demonstrated positive attitudes (by a strongly agree or agree response to a positive statement) or negative attitudes (by a strongly agree or agree response to a negative statement) to problem-solving for each student, before and after the problem-solving sessions, were collated and plotted for the cohort. This is shown in Fig. 14, and shows a significant shift in students' attitudes toward more positive responses following the problem-solving sessions.

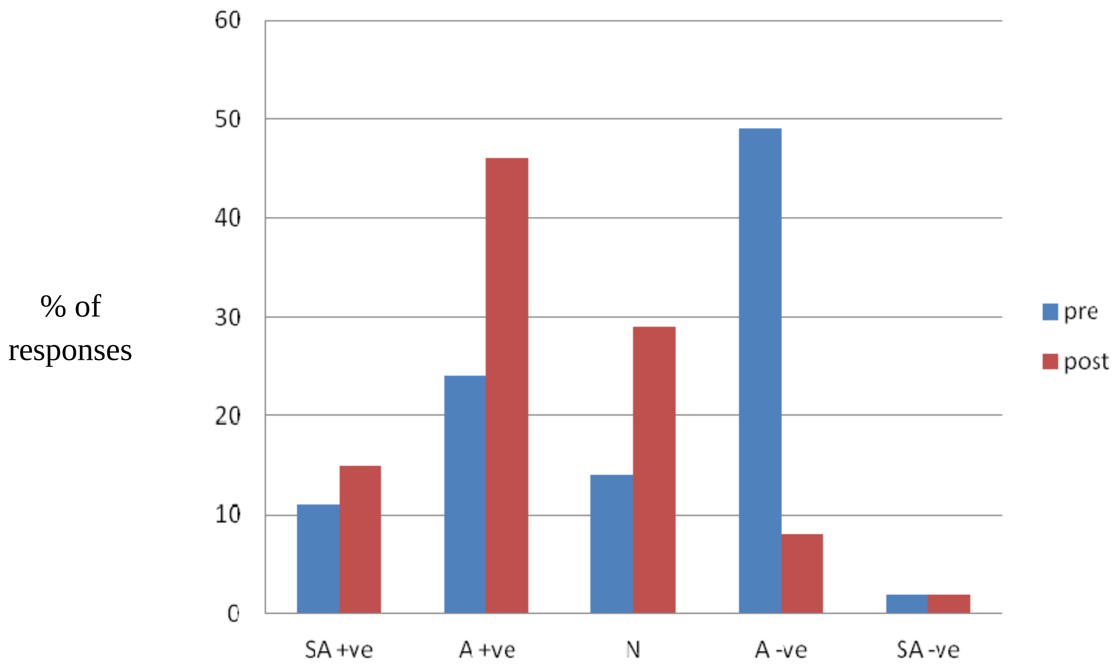

Figure 15: Changes in attitudes to open-ended problem-solving (N = 204)

3.6 Questionnaire responses

The post module questionnaire ended with the following question: "Please tell us how the problem-solving activities you have tackled over the past two weeks has compared to problem-solving you have done previously, Were they easier, more difficult, more interesting, less interesting etc?" The following responses were obtained:

"Far more difficult. The lack of information hindered progress and, while it was useful for making assumptions, it often led to some panic."

"More interesting."

"More interesting and challenging."

"The first was useful and enjoyable. The last, boring."

"The problem solving activities I tackled over the past two weeks, some of them I did similar on other modules but some not. Some of them were difficult for me but the others were ok."

"Easier in terms of knowledge required. Harder cos had to assume a lot of stuff."

"Much more difficult and complicated than anything I have done previously."

"More difficult as there was far too much to assume."

"Problem solving activities were very different to those tackled in the past especially the "shapes" exercise. I found some exercises more difficult & some more easier than what I have done previously."

"More interesting as they related to the outside world."

"In my opinion, this type of problem solving is more enjoyable than other done before. And also, I think they are closer to what we will find in the future workplace."

Only a small number of responses were obtained. Only ten students from a cohort of 72 (14%) wrote a response. It was clear, however, that most of the students who did write a response to the question found the problems more interesting and enjoyable. Most of the students found the problems more challenging but some realised the value in such activities.

3.7 Responses to interview questions

Six students who had completed the problem-solving sessions volunteered to be interviewed about their experiences. The detailed responses for each individual interview can be found in appendix 5. For question 1, "How did the problems compare to problems that you've done before on your course?", students responded with comments on how different these problems were and in some cases that they were more difficult and "*meant you had to work harder*". Some comments identified the difficulty arising from the open-ended nature of the problems. The problems were also judged to be, "*More grounded in reality.*" and that they "*encouraged teamwork*" and were enjoyable. Question 2 asked "Did you find them more or less challenging than conventional problems? Why?" Each student found them more challenging. According to the students the reasons for this were the fact that an unfamiliar method had to be used to reach a solution. Other comments referred again to the open-ended nature of the problems. e.g. "*No single right answer. Made you think more.*" and *"made you think outside of the box"*. One student commented that some of the problems would have been too challenging had they not been tackled in groups. *"Everyone had their own little snippets of ideas to chuck into the equation".* The next question posed was: "Did you find them more or less enjoyable than conventional problems? Why?" Every student responded positively to this question saying that they found the problems more enjoyable. Reasons for this included the fact that group members were required to debate and then decide upon a method to solve a problem. Students also referred to the fact that the problems were related to real-life, required them to explore their knowledge of chemistry and required them to think more, "*made you think, got you stimulated"*. Question 4 asked: "In groups, how did you go about tackling a difficult problem?" In response to this question one student mentioned that the group didn't really work together to solve the problems. Ideas were put forward but there was "*No attempt to agree on a method first."* The remaining students reported that their groups tackled difficult problems by first, pooling their knowledge, contributing ideas about possible methods and then following a chosen method to reach a solution. Student 5 summarised the problem-solving process succinctly by saying: "*Went through question together. Explained to those who didn't understand question. Suggested method they favoured individually. Agreed on one method then followed it.*" Question 5 asked: "Was it more or less challenging tackling them individually compared to in a group? Why?" One student found the individual problem less challenging because they judged that particular problem to be an easier one to solve. The remaining students found the individual problems more challenging and found group problem-solving more enjoyable. The reasons attributed to this were generally that, in a group situation, contributions from the group members lead to a more effective way of solving a problem. Some students also reported having more doubts and less confidence about their ability to solve a problem on their own. e.g. "*Others offer other viewpoints. Can help each other. Have doubts if you are working alone. Can get information from others. Doing group questions helped* *doing a question alone.*" Question 6 was: "What skills do you think these problems help you develop?" For this question most students mentioned communications skills and working as part of a team. Problem-solving skills and thinking skills were also mentioned as was developing alternative strategies for solving problems. Question 7 followed up on the previous question about skills by asking: "Would these skills be useful in your future career? Why?" Each student agreed that the skills they had identified would be useful. Their reasons varied. Two students stated that they were planning to work in the chemical industry and research. One student thought that such skills would be useful in any future career. Another student believed that these skills would be useful in management and in situations where teamwork was required. The final question asked: "Would you be prepared to have a go at more problems to help us with this research?" Every student indicated that they would be prepared to tackle more problems to assist in the research.

3.8 Study of approaches to open-ended problem-solving

The observations made from the recordings and scripts can be found in appendix 6. The following extracts and notes are examples of observations made from the students' attempts at the problems. Question one was: "You've got home after a hard day's study and you're starving. You search the freezer and find a chicken curry with rice. How much energy is required to heat the frozen curry?" In tackling this problem, student C initially thought about working out the energy required based upon the power rating of a microwave oven. Student C: *"I can work out the energy based on the time it takes to cook and wattage of the microwave."* Student C realised the need to use the power rating of a microwave oven and then estimated the time it would take to heat the food. The student then switched strategy to look at the amount of heat required to heat the curry to a temperature suitable for consumption. The student decided that the curry would have to be heated from -15ºC to 70ºC. Student C then made the assumption that the water would be heated by the microwave and started to think about how to work out the energy required for that change in temperature. The student estimated the mass of the curry and then estimated the specific heat capacities of ice and water and used them to work out a value for the energy required. Student C approached the problem in a logical and structured way (Category 1: ability to reason and work systematically) and was able to make sensible estimates and assumptions (Category 2: ability to estimate and make assumptions). This approach allowed the student to reach a solution to the problem and this was deemed to be a successful strategy. Student G tackled problem one in much the same way as student C, assuming the energy required would be used to heat water from -5ºC to 50ºC and estimating a value for the specific heat capacity of water (Category 2: ability to estimate and make assumptions). This was followed by a logical progression to a solution by calculating the energy value using the estimates and assumptions already made (Category 1: ability to reason and work systematically).

For this problem student G used a successful strategy. When presented with problem two however, student G did not fare so well. Problem two was: "Many commercial hair restorers claim to stimulate hair growth. Human hair is composed mainly of the protein α-keratin. Assuming the protein is made up of amino acid units estimate the rate of incorporation of amino acid units per follicle per second." Student G once again approached this problem in the same systematic way as before but was initially distracted by the context in the problem. *"I don't understand that. Is that the amino acids from the hair restorers or just naturally when you're growing your hair?"* (Category 4: distracted by context). The student was then hindered further by a lack of prior knowledge. Student G: *"We're doing that at the minute,* (studying the structure of amino acids) *but I don't really get it at the minute."* Researcher: *"Well if it helps, draw the structure."* Student G: *"I wouldn't even know where to start on that one. Cos I can't even think of any sizes or anything. I don't know where to go from there."* (Category 5: lack of prior knowledge). The student made little further progress from this point and was deemed to be unsuccessful with this problem. Student G was an example of a participant who had displayed instances of both successful and unsuccessful approaches to problem-solving. Student D was presented with problem one and struggled from the beginning appearing to misunderstand the question. Student D: *"How long have I been working through the day. How much energy do I require for this?"* (Category 4: distracted by context). *"I'm really stuck with this."* Researcher: *"Ok, what do you understand the question is asking?"* Student D repeated the question almost word for word. Researcher: *"So what do you think?"* Student D: *"Must depend on how long the food is gonna heat."* (Category 6: having difficulty identifying relevant data and making estimates). Researcher: *"So can you make an estimate of how long it would take?"* Student D: *"thirty minutes, twenty, thirty minutes."* Researcher: *"What else do you need to know to reach an answer?"* No response. (Category 3: Unable to identify the problem or propose a solution).

The student continued to struggle, unable to identify the data required to work out the problem. The second problem was tackled in a similar manner and this student's approach to problem-solving was deemed to be unsuccessful. From analysis and coding of the recordings and scripts a number of common approaches to problem-solving were identified. Six categories of approaches to open-ended problem-solving were identified and each student's attempts at solving open-ended problems were assigned the following categories.

1. Logical/structured

A logical structured approach was identified where a student worked through the problem systematically and was able to show or explain their reasoning.

2. Ability to make estimates/assumptions

Students displaying this category were comfortable making estimates when they decided they needed a value for a calculation. Also included in this category were cases where assumptions were made in order to proceed towards a solution.

3. Unable to identify the problem/unable to propose a solution

Students lacking any logical, structured approach, who were unable to identify the problem and subsequently unable to attempt a solution fell into this category.

4. Context-related

Some students became distracted by some of the information given in the problem that was there as context. They appeared to want to stick to what they knew and not venture outside of their comfort zone. This approach hindered progression towards a solution.

5. Prior knowledge

Related to category 4 was the inability to work through the problem due to lack of prior knowledge. In some cases this led to the student trying to use something they already knew to explain the problem whilst others struggled or failed to make any progress.

6. Data related

When presented with the problems, some students found it difficult to: a. identify data relevant to the solution or; b. make sensible estimates and assumptions in the case of missing data.

The table 20 shows which approaches to solving open-ended problems each student displayed. Each shaded box indicates one or more instance of a student using an approach that fell into one of the categories. For example, student A's approach to problem-solving showed an inability to identify the problem (category 3), a focus on context and prior knowledge (categories 4 & 5) as well as an inability to make estimates and assumptions (category 6). Student C, however, applied a logical structured approach to solving the problems (category 1) and was comfortable making estimates and assumptions (category 2). Categories 1 and 2 (shaded light grey) indicate useful strategies and categories 3 to 6 (shaded dark grey) indicate unhelpful strategies.

Table 20: Categories of approaches to problem-solving from students A-O

Category	***A***	***B***	***C***	***D***	***E***	***F***	***G***	***H***	***I***	***J***	***K***	***L***	***M***	***N***	***O***
1															
2															
3															
4															
5															
6															

The students who did not get distracted by the context were the ones who knew more about the context. For example, one of the students who had previously worked as a chef had no problem getting through the question about heating curry. The knowledge he had gained from being a chef helped him arrive at some assumptions much more easily than some of the other students. Conversely, those students who could not identify the problem and/or propose a solution became distracted by context or prior knowledge.

These students were unable to cope with too much or too little data and experienced difficulty in getting started and working through a problem. Fifteen students took part in the one to one problem-solving sessions. Nine of those students took approaches to problem-solving that fell into categories three to six. These students were unsuccessful in solving the problems they attempted. Nine of the students' approaches to problem-solving fell into categories one and two. Three of these students, however, also used approaches from categories three to six which hindered their success in solving these open-ended problems. Therefore, only six of the students showed successful approaches to problem-solving.

4.0 Discussion

4.1 The quantitative research

During the group problem-solving activities, only the groups of field medium and field independent students showed proficiency in open-ended problem-solving. This may in part be due to the contextualisation of the problems. The problems contained information presented in order to provide a context aimed at revealing a real-life application to the chemistry. The context was present in order to engage and motivate the students. Therefore, in order to reach a solution the students were required to focus on and process only the most relevant information and ignore the information provided as context. Field dependent individuals find it more difficult to separate the essential information contained within the problems from the information used to provide a context. As a result they are processing too much information and have much less working memory available for carrying out the operations required to reach a solution. The same issues appear to have affected the students when they individually attempted to solve the open-ended problems. Students with high scores on both the FIT and GEFT gained higher scores in the problem-solving activities. These students' greater M-capacities and field independence allowed them to focus on only the relevant information which left a greater proportion of working memory available for processing that information and reaching a solution. Students' ability to solve open-ended problems appeared to be significantly affected by their M-capacities. Figure 12 shows a plot of individual open-ended problem solving scores against M-capacity. The plot shows that the only students with open-ended problem solving average scores of greater than 40% were those with M-capacities of five or more. These data suggest that there is an M-capacity threshold below which students will experience difficulties in successfully completing problem solving activities.

Students categorised as field dependent had difficulties coping with the demands of the open-ended problems as did those students with lower M-capacities. Many of these students had both a low M-capacity and a weaker disembedding ability. In attempting to solve the open-ended problems these students were processing irrelevant information in an already smaller working memory, thus leaving too little working memory available for processing the details of the problems, leading to unsuccessful attempts at problem-solving.

The algorithmic problem-solving scores obtained from exam papers produced a correlation with FIT scores but not with GEFT scores. This reflects the fact that the algorithmic problems used in the analysis contained only relevant information and placed much less of a demand on the students. In the case of these problems, it was only the students M-capacities that limited their ability to solve the problems. The findings from the group and individual problem-solving research agree with previous work where both M-capacity and disembedding ability were found to correlate with performance in problem-solving (Tsaparlis, 2005, Danili and Reid, 2006).

When students' degree scores were compared with the scores from the cognitive tests no strong, significant correlations were found. Degree marks are comprised of many points of performance data, each produced by a variety of activities that use multiple cognitive resources. Previous studies have compared cognitive abilities with individual tasks and found correlations. In addition to this such studies have often been concerned with lower levels of education. These factors may explain the lack of significant correlations observed here from the comparison of cognitive data with degree scores.

The degree scores were also compared with the scores of the open-ended problems. No correlations were found between degree scores and group problem-solving, which may have been due to the small sample sizes and the fact that degree scores are not awarded to groups of students by averaging an assessment score out over the members of the group. Comparison of degree scores with individual open-ended problem-solving scores produced a weak positive correlation, which suggests that the ability to solve open-ended problems is rewarded to a small extent.

A very strong positive correlation was found when the algorithmic problem-solving scores were compared with degree scores. Such strong correlations have not appeared in any of the other statistical analyses in this research. While the sample size is small, such correlation coefficient values suggest that throughout the majority of a chemistry degree the ability to solve algorithmic problems is well rewarded in assessment schemes. When considered alongside the results previously mentioned, where no correlations were found between the cognitive tests and degree scores, this suggests that the assessments of chemistry degree courses do not tax students to the same extent as the open-ended problems and the cognitive tests. These results align with the findings of Bennett who discovered that over 90% of the questions within examination papers from university chemistry departments in the UK, USA and Australia could be categorised as algorithmic or Johnstone Type 1 problems (Bennett, 2004). Type 1 problems have been more accurately described as exercises and do not sufficiently challenge students. Such examination questions are seen as *"easy to set and easy to mark"* but will not help students develop many of the higher order cognitive skills required of them in their graduate endeavours. Probably because assessments which test lower order cognitive skills are easier to set and mark, lower order cognitive skills are over assessed and over rewarded. Conversely, the kind of activities and assessments that would enable students to develop and demonstrate higher order cognitive skills are much more difficult to design and mark. As a result students' development and demonstration of these skills are under assessed and under rewarded. Consequently, students tend not develop higher order cognitive skills to the extent that many graduate employers require, resulting in many graduates finding themselves lacking in skills upon entering the workplace as Hanson and Overton (2010) have reported.

Further statistical analysis revealed that no correlations were found between algorithmic problem-solving scores and open-ended problem-solving scores. This suggests that students adept at solving algorithmic problems are not necessarily adept at solving more complex open-ended problems and vice-versa. According to Zoller algorithmic problems (or exercises) and questions that require only the recall of knowledge assess only lower order cognitive skills. Repeated use of such questions, as part of instruction and assessment will lead to students developing only lower order cognitive skills. Problem-based approaches, such as open-ended problem-solving, have been shown to promote the development of higher order cognitive skills (Zoller, 1993, 1999a, 2002, Zoller and Pushkin, 2007). This lack of correlation between algorithmic problem-solving scores and open-ended problem-solving scores agrees with the work of Tsaparlis and Zoller (2003) who assessed an examination paper used nationally in Greece. They found that there was no correlation between students' scores on questions that required lower order cognitive skills and questions that required higher order cognitive skills. Like the results of Tsaparlis and Zoller (2003) the results of this research are surprising because, according to Bloom's taxonomy lower order cognitive skills are a prerequisite for higher order cognitive skills (Bloom, 1956). This means that students who have developed higher order cognitive skills are expected to have already developed lower order cognitive skills. As these results suggest this is clearly not the case. Students adept at tackling open-ended problems (i.e. problems that require higher order cognitive skills) are not necessarily adept at tackling algorithmic problems (i.e. problems that require only lower order cognitive skills). It appears that some students can bypass the development of lower order cognitive skills and display higher order cognitive skills. This suggests that lower order cognitive skills and higher order cognitive skills are different sets of skills that can be acquired and developed independently. It appears that open-ended and algorithmic questions measure and require different skills. If university chemistry degrees aim to develop students' ability to solve open-ended problems and foster the benefits of developing those skills then courses need to reduce their focus on the development and assessment of lower order cognitive skills and algorithmic problem-solving abilities. Instead courses need to focus on developing, and assessing the development of, those skills which both graduates and graduate employers value (HM Treasury, 2006, Department for Innovation Universities and Skills, 2007, QAA, 2007, Archer and Davison, 2008, Cogent Sector Skills Council, 2009, Department for Children Schools and Families, 2009, Department for Innovation Universities and Skills, 2009, UUK/CBI, 2009, Hubble, 2010).

4.2 The attitudinal research

The results of the attitude questionnaires completed before and after the problem-solving sessions indicated that, overall, the students' attitudes towards problem-solving became more positive as a result of taking part in the problem-solving sessions. Berg (2005) found that a positive change in attitude was an indication of a greater motivation towards learning. It could, therefore, be suggested that the students who participated in this research found an increased motivation as a result of taking part in the problem-solving sessions. In addition to this, the final question on the post-module questionnaire elicited some responses that went some way to further explain the changes in attitude. The students commented on the ability to use different methods to solve the problems and the fact that there was no single correct answer for each problem. Also mentioned was that, although the problems were challenging, the real-life context was a motivating factor. The students also found the activity enjoyable and thought it would be useful in future employment. Such comments from students reflect shifts in attitudes often observed in university students as they progress through the Perry levels, moving through the stages of dualism and multiplicity towards more relativistic thinking where more challenging methods of teaching and learning are increasingly appreciated as are problems of the more open-ended types (Perry, 1970). These attitude changes also suggest that framing the problems within a real-life context has also had the desired effect of providing a greater motivation to engage with the learning process. These findings are also consistent with investigations into the effectiveness of context-based and problem-based teaching and learning strategies, (Bennett and Lubben, 2006, Gilbert, 2006, Zoller and Pushkin, 2007, Fensham, 2009, Gilbert *et al.*, 2010, King, 2012, Sandi-Urena *et al.*, 2012) where improved motivation and attitudes were identified as well as increased confidence and the development of higher order cognitive skills.

The six students interviewed about their participation in the problem-solving sessions provided further information regarding their experience of open-ended problem-solving. The students commented on how different the problems were compared to previous experiences of problem-solving. They also found the problems more realistic and more challenging due to the fact that the problems had no single correct answer. Each student indicated that they had enjoyed the experience, citing the group-work aspects and the fact that they were required to think more and apply their knowledge in different ways. Most of the students reported that the members of their group contributed equally and managed to work together in a productive manner to reach a solution. These students indicated that they found working in groups easier and more enjoyable when compared to working individually. They attributed this to the group situation being a more effective way of solving the problems. One student, however, commented that his group had been less cooperative and often failed to agree upon a method together before proceeding towards a solution. This observation makes sense in light of the fact that this particular student had been a member of a field dependent group. The field dependent students would, individually, have had difficulties identifying the relevant data within the problems and these difficulties would have been brought to the group situation, making the collaboration less productive. Whilst these are the data from just one student reporting upon the experiences of one group it is in agreement with the quantitative findings, showing that the field dependent groups were less proficient at problem-solving. The interviews also revealed that the students were able to identify a number of skills that they thought these types of problems helped them to develop. They also believed that these skills would prove useful in the future. These findings agree with a number of recent investigations that have reported the development of problem-solving skills and other higher order cognitive skills as a result of problem-based group work (McDonnell *et al.*, 2007, Zoller and Pushkin, 2007, Sandi-Urena *et al.*, 2011, Sandi-Urena *et al.*, 2012).

4.3 The qualitative study of approaches to open-ended problem-solving

The study of approaches to open-ended problem-solving revealed some of the reasons for students' successes and failures in tackling these problems in a way that the quantitative research did not by closely observing the processes that students go through in their attempts to solve these types of problems. The students showing the greatest proficiency were those that approached the problems in a systematic and logical manner, were able to manage a lack of data and demonstrate an ability to make assumptions and/or estimates that allowed them to carry out mental calculations before evaluating their results. This approach to problem solving corresponds to the "scientific approach" identified in a study of students' approaches to algorithmic physics problems (Walsh *et al.*, 2007). The least successful approaches to open-ended problem-solving were characterised by an inability to identify the problem, a lack of prior knowledge, a focus on the context of the problem at the expense of an attempt to solve it, and an inability to make any assumptions or estimates. The students categorised as using these approaches were consistent with the "no clear approach" identified in the physics study (Walsh *et al.*, 2007). A third category of students showed instances of each category of approach, often within a single problem. Their ability to identify the problem, deal with insufficient data and make the required assumptions and estimates seemed to depend upon the individual context. In some cases this arose from a lack of prior knowledge about a particular problem or aspect of a problem. With other students it appeared that some aspect of the context caused a distraction and led to an ineffective attempt to solve the problems. These students usually evaluated their solutions, when they were able to reach one, but they also showed algorithmic approaches. Some students recalled methods that they had previously used to solve algorithmic problems and attempted to make the data from the new problems fit into a known method.

It is, perhaps, not surprising that some students approached these problems in an algorithmic fashion when most of their previous experience of problem-solving has been of the algorithmic, structured type (Bennett, 2004, 2008, Pappa and Tsaparlis, 2011).

Students who take a less structured approach to problem-solving and those that take a structured or scientific approach have been described as novices and experts respectively (Bodner and Domin, 2000, Cartrette and Bodner, 2010). It could, therefore, be said that the students in this study who exhibited successful approaches are functioning as expert problem-solvers. Those who adopted only unsuccessful approaches are novice problem-solvers as they have found solving these types of problems too challenging. Those using the full range of approaches may be in a transitional stage on the journey from being novice to expert problem-solvers. These findings have implications for teaching and learning. Problem-based methods are increasingly popular in undergraduate chemistry education (Belt *et al.*, 2002, Kelly and Finlayson, 2007, 2009, Hicks and Bevsek, 2011, Tosun and Taskesenligil, 2013). PBL uses open-ended problems with real-life contexts and students have to develop a strategy, find missing information and data. Taking an algorithmic approach to solving such problems is insufficient and unproductive. This research indicates that, within a student cohort, there will be a significant number of students who experience difficulties both identifying the details of a problem and dealing with a lack of data. Some of these students will also be distracted by the context and by their lack of knowledge and will be unable to evaluate their progress. These students will require additional support if they are to succeed in problem-based activities.

4.4 The problem-solving research in terms of the information processing model

When considered in terms of the information processing model, the combined results of the quantitative and qualitative research can provide a more detailed explanation of the process of problem-solving as investigated in this research. The marking scheme for the open-ended problems, derived from Johnstone’s problem types, awarded marks based on the ability to: focus on relevant information; make estimates and/or assumptions; apply known methods; develop new methods; define goals; work towards goals; reach goals and evaluate goals. Many of these skills were identified as being essential elements of successful approaches to problem-solving in the qualitative study of open-ended problem-solving. The quantitative research found that the most successful problem-solvers were those categorised as field independent with high M-capacities. This means that these students were able to focus on the relevant information which in turn allowed them to use a greater proportion of their working memory to hold and process the information required to solve the problems. Access to a larger amount of working memory meant that these students possessed an increased ability for solving the problems. The results gained from the qualitative study of problem-solving showed that successful problem-solvers were those that: approached the open-ended problems in a logical, systematic manner; were able to make estimates and assumptions; possessed some or all of the required prior knowledge; were not distracted by the context of the problem and were able to evaluate their solutions. Although the students who participated in the qualitative study of problem-solving had not completed the three cognitive tests those students that had displayed successful approaches to solving open-ended problems were likely, in accordance with the findings from the quantitative research, to be field independent with high M-capacities. The approaches to problem-solving identified from the successful problem-solvers can be explained in terms of the information processing model.

The relevant prior knowledge of these students aided a more efficient use of their perception filters, allowing them to identify and focus on the relevant information and avoid the potential distractions of the information presented as context. This prior knowledge is likely to have taken the form of some content knowledge combined with knowledge of dealing with information logically and knowledge of making sensible estimates and/or assumptions. This prior knowledge meant a greater proportion of working memory was available for processing the information in the problems. The available working memory was used to make the required estimates and assumptions, work towards a solution in a logical, systematic manner and finally evaluate the solution. The extra working memory that was available to them made these steps possible.

The students who gained low scores for open-ended problem-solving in the quantitative research were field dependent with low M-capacities. According to the marking scheme these students were less able to: avoid irrelevant information; make estimates and/or assumptions; apply known methods; develop new methods; define goals; work towards goals; reach goals and evaluate goals. The difficulties of these students in displaying these skills can also be explained in terms of their cognitive abilities and the information processing model. Field dependent students are less able to separate the relevant information from the information presented as context within the problems. As a result a greater proportion of their working memory is occupied by the information presented within the problem (both relevant and irrelevant). This leaves much less space available for dealing with the processing required for making estimates and/or assumptions, selecting methods, defining, working towards, reaching and evaluating goals. The impact of this was such that some of the field dependent/low M-capacity students failed to reach the stages of the open-ended problems concerned with goals.

These students had too little working memory available for the processing required to work towards the solutions to the problems. As a result these students were processing too much information and were experiencing cognitive overload.

The phenomenon of cognitive overload and its impact upon learning has been described in a number of publications (Sweller, 1988, Paas *et al.*, 2003, Johnstone, 2006, Reid, 2009). Cognitive overload will result when learners are presented with more information than they can handle and will lead to ineffective learning and poor performance in assessments. The implications of cognitive overload are such that if methods of teaching and assessment are employed that fail to take account of the limitations of cognitive factors then some forms of assessment will merely test the students' cognitive limitations rather than any knowledge or skills that have been the focus of instruction (Johnstone, 2006). The impact of working memory limitations was illustrated by Reid (2009) who found that the average difference in performance between school students with a working memory capacity of five and those with a working memory capacity of seven was nearly 13%.

The qualitative study of open-ended problem-solving further identified the factors involved in students' unsuccessful attempts to solve open-ended problems. These students' approaches were characterised by: an inability to identify the problem; an inability to focus on only relevant information; a lack of relevant prior knowledge; an inability to make sensible estimates and/or assumptions and therefore an inability proceed logically and systematically towards a solution. In accordance with the findings of the quantitative research, it is not unreasonable to speculate that, had these students completed the cognitive tests, they would have been categorised as field dependent with low M-capacities. The methods that unsuccessful students employed in their attempts at solving open-ended problems indicated that they were inexperienced in the aspects of problem-solving that these particular problems required of them. Their inability to focus on only relevant information combined with a lack of prior knowledge meant that a greater proportion of their working memory was occupied with new and irrelevant information. This meant that too little working memory was available for the remaining steps of the problem-solving process. As with the participants of the quantitative research, these students had experienced cognitive overload, leading to unsuccessful attempts at solving these open-ended problems.

The students identified as field medium with medium M-capacities in the quantitative research, showed a medium performance in open-ended problem-solving ability. These students are similar to those identified as transitional problem-solvers in the one-to-one problem-solving sessions. These students' abilities to solve open-ended problems were seen to vary from problem to problem. Their ability to apply some of the required skills and knowledge often varied within individual problems. Such observations mean that these particular students are in the process of acquiring knowledge and developing the skills required for successful problem-solving. Some of these students showed competency in identifying a particular problem and making sufficient estimates but then became distracted by an aspect of the context or experienced a lack of prior knowledge that hindered their progress. In such a case a student had acquired sufficient knowledge and skills to allow them enough free working memory to reach a certain point in the problem solving process. Having reached that point they then encountered a hindrance that caused cognitive overload and led to an unsuccessful attempt at solving a particular problem. In some cases students would display a particular skill, such as the ability to make an estimate, in one problem and fail to replicate that skill in another problem or another part of the same problem. This suggests that these transitional students are in the process of developing the knowledge and skills required for solving open-ended problems but have not developed them to the extent that they can transfer the knowledge or skills from one situation or context to another. In these cases problem-solving ability will depend upon the level of familiarity with the specific content and context of a problem.

Acquiring this familiarity, i.e. gaining knowledge is achieved through the process of chunking (Johnstone and El-Banna, 1986). Chunking takes place when pieces of information and knowledge are connected through mental processing and stored as chunks that, when required, can be retrieved from the long-term memory and used within working memory to aid learning, solve problems etc.

Chunked knowledge occupies less space in working memory than new, unconnected information. Therefore these chunks of knowledge allow a greater proportion of working memory to be used for processing of new information leading to a greater likelihood of successful learning and/or problem-solving. The method used to effect chunking and the ability to do it varies with knowledge and experience. An expert will perceive the size and number of information units differently than a novice (Danili and Reid, 2004). Reid and Yang (2002) described school students' knowledge as existing as "islands" within the long-term memory and suggested teachers should aim to facilitate their learners' linking together of these islands of knowledge (chunking) in order to make that knowledge more accessible. Learning clearly needs to be structured so as to reduce cognitive load and therefore the risks of cognitive overload. This will promote the increased likelihood of students successfully meeting the required learning outcomes. Research that has focused on reducing cognitive load with a view to enabling effective learning has recommended instruction that begins with worked examples of problems (Paas, Renkl *et al.*, 2003). Renkl and Atkinson (2003) described an approach that involves, during the earliest stages of learning, beginning with simple presentation of the content. As learners gain familiarity with the subject matter more working memory becomes available and learners are given worked examples of problems. Study of these worked examples promotes familiarity with the process of problem-solving and allows the instructors to gradually decrease the amount of information provided. The familiarity with the problem-solving process means more working memory becomes available for working with the information that is left out. Finally, once learners have gained competence completing worked examples and part problems, they are exposed to full problems. Johnstone (2006) recommends pre-learning as a method to reduce cognitive load. Before any new material is presented to students, prior relevant knowledge is presented, discussed and/or assessed using exercises or problems. The prior knowledge has been reactivated, and can be linked more easily to the new learning material without the working memory being overloaded by new apparently unconnected information.

4.5 Problem-solving and development

The qualitative analysis of approaches to problem-solving carried out in this research has revealed aspects of problem-solving that were not identified when the quantitative data was analysed. The marking scheme used in the quantitative research was designed to reward the use of some higher order cognitive skills that were only required when solving open-ended problems. The marking was carried out primarily in order to obtain a numerical value reflecting a student's problem-solving ability that could then be used alongside other performance data for statistical analysis. It was only when the data from the qualitative study of open-ended problem-solving was analysed that a greater insight into the process of open-ended problem-solving was obtained. A qualitative study of students' approaches to stoichiometry problems identified similar competencies in student's ability to solve the problems (Gulacar *et al.*, 2013). The study also revealed the sources of the difficulties that led to unsuccessful attempts at solving the problems. Lack of prior knowledge, poor planning and cognitive overload were attributed as the sources of many of the students' difficulties. Both the quantitative and qualitative research has demonstrated that university chemistry students are able to tackle and solve problems of the higher Johnstone types. Other publications have also reported the use of problem-based approaches to teaching and learning that observed students at both school and university levels being successful at solving problems requiring higher order cognitive skills (Ashmore *et al.*, 1979, Reid and Johnstone, 1979, Waddling, 1988, Hadden and Johnstone, 1989, Stamovlasis and Tsaparlis, 2001, Reid and Yang, 2002a, Wood, 2006, Sandi-Urena *et al.*, 2011, Sandi-Urena *et al.*, 2012, Yoon *et al.*, 2012). Furthermore, research has revealed that the use of purely algorithmic problems as methods of teaching and assessment led to students developing purely algorithmic approaches to learning and problem-solving (Sawrey, 1990, Nakhleh, 1993, Nyachwaya *et al.*, 2014).

Algorithmic problems can often be solved without a thorough understanding of the scientific concepts involved. Problem-based strategies for teaching and learning are increasingly being found to be more effective than conventional instruction in improving students' learning and scientific skills. Such strategies have also resulted in students' showing increased levels of: accessing and using knowledge; working in groups; independent learning and problem solving skills (Zoller, 1993, Tosun and Taskesenligil, 2013).

Successful problem-solvers display traits similar to those described by Piaget as the traits of formal operational thinkers. Piaget described children's efforts to solve problems, in the earlier stages of development, as trial-and-error. The ability to solve problems in a logical and methodical way emerges during the formal operational stage. During this stage of cognitive development children are sometimes able to plan an approach to solving a problem in a prompt and organized manner. However, many people never reach the formal operational stage because they are never called upon to think in such a manner or use the skills that characterise this stage of development. This suggests that the participants of this research found to be less adept at solving open-ended problems have not yet reached the formal operational stage of cognitive development, at least not with respect to their chosen course of study. The results of this research, alongside many similar studies, suggest that, exposure to more challenging forms of instruction and assessment can help students develop valuable skills and reach the more advanced stages of intellectual development.

The results of this research have also described better uses of and development of Gardner's intelligences (Gardner, 1999). Students participating in open-ended problem-solving were given opportunities to use and develop a number of intelligences. The open-ended problems that required the ability to think logically and make estimates and assumptions made use of the students' logical/mathematical intelligence. The group problem-solving activities made better use of students' interpersonal intelligences by facilitating group work and communication. Intrapersonal intelligence was required where students were asked for qualitative and reflective statements about their experiences. Such activities took the form of the attitude questionnaires, interviews about the open-ended problem solving sessions and the qualitative study of open-ended problem-solving. The qualitative study of open-ended problem-solving also made use of verbal/linguistic intelligence by asking students to think aloud and talk through their problem-solving processes. A number of the open-ended problems used in the research required students to visualise some of the chemical concepts, thus making use of spatial/visual intelligence.

4.6 The use of context

Responses from the attitude questionnaires and the interviews showed that framing the open-ended problems within real-life contexts had a positive effect on their engagement with the problem-solving activities. The students reported greater levels of enjoyment and saw the point of participating in the problem-solving activities that presented real-life problems. They could see that they may encounter similarly challenging problems in their future workplaces. As a result they were able to relate to these types of problems and were more motivated to take part in the activity. The effect of the use of context upon the learning objectives is less clear and is, in part, illustrated by the following example. Problem 1 (appendix 1) required students to work out the amount of curry that Andrew "Freddie" Flintoff would need to eat to provide him with the energy required to compete in two cricket matches. Most of the required data was provided, so at its heart this problem was fairly algorithmic. An estimate of the amount of activity involved in playing cricket was required and the remaining calculations could be made using the data provided. The context of cricket was used because the problem was written just after the England cricket team had beaten Australia in England to regain the Ashes for the first time in a long time. This had been major national news at the time and it was thought that the students' familiarity with this would help them engage with the problem.

However, from the first time the problem was used, it became clear that many students were having difficulties reaching a solution. Based upon the observations made during the sessions and from examination of the scripts the reasons for these difficulties became clear. Many of the students had no interest in cricket and were not sufficiently familiar with the game to make the required estimates and assumptions. This lack of interest in the context and lack of familiarity produced cognitive overload and became an obstacle to the problem-solving process. The use of this particular problem is an example of how the use of an inappropriate context can result in ineffective learning and unsuccessful attempts at solving open-ended problems. The observations from the attempts to solve this particular problem show that selecting an appropriate and relevant context with which to engage and motivate students needs to be an important part of instruction and problem design. Reid (2000) reported that a course involving a more descriptive approach to chemistry was used to introduce 13-year-old school students to chemistry for the first time. Chemistry was presented purely at the macro level by exploring real-life examples and applications of chemistry which led naturally to concepts such as bonding, properties of matter and energy being investigated. This change of approach, led to a twofold increase in students opting to study chemistry in the following two years. Stuckey and Eilks (2014) showed that careful selection of a context can lead to increased engagement and motivation on the part of the students. Broman and Parchmann (2014) developed context-based problems, about tattoos. The students were unfamiliar with the scientific content but were interested in the context. These problems required higher order cognitive skills and were found to not only motivate and engage students but to help them develop their problem-solving skills and improve their explanations. The problems were also observed to enhance students' appreciation of the fact that scientific problems have more than one single correct answer.

4.7 Group work

Group work played a small but not insignificant part of the research and highlighted some reasons to make more considered use of group activities. The majority of the students were observed to work well together and reported enjoying the experience. The group tasks gave them opportunities to use communication skills that individual activities do not. The only issues arose from the fact that the students in this research were grouped together according to their degree of field dependence. As a result of students with similar cognitive abilities working together it was found that the more able groups were the most successful. Studies have found that working in small groups has exposed students to multiplicity and helped them to model the required cognitive skills (Culver and Hackos, 1982, Pavelich and Moore, 1996). Often during group work activities, students are randomised into their groups. The results of this research suggest that groups arranged purposefully to contain students of a mixture of abilities may have greater chances of success when tackling open-ended problems.

4.8 Summary

This research set out with the following aims:

- To investigate whether there is a correlation between the three cognitive factors and the academic performance of chemistry undergraduates, particularly performance in problem-solving.

The cognitive factors of field dependence and M-capacity were found to correlate significantly with students' ability to solve open-ended problems both in groups and individually. M-capacity was found to correlate significantly with students' ability to solve algorithmic problems. Students' cognitive abilities were found to have no correlations with their degree scores.

A significant correlation was found between open-ended problem-solving ability and degree scores. A very strong significant correlation was found between algorithmic problem-solving ability and degree scores. No significant correlation was found between open-ended problem-solving ability and algorithmic problem-solving ability.

- To investigate student attitudes towards the use of context-rich open-ended problems.

The students found the open-ended problems used in this research more challenging than problems they had previously encountered. Despite this they displayed increased positive attitudes towards these particular methods of teaching and learning. The students were more motivated to solve these problems and found the activities more enjoyable. Many students saw the value in these experiences and thought that such problems would help them to develop valuable skills.

- To investigate the strategies used by undergraduate students to solve context-rich open-ended problems.

The qualitative research revealed the details of both successful and unsuccessful approaches to problem-solving. Three types of problem-solver were identified as novice, transitional and expert.

5.0 Conclusions

The final aim of the research was to:

- To identify the implications of the research findings with respect to chemistry education.

The research reported thus far has revealed a number of findings that have implications for the future practice of teaching and learning. Many of these implications may well be just as applicable to pre-university education as they are for university education. This chapter will focus on the findings and implications related to university education.

The cognitive factors of mental capacity and disembedding ability have produced significant correlations with academic performance. The most significant correlations were produced for M-capacity and disembedding ability against students' ability to solve open-ended problems. This research only managed to gain a snapshot of students' abilities and skills in open-ended problem-solving because these abilities were only assessed over a short period of time. This research did not investigate whether problem-solving skills can be acquired and developed with practice over a longer period of time.

Whereas students' ability to solve open-ended problems correlated with both M-capacity and disembedding ability, algorithmic problem-solving ability correlated only with M-capacity. No correlations were found between open-ended problem-solving ability and algorithmic problem-solving ability. These findings indicate that algorithmic problems require different skills than open-ended problems. Algorithmic problems test and reward the use of only lower order cognitive skills whereas open-ended problems test and reward the use higher order cognitive skills.

For the students whose open-ended problem-solving abilities were limited by their field dependence and/or low M-capacity, cognitive overload appears to have been a significant barrier to their performance. This does not mean, however, that these students cannot become proficient at problem-solving. During the interviews many of the students' commented that it was the first time that they had encountered such problems. These activities were new to students and their open-ended problem-solving abilities were only tested over a short period of time. It may be that these students' low M-capacities and weak disembedding abilities only limit their ability to solve open-ended problem during the initial stages of exposure to these activities.

Correlations were also found between disembedding ability and open-ended problem-solving in groups. Groups of field independent students were more successful at solving open-ended problems than groups of field dependent students. Therefore, groups of students with an even mix of abilities may be more successful in tackling open-ended problems. Students with low M-capacities and/or weak disembedding abilities, working in groups containing students with high M-capacities and/or strong disembedding abilities may be aided in learning successful problem-solving strategies. These strategies may be more difficult to learn through independent study. The findings of the quantitative research into open-ended problem-solving suggest that future teaching and learning strategies need to take into account the limitations of students' cognitive abilities.

The students who attempted the open-ended problems reported finding them more enjoyable. Their experiences of these activities produced a shift towards more positive attitudes to problem-solving. These students had not encountered such problems before. They also found them more challenging. Despite this, the students appeared to be more engaged and motivated by these activities. It appears that using these context-rich, open-ended problems led to greater levels of enthusiasm and motivation on the part of the students.

The attitudinal research also identified the students' abilities to reflect upon their learning experience. Other research indicates that this ability can benefit students' development and academic performance. Students may, therefore, benefit from having their ability to reflect on their learning rewarded in assessments. This would also allow them to gain feedback from tutors enabling them to improve these abilities.

Another factor affecting engagement with and success in open-ended problem-solving was the contexts used. Students unfamiliar with or not interested in the contexts used to present the problems were less successful in their attempts to solve the problems. Therefore, the development of context-based learning materials should be informed by knowledge of the effect of different contexts. Students need to have some familiarity with the context in order to find the subject matter interesting and motivating. Careful selection of an appropriate context can provide students with a more meaningful and rewarding learning experience.

The qualitative study of approaches to open-ended problem-solving revealed the details of students' problem-solving strategies that are often overlooked by more traditional forms of instruction and assessment. The students' approaches to solving open-ended problems were identified as novice, transitional and expert. Novice problem-solvers employed unsuccessful approaches, expert problem-solvers employed successful approaches and transitional problem-solvers employed a mixture of approaches that seemed to depend upon the specifics of the problems. The qualitative study into students' approaches to open-ended problem-solving also validated the marking scheme and results of the quantitative research.

The very strong correlation produced between algorithmic problem solving scores and degree scores appears to show a dependence upon methods of assessment, within university chemistry courses, that require the use of only lower order cognitive skills. The results of both the quantitative and qualitative research clearly demonstrate that students are able to solve open-ended problems, thus demonstrating the use of higher order cognitive skills. Opportunities for students to develop higher order cognitive skills, and the assessment of these skills, need to be increased within university chemistry courses. In order to make room in curricula and courses for skills development, a reduction in the amount of scientific content may be required.

In summary, it is clear that the skills required to solve algorithmic problem are different from those required to solve open-ended problems. The lower order cognitive skills assessed by algorithmic problems are over-rewarded within undergraduate chemistry courses. Conversely, the higher order cognitive skills assessed by open-ended problems are under-rewarded within undergraduate chemistry courses. The details of successful and unsuccessful approaches to open-ended problem-solving have been identified and categorised. The participants of this research found context-rich open-ended problems a challenge to tackle. They also found them motivating and enjoyable. Therefore, an increase in the use of open-ended problems would clearly be beneficial to all interested parties.

6.0 Further Work

The data produced in this research has been significantly limited by the number of student participants. Data such as M-capacities and disembedding abilities could be obtained for greater numbers of students and compared with academic performance data in order to assess the validity of the results obtained here.

M-capacity and disembedding ability correlated significantly with performance in open-ended problem-solving. The qualitative study of approaches to problem-solving identified the details of novice, transitional and expert problem-solving strategies. An investigation that tests students' cognitive abilities and also identifies those students' approaches to solving open-ended problems could be used to determine if there are correlations between the cognitive factors of M-capacity and disembedding ability and the three approaches to solving open-ended problems.

Further investigations into the cognitive factors that affect academic performance may reveal further data that could inform educational practice. Flor *et al* (2013) asked students to participate in a relaxation training course of 12 sessions of deep breathing exercises over a period of four weeks. Pre and post-tests of working memory capacity and academic achievement were administered with test and control groups. The test group gained significantly higher scores in post-tests than the control group. The impact of relaxation training upon problem-solving performance could be investigated. There are also cognitive training software packages that claim to increase working memory capacity although there is much debate as to the validity of these claims (Alloway *et al.*, 2013, Tulbure and Siberescu, 2013). The impact of cognitive training upon academic performance could also be investigated.

It may be that only initial attempts at open-ended problem-solving are adversely affected by limiting cognitive factors such as M-capacity and disembedding ability. A longitudinal study could further investigate students' development of open-ended problem-solving abilities by exposing them to more open-ended problems over longer periods of time. This could determine whether students become more proficient problem-solvers with more experience. Students' ability to develop higher order cognitive skills over longer periods of time can be compared to their cognitive abilities such as M-capacity and disembedding ability. Statistical analysis could identify any correlations between the long-term acquisition of advanced problem-solving skills and the cognitive factors of M-capacity and disembedding ability. Such an investigation could determine whether students with low M-capacities and disembedding abilities could overcome these cognitive limitations and become successful problem-solvers.

Before participating in activities involving open-ended problem-solving, students could be informed of the particular skills that will be required of them if they are to become successful problem-solvers. Their demonstration of these skills should be rewarded in assessments and they should be informed of this. Students could be given examples of successful and unsuccessful approaches to problem-solving with key aspects of the process highlighted. An illustration of how and when these skills will be useful may also provide a greater motivation to engage with problem-solving activities. Techniques such as fading and pre-learning could also be employed to assess their effect upon skills development. The effect of these techniques upon performance could also be compared to the cognitive abilities.

The use of context aimed at promoting interest in and engagement with the learning material, in this research, was a success, with the exception of the problem using a cricket related context. Therefore, the selection and use of appropriate contexts need to be given significant consideration. Knowledge of students' interests may be useful in selecting appropriate contexts. Contexts that more closely relate to the applications of the scientific content and concepts involved in a particular topic may be effective. Linking topics of study to the career opportunities within these areas may also engage and motivate students.

Further investigation of group work could assess whether students working together in groups of mixed abilities can lead to increased success in problem-solving. Student data such as: M-capacity; field dependence; expert, transitional and novice problem-solvers could be gathered and any relationships between them identified. Students participating in group work could then be arranged so as to have an even mix of abilities within each group. Group problem-solving ability could then be investigated with respect to a particular ability. These activities could also reveal whether more able students can influence less able students and help them develop or enhance their abilities.

Group problem-solving involves the use of communication skills to a greater extent than independent learning activities. Assessments could be developed that reward these skills that could, in turn, lead to students realising the value of group work and the skills that can be developed as a result of group problem-solving activities. Students may also benefit from seeing that problem-solving may be more successful as a result of working in groups.

Curricula and courses should be designed that aim to develop and reward more than just algorithmic problem-solving skills. It is clear from this work that algorithmic problem-solving activities develop and assess only lower order cognitive skills. Complex open-ended problem-solving activities could be embedded in curricula in order to develop and reward higher order cognitive skills and promote the development of the kind of transferrable skills that graduate employers seek.

Finally, it appears that the extent to which educational research has informed and/or reformed teaching practice is small. There are large numbers of publications reporting the findings of research, giving theoretical explanations for these findings and suggesting the implications of these findings for educational practice. There is, however, much less evidence that the research has been used to inform practice and that educational practice has benefited from the wealth of research. Some reasons for this may be that:

- Some educators are simply not aware of much of the educational research being undertaken.
- The language used within educational research publications may be significantly different from the language used in publications that educators are more familiar with.
- Educators may often develop their teaching philosophy based upon their own experiences of education rather than based upon evidence from educational research publications.

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Appendix 1: The open-ended problems

1. Andrew "Freddie" Flintoff loves cricket, he also loves curry and once again he will be able to indulge both passions on his return to the subcontinent for England's tour of India.

Freddie's Career Stats:

5-Day Test Matches:

Batting: Average 50 runs per match

Bowling: Average 30 overs per match

One Day Internationals:

Batting: Average 35 runs per match

Bowling: Average 10 overs per match

Use the following data to calculate how much curry Freddie will need to eat to provide with him the energy he needs to get through a test match and a one day game.

Energy required

Basal metabolic rate:

Amount of energy which is required to maintain all body functions at rest (relatively constant)

kJ/day = body weight [kg] $\times$100

+

Performance:

Amount of energy which is required for all additional "efforts" (very variable)

Additional energy consumption of different types of sport	
Endurance sport (e.g. distance running)	1600 — 2100 kJ/hour
Heavy athletic endurance sport (e g cycling)	2000 — 3200 kJ/hour
Games (e.g. soccer)	1400 — 2400 kJ/hour
Speed sport (e.g. track-and-field sports)	1200 — 1700 kJ/hour
Combatant sport (e.g. boxing)	1200 —1700 kJ/hour
Heavy athletic sport (e.g. weight lifting. body building)	1000 —1600 kJ/hour

Energy content of nutrients

1g carbohydrates	16kJ
1g fat	36kJ
1g protein	16kJ
1g alcohol	28kJ

Curry Nutritional Data: ***Chicken Jalfrezi with rice***

Typical values	Per 600g serving	Per 100g
Protein	33.2g	5.5g
Carbohydrate	86.0g	14.3g
(of which sugars)	(11.9g)	(2.0g)
Fat	19.8g	3.3g
(of which saturates)	(5.7g)	(0.9g)

2. On his return to England Freddie will be wanting to spent some quality time at home with his family. His wife will no doubt have the freezer well stocked with curries. How much energy would be required to heat a frozen curry?
3. Flatulence from sheep, cows and other farm animals accounts for around 20% of global methane emissions. The gas is a potent source of global warming because, volume for volume, it traps 23 times as much heat as the more plentiful carbon dioxide. A single cow can produce about 600 litres of methane per day. Scientists are currently researching the use of foodstuffs and vaccines that reduce the amount of methane produced in cow's stomachs. If, however, the methane produced by cows could be captured and used, how many cows would you need to generate enough methane to heat a house in winter?
4. You've been on Who Wants To Be a Millionaire and won £64,000. You decide to treat yourself and some mates to a holiday in America. The flight from Heathrow to New York is 7 hours. To provide breathable air on an aircraft recirculation cells containing KO_2 are used. Potassium dioxide reacts with the exhaled carbon dioxide as follows:

$$4KO_2 + 2CO_2 \rightarrow 2K_2CO_3 + 3O_2$$

$$K_2CO_3 + CO_2 + H_2O \rightarrow 2\ KHCO_3$$

What mass of KO_2 would be needed on a Boeing 747 for this flight?

5. The rivers and oceans contain levels of dissolved gold of between 5 and 50 ppt. Extraction of gold from seawater has been seriously considered many times. Approximately how many kg of gold are present in the world oceans.
6. Many commercial hair restorers claim to stimulate hair growth. If human hair is composed mainly of the protein a-keratin, estimate the rate of incorporation of amino acid units per follicle per second.
7. On November 13 2005 an explosion at a chemical plant in Jilin City in north eastern

China released 100 tonnes of benzene and nitrobenzene into the Songhua River. Two weeks later, nearly 700 miles downstream, the spill flowed into the Amur River flowing through the Russian city of Khabarovsk. The Chinese and Russian authorities used activated carbon in water treatment facilities to stop the contaminants getting into the municipal water supplies. Quantities of carbon were also dumped in the river. Below is a table giving the specifications of activated carbon typically used for water treatment. What mass of activated carbon would be required to completely eliminate the pollutants from the water in the affected areas?

Grade	***Filtracarb FY5***	***Filtracarb CC65/1240***
Type	Granular	Granular
Surface area BETN$_2$(m^2/g)	1150	1050
CTC (%)	55	65
Bulk density (g/cm^3)	0.49	0.45
Hardness (%)	99	90
Iodine n° (mg/g)	1100	1050

8. A soccer club believes they may gain an advantage from pumping the ball up with helium rather than air (compensating for the mass difference using a thicker lining).
    - Are there any advantages?
    - How could this practice be detected by the match referee?
    - How much would this cost the cheating team in a season?
9. Out hiking on a clear dark night I find that I can just make out a single bulb LED torch at a distance of 1 mile. Estimate the quantum efficiency of the rod cells in the human retina.
10. Research chemists want to produce nanoparticles on an oxide surface for catalysis. Their landlady gave the research team her Krugerrand. How many nanoparticles can the team produce?
11. Stoke-on-Trent wants to reduce its CO_2 emissions by 5%. How many fewer car journeys are needed?

12. How many oxygen atoms are there in a cup of tea and how many are there in the room?
13. Taxol is obtained from Yew trees. It can be extracted from Yew tree clippings and Harpenden cemetery has reported how they are contributing to cancer treatment. A dose of 1mg of taxol when given to a rat is an effective dose and is cleared from the blood in 3 hours. How many yew trees are needed for a daily oral dose in humans?
14. It is 2050 and the oil has run out. What is the maximum number of cars the UK could support by domestically produced bioethanol?

Table 1: *Crop yields per hectare*

15. Fuzzy Pharmaceuticals

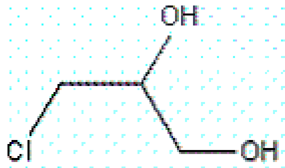
    We are looking to appoint an experienced synthetic chemist to run our new combinatorial chemistry laboratory. As part of a team you will be required to oversee product development from bench testing up to clinical trials. You will be required to liaise with our sister companies in Japan and USA.

    From the following three CVs only (no interview) award the available post.

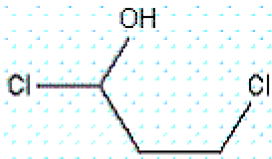
A.	B.	C.
26 yrs old	22 yrs old	32 yrs old
Biochemistry PhD Cambridge	BSc (Hons) Pharm. Chem.	BSc (Hons) Pharm. Chem. York
1 yr Post Doc Yale	1yr Astra Zeneca	10 yrs bioinorganic chemistry research
Chess	Japanese (English 2nd Language)	No Japanese

16. Worked Example Question: Chloropropanols have been detected in many foodstuffs including soy sauce, acid-hydrolysed vegetable protein (acid-HVP) and many other flavourings. 3-Monochloropropane-1,2-diol (3-MCPD) and 1,3-Dichloropropane-1-ol (1,3-DCP) are the most commonly formed chloropropanols and have been classified as genotoxic carcinogens. They are often formed during the manufacturing processes of these foods. Analyses are performed to detect the levels of these

contaminants with a reporting limit of as little as 0.05 mg/kg (5ppb). Naturally food manufacturers want to reduce the levels of these contaminants and if at all possible eliminate them altogether. Analytical chemists have been tasked with the job of finding precursors to the chloropropanols and the conditions required to form the chloropropanols during the manufacturing process. Produce a brief project plan or strategy to tackle this problem.



3-monochloropropane-1,2-diol



1.3-dichloropropanol

- Decide what precursors may be:
    - Presence of chemicals with a propane backbone in ingredients?
    - Hydrolysis process may provide -OH group?
- Source of chlorine:
    - Acid hydrolysis- acid used HCl?
    - Presence of NaCl in ingredients?
- Analysis of raw ingredients and process samples for precursors.
- Manipulate the manufacturing conditions to minimize the production of harmful contaminants.
- This is a real problem and the presence of chloropropanols in food, particularly soy sauce, has made national and international headlines.
- HCl and NaCl are being investigated as the sources of chlorine in the chloropropanols.
- The propane back bone is thought to be present in the form of glycerol or glycerides.
- Work has been done on identifying the presence of these precursors in foods and ingredients before processing and on varying the manufacturing conditions such as time and temperature.

17. Authentication of foods.

Some unscrupulous food producers often adulterate products or claim certain products are from a different region than they actually are.

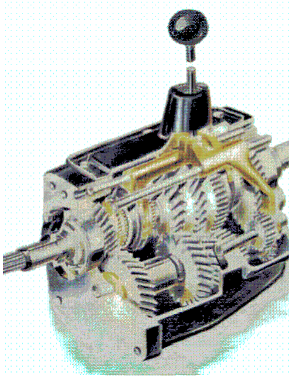
Adulteration of orange juice: High quality Californian orange juice is often mixed with an inferior orange juice or beet sugar to increase volume. It is however sold as authentic Californian orange juice. Greater profits are made by adulterating the juice. How would you go about detecting this adulteration?

18. Packaging Migration:

Phthalates are a group of chemicals called phthalic acid diesters. They have a variety of industrial uses and are found in lubricating oils and a wide range of household and consumer goods. In food packaging, phthalate use is limited, mainly to the manufacture of materials such as adhesives and some printing inks. Phthalates are also a medium that carries other substances that perfume cosmetics. They are used in children's toys, intravenous blood bags and other medical equipment, some paints and inks and vinyl flooring. Phthalates take a long time to degrade, or break down, in the environment. This means that they may be found at low levels in some foods. In animal studies, phthalates have been found to affect the liver, but this is not thought to be a risk for humans at the levels of phthalates that we might consume in food. In recent years, there also has been some concern that phthalates may have a harmful effect on human reproductive development, because they have been reported to be endocrine disrupters. The adhesives and ink used in the packaging of Gangster's pasties, slices, pies, savouries, bakes, sandwiches and wraps contains phthalates. Some of the phthalates are believed to migrate from the packaging into the food. Design an experiment which will test the levels of phthalates in the packaging material and how much of these phthalates will migrate onto the pasties, slices, pies, savouries, bakes, sandwiches and wraps.

19. Gearbox failure:

Mechanics for a rally car team are experiencing frequent gearbox failures of oil filled gearboxes during track testing. There appears to be no evidence of gross mechanical failure and they have asked you to investigate. How do you go about finding the cause of failure?



20. Contamination of cargo:

A shipment of Austrian Pumpkin Seed Oil arrives in the UK and upon inspection customs find suspended matter in a sample of the oil. You have been asked to ascertain the nature and origin of the foreign matter. How do you proceed?

Appendix 2: Worked problems

1. *Andrew "Freddie" Flintoff loves cricket, he also loves* curry and once again he will *be* able to indulge both passions on his return to the subcontinent for England's tour of India.

Freddie's Career Stats:

5-Day Test Matches:

Batting: Average 50 runs per match

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One Day Internationals:

Batting: Average 35 runs per match

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Use the following data to calculate how much curry Freddie will need to eat to provide with him the energy he needs to get through a test match and a one day game.

Energy required Basal metabolic rate: Amount of energy which is required to maintain all body functions at rest (relatively constant) kJ/day = body weight [kg] $\times$100 + ***Performance:*** Amount of energy which is required for all additional "efforts" (very variable)

Additional energy consumption of different types of sport	
Endurance sport (e.g. distance running)	1600 — 2100 kJ/hour
Heavy athletic endurance sport (e g cycling)	2000 — 3200 kJ/hour
Games (e.g. soccer)	1400 — 2400 kJ/hour
Speed sport (e.g. track-and-field sports)	1200 — 1700 kJ/hour
Combatant sport (e.g. boxing)	1200 —1700 kJ/hour
Heavy athletic sport (e.g. weight lifting. body building)	1000 —1600 kJ/hour

Energy content of nutrients

1g carbohydrates	16kJ
1g fat	36kJ
1g protein	16kJ
1g alcohol	28kJ

Curry Nutritional Data: ***Chicken Jalfrezi with rice***

Typical values	Per 600g serving	per 100g
Protein	33.2g	5.5g
Carbohydrate	86.0g	14.3g
(of which sugars)	(11.9g)	(2.0g)
Fat	19.8g	3.3g
(of which saturates)	(5.7g)	(0.9g)

Steps for solution:

1. Energy is amount required for 5 + 1 = 6 days
2. ***Estimate*** Freddie's weight: He's 6'4". Probably weighs 100kgs
3. Basal metabolic rate BMR = 100 $\times$100 = 10000 kJ/day
4. ***Estimate*** performance: e.g.

Test Match; batting ≈ 2hrs; bowling ≈ 2hrs

ODI; batting ≈ 0.75hrs; bowling ≈ 0.66hrs

Total ≈ 5.5 hrs

5. Energy for Games ***(from table)*** = 1400 — 2400 kJ/hour
6. Energy from BMR = 10000 $\times$6 = 60000 kJ
7. Energy from performance = 6$\times$2400 = 14400 kJ
8. Total = 60000 kJ + 14400 kJ = 74400kJ
9. Energy from curry & rice/100g:

Protein = 5.5 $\times$16 = 88 kJ

Carbohydrate = 14.3 $\times$16 = 228.8 kJ

Fat = 3.3 $\times$36 = 118.8 kJ

Total = 435.6 kJ/100g = 2613.6 kJ per curry

10. $n_{curries} = \frac{\text{energy required}}{\text{energy per curry}} = \frac{74400}{2600} = 29$ *Curries*

2. On his return to England Freddie will be wanting to spent some quality time at home with his family. His wife will no doubt have the freezer well stocked with curries. How much energy would be required to heat a frozen curry?

Steps for solution:

12. ***Assume*** 600g of Curry.
13. ***Estimate*** amount of water in curry or ***assume*** 600g of ice.
14. ***Assume*** frozen curry at -18°C

15. ***Assume*** hot food needs to be ≈ 70°C

16. ***Need to know*** Specific Heat Capacity of ice = 2.02 kJ kg^{-1} K^{-1}

17. Energy for ΔT -18°C to 0°C = (2.02 × 18 × 0.6) = 22kJ

18. ***Need to know*** Specific Latent Heat of fusion of ice at 0 ºC, = 334 kJ kg^{-1}

19. Energy for fusion at 0°C = (334 × 0.6) = 200kJ

20. ***Need to know*** Specific Heat Capacity of Water = 4.1818 kJ kg^{-1} K^{-1} at 20°C

21. Energy for ΔT 0°C to 70°C = (4.1818 × 70 × 0.6) = 170 kJ

22. Total = 22 + 200 + 170 = 400kJ

3. Flatulence from sheep, cows and other farm animals accounts for around 20% of global methane emissions. The gas is a potent source of global warming because, volume for volume, it traps 23 times as much heat as the more plentiful carbon dioxide. A single cow can produce about 600 litres of methane per day. Scientists are currently researching the use of foodstuffs and vaccines that reduce the amount of methane produced in cow's stomachs. If, however, the methane produced by cows could be captured and used, how many cows would you need to generate enough methane to heat a house in winter?

Steps for solution:

1. 600L CH_4/cow/day.
2. ***Estimate*** temperature of water in central heating system when off. 15°C
3. ***Estimate*** temperature of water in central heating system when on. 60°C
4. ***Estimate*** amount of water in central heating system. 100L
5. ***Need to know*** Specific Heat Capacity of Water = 4.1818 kJ kg^{-1} K^{-1} at 20°C
6. Calculate energy required to heat water (S.H.C. × ΔT × m) = (4 × 45 × 100) = 18000kJ.
7. ***Estimate*** time taken to heat up = 2h
8. Calculate energy per hour at start up = 36000kJ

9. ***Estimate*** energy per hour for maintenance = 9000kJ/h

10. Calculate total energy in 24 hours = 130000 kJ/day

11. $CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l)$ $\Delta H = -882kJ\ mol^{-1}$

12. $\frac{\text{Total energy}}{\Delta H} = \frac{130000}{882}$ = 150 mol CH_4

13. Mol $CH_4 \times 24 = 15 \times 24$ = Vol CH_4 3500 L

14. $n_{cows} = \frac{\text{Vol } CH_4}{600} = \frac{3500}{600} = 6$ cows

4. You've been on Who Wants To Be a Millionaire and won £64,000. You decide to treat yourself and some mates to a holiday in America. The flight from Heathrow to New York is 7 hours. To provide breathable air on an aircraft recirculation cells containing KO_2 are used. Potassium dioxide reacts with the exhaled carbon dioxide as follows:

$$4KO_2 + 2CO_2 \rightarrow 2K_2CO_3 + 3O_2$$

$$K_2CO_3 + CO_2 + H_2O \rightarrow 2\ KHCO_3$$

What mass of KO_2 would be needed on a Boeing 747 for this flight?

Steps for solution:

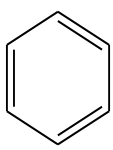
1. 7hr Flight. t = 420 min
2. ***Estimate*** No. of passengers on 747 $n_p \approx 400$
3. ***Estimate*** average human rate of respiration ≈ 12 and 20 times per minute
4. ***Estimate*** tidal volume of lungs ≈ 0.5L
5. ***Estimate*** average respiration rate of passengers $R_r \approx 4000Lmin^{-1}$
6. Total volume of CO_2 exhaled during flight = $4000 \times 420 \times 0.044$ = 7500 L
7. Mol CO_2 = $7500 \div 24$ = 3000 mol
8. Mol KO_2 = 4×3000 Mol CO_2
9. Mass KO_2 = 12000 Mol KO_2 $\times$RMM KO_2 (71) = 840kg

Composition of Air			
Component	**Symbol**	**Volume**	
Nitrogen	N_2	78.084%	99.998%
Oxygen	O_2	20.947%	
Argon	Ar	0.934%	
Carbon Dioxide	CO_2	0.033%	
Human Respiration The air that leaves a person's lungs during exhalation contains 14% oxygen and 4.4% carbon dioxide.			
Atmospheres with oxygen concentrations below 19.5 percent can have adverse physiological effects, and atmospheres with less than 16 percent oxygen can become life threatening.			

5. On November 13 2005 an explosion at a chemical plant in Jilin City in north eastern China released 100 tonnes of benzene and nitrobenzene into the Songhua River. Two weeks later, nearly 700 miles downstream, the spill flowed into the Amur River flowing through the Russian city of Khabarovsk. The Chinese and Russian authorities used activated carbon in water treatment facilities to stop the contaminants getting into the municipal water supplies. Quantities of carbon were also dumped in the river. Below is a table giving the specifications of activated carbon typically used for water treatment.

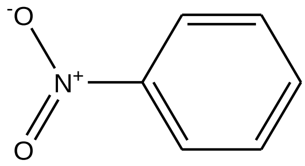
Grade	*Filtracarb FY5*	*Filtracarb CC65/1240*
Type	Granular	Granular
Surface area BETN_2(m^2/g)	1150	1050
CTC (%)	55	65
Bulk density (g/cm^3)	0.49	0.45
Hardness (%)	99	90
Iodine n° (mg/g)	1100	1050

What mass of activated carbon would be required to completely eliminate the pollutants from the water in the affected areas?



benzene
RMM 78

1. ***Recall*** structure of benzene.



nitrobenzene
RMM 123

2. ***Recall*** structure of nitrobenzene.
3. ***Estimate*** dimensions of benzene $s.a._{benzene}$ molecule
4. Calculate surface area of benzene $s.a._{benzene}$ molecule
5. ***Estimate*** dimensions of nitrobenzene $s.a._{nitrobenzene}$ molecule
6. Calculate size/surface area of nitrobenzene $s.a._{nitrobenzene}$ molecule
7. ***Recognize*** surface area is only useful spec for activated carbon. $S.A._c$
8. ***Assume*** a w/w ratio for benzene : nitrobenzene
9. $mol_{benzene} = M \div RMM_{benzene}$
10. $mol_{nitroenzene} = M \div RMM_{nitrobenzene}$
11. $n_{benzene} = mol_{benzene} \times N_A$
12. $n_{nitroenzene} = mol_{nitrobenzene} \times N_A$
13. $S.A._{benzene} = n_{benzene} \times s.a._{benzene}$
14. $S.A._{nitrobenzene} = n_{nitrobenzene} \times s.a._{nitrobenzene}$
15. $Mass_c = \dfrac{S.A._{benzene} + S.A._{nitrobenzene}}{S.A._c}$

6. Research chemists want to produce nanoparticles on an oxide surface for catalysis. Their landlady gave the research team her Krugerrand. How many nanoparticles can the team produce from the Krugerrand?
    1. A Krugerrand is a 1oz gold coin
    2. 30g Au
    3. RMM Au = 197 $gmol^{-1}$
    4. 30g/197 = 0.15 mol
    5. 1 nanoparticle is 1 x 10^{-9} m

6. 1×10^{-9} m = 10Å
7. 1 atom = 1-2 Å
8. 10 nanoparticles per Å
9. 0.15 mol x N_A(6×10^{23}) = 9×10^{22} atoms of Au
10. $9 \times 10^{22}/10$ = <u>9×10^{21} nanoparticles from 1 Krugerrand</u>

7. Taxol is obtained from Yew trees. It can be extracted from Yew tree clippings and is used in cancer treatment. A dose of 1mg of taxol when given to a rat is an effective dose and is cleared from the blood in 3 hours. How many yew trees are needed for a daily oral dose in humans?
   1. 1mg taxol in a rat for 3 hours
   2. Rat weighs 1kg
   3. Average human weighs 80kg
   4. 80mg taxol is effective human dose for 3 hours
   5. Concentration of taxol in yew tree clippings 0.05%
   6. Mass of clippings required is $\frac{80 \times 10^{-3}}{0.05} \times 100 = 160g$

8. How many oxygen atoms are there in a cup of tea?
   1. Assume only substance containing significant amounts of oxygen is water
   2. Average cup of tea contains 300ml
   3. 300ml H_2O
   4. RMM H_2O = 18 $gmol^{-1}$
   5. $\frac{300}{18} = 15$ mol H_2O
   6. 15 mol Oxygen
   7. 15 x N_A (6×10^{23}) = <u>9×10^{23} oxygen atoms per cup</u>

9. How many oxygen atoms are there in the room?
   1. Assume room empty or only significant amounts of oxygen are in air

2. Estimate room dimensions e.g. 3m x 5m x 10m

3. 150 m^3

4. 20% O_2 in air

5. $\therefore$ 30 m^3 O_2 = 30 x 10^3 dm^3

6. 1 mole of O_2 = 24 dm^3

7. $\frac{30 \text{ x } 103}{24} = 1250$ mol O_2

8. 1250 x 2 = 2500 mol Oxygen

9. 2.5 x 10^3 x 6 x 10^{23} = <u>1.5 x 10^{27} oxygen atoms in the room</u>

10. The rivers and oceans contain levels of dissolved gold of between 5 and 50 ppt. Extraction of gold from seawater has been seriously considered many times. Approximately how many kg of gold are present in the world's oceans?

1. ***Estimate*** circumference of earth ≈ 40 000 km
2. C = πd $\therefore$ $d = C/\pi = 40\ 000/\pi = 12\ 700$ km
3. ***Work out*** surface area of earth $A_{earth} = 4\pi r^2 = \pi d^2 = \pi(12\ 700)^2 = 5 \text{ x } 10^8$ km^2
4. ***Estimate*** % H_2O on earth's surface 30%
5. Calculate surface area of earth covered in water 5 x 10^8 x 0.3 = 1.5 x 10^8 km^2
6. ***Estimate*** average depth of H_2O on earth's surface ≈3 km
7. Calculate volume of H_2O on earth's surface Vol H_2O = 1.5 x 10^8 x 3 = 4.5 x 10^8 km^3
8. Calculate Vol H_2O 1 km^3 = 1x10^{12}L (dm^3)
9. 4.5 x 10^8 km^3 H_2O = 4.5 x 10^{20} dm^3 H_2O
10. $\therefore$ 4.5 x 10^{20} kg H_2O
11. [Au] = 5-50 ppt
12. ppt is 1 part in 1,000,000,000,000 = ng/kg
13. Calculate [Au] = 50 ng/kg
14. Mass Au (ng) = [Au] 50 ng/kg $\times$ 4.5 x 10^{20} kg H_2O

15. <u>23×10^6 kg Au</u>

11. Many commercial hair restorers claim to stimulate hair growth. If human hair is composed mainly of the protein α-keratin, estimate the rate of incorporation of amino acid units per follicle per second.

1. ***Estimate*** rate of growth of hair ≈ 1cm per month
2. ***Assume*** amino acid unit is cylindrical
3. ***Estimate*** length of amino acid unit ≈ 10 Å
4. ***Estimate*** diameter of amino acid unit ≈ 6 Å
5. Calculate volume of amino acid unit.

$V = \pi r^2 h = \pi \times (3 \times 10^{-10})^2 \times 10 \times 10^{-10} = 3 \times 10^{-28}\ m^3$

6. ***Estimate*** diameter of hair ≈ 1 μm
7. Calculate volume of 1cm of hair

$V = \pi r^2 h = \square \times (0.5 \times 10^{-6})^2 \times 1 \times 10^{-2} = 8 \times 10^{-15}\ m^3$

8. n_{amino} per month $= \dfrac{\text{volume of 1cm of hair}}{\text{volume of amino acid unit}} = \dfrac{8 \times 10^{-15}}{3 \times 10^{-28}} = 3 \times 10^{13}$

9. n_{amino} per second $= \dfrac{n_{amino}\ \text{per month}}{\text{No of seconds per month}} = \dfrac{3 \times 10^{13}}{3 \times 10^{6}} = \underline{1 \times 10^{7}}$

12. Authentication of foods.

Some unscrupulous food producers often adulterate products or claim certain products are from a different region than they actually are.

Adulteration of orange juice: High quality Californian orange juice is often mixed with an inferior orange juice or beet sugar to increase volume. It is however sold as authentic Californian orange juice. Greater profits are made by adulterating the juice. How would you go about detecting this adulteration?

Things to think about are:

- Differences between orange juice and beet sugar such as:

  - Composition e.g. types of saccharides
  - Geographical location, of authentic juice and adulterants

- Methods of analysis
- Choose method
- Obtain samples
- Analyse
- Interpret data
- *Methods used include:*
- *Analysis of Oligosaccharides by HPLC to detect addiction of beet sugar.*
- *Stable Isotope ration mass spectrometry (SIRMS) $^{18}0/^{16}0$, $^{13}C/^{12}0$, $^{2}H/^{1}H$ to confirm geographic origin.*
- *Profile analyses look for adulteration by differences in components such as, Amino acids, Sugars, Organic acids, Trace metals etc by HPLC and ICP-MS.*

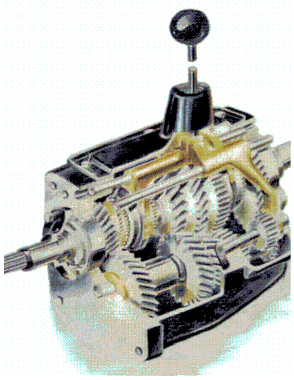
13. Packaging Migration

Phthalates are a group of chemicals called phthalic acid diesters. They have a variety of industrial uses and are found in lubricating oils and a wide range of household and consumer goods. In food packaging, phthalate use is limited, mainly to the manufacture of materials such as adhesives and some printing inks. Phthalates are also a medium that carries other substances that perfume cosmetics. They are used in children's toys, intravenous blood bags and other medical equipment, some paints and inks and vinyl flooring. Phthalates take a long time to degrade, or break down, in the environment. This means that they may be found at low levels in some foods. In animal studies, phthalates have been found to affect the liver, but this is not thought to be a risk for humans at the levels of phthalates that we might consume in food. In recent years, there also has been some concern that phthalates may have a harmful effect on human reproductive development, because they have been reported to be endocrine disrupters. The adhesives and inks used in the packaging of Gangster's pasties, slices, pies, savouries, bakes, sandwiches and wraps contains phthalates. Some of the phthalates are believed to migrate from the packaging into the food. Design an experiment which will test the levels of phthalates in the packaging material and how much of these phthalates will migrate onto the pasties, slices, pies, savouries, bakes, sandwiches and wraps.

- Migration may depend on many factors, temperature, light, age, moisture, shelf life of food, food matrix, type of film used in package.
- Need a method for analysis of phthalates.
- Need a method for extraction of phthalates from food matrix.
- Decide on main factors affecting migration, investigate the effect of varying these factors.
- Use something with similar matrix to test migration.
- Vary conditions. Perform extractions and analyses
- Gather experimental data and interpret, decide on further course of action.

14. Gearbox failure

Mechanics for a rally car team are experiencing frequent gearbox failures of oil filled gearboxes during track testing. There appears to be no evidence of gross mechanical failure and they have asked you to investigate. How do you go about finding the cause of failure?



- At first glance this will appear to be an engineering problem.
- Oil from gearbox could hold vital clues so don't discard.
- Drain oil.
- Look for particulates.
- Filter
- Surmise what particulates could be considering what the oil could have come into contact with
- Analyse samples.
- Decide from evidence where it came from.

15. Contamination of cargo:

A shipment of Austrian Pumpkin Seed Oil arrives in the UK and upon inspection customs find suspended matter in a sample of the oil. You have been asked to ascertain the nature and origin of the foreign matter. How do you proceed?

- Filter out solid matter. Organic/Inorganic?
- Decide on a method of analysis.
- Analyse it.
- Depending on what it is, trace back through supply chain.
- Who's handled it?
- What forms of transport has it used
- Who's packaged it?
- How is it processed?

Appendix 3: Digit Span Test Instructions

This is carried out in the following way:

(1) Give each student a sheet with spaces for writing down answers

Instruct them to write their names, matriculation numbers or some other identifier.

(2) Read them the following instructions:

"This is an unusual test. It will not count for your marks or grades in any way. We are trying to find out more about the way you can study and this test will give us useful information. You will not be identified in any way from it.

I am going to say some numbers. You must not write as I speak. When I stop speaking, you will be asked to write the numbers down the boxes on your sheet.

Are we ready? Let's begin.

(3) You say the numbers ***exactly at a rate of one per second*** (use a stop watch or heart beat to keep your time right). You allow the same number of seconds for the students to write down the answers. Thus, if you gave the numbers: 5,3,8,6,2. You give them five seconds for writing them down. I follow the procedure:

"5,3,8,6,2 - say: 'write' - five seconds allowed for writing, then, say: 'next'"

(4) Here are the numbers used by El Banna in his early work:

5	8	2				
6	9	4				
6	4	3	9			
7	2	8	6			
4	2	7	3	1		
7	5	8	3	6		
6	1	9	4	7	3	
3	9	2	4	8	7	
5	9	1	7	4	2	8

4	1	7	9	3	8	6		
5	9	1	9	2	6	4	7	
3	8	2	9	5	1	7	4	
2	7	5	8	6	2	5	8	4
7	1	3	9	4	2	5	6	8

(5) When this is finished,.....allow a short break and then....

You now give a second set of instructions.

"Now I am going to give you another set of numbers. However, there is an added complication! When I have finished saying the numbers, I want you to write them down in ***reverse*** order. For example, if I say "7,1,9", you write it down as "9,1,7".

Now, no cheating!! You must not write the numbers down backwards. You listen carefully, turn the numbers round in your head and then write them down normally.

Have you got this? Let's begin."

(6) Here are the numbers:

2	4					
5	8					
6	2	9				
4	1	5				
3	2	7	9			
4	9	6	8			
1	5	2	8	6		
6	1	8	4	3		
5	3	9	4	1	8	
7	2	4	8	5	6	
8	1	2	9	3	6	5

4	7	3	9	1	2	8	
9	4	3	7	6	2	5	8
7	2	8	1	9	6	5	3

(7) This is the version used for adults (those over 16).

(8) Marking: the main thing is to be consistent. Ideally, if a person achieves success at, say, 4,5,6 and 7 but fails at eight digits, then their working memory is 7. However, they can often fail an odd one (by simple slips) or succeed at one at, say, eight digits and fail at the other. I use the simple rule that, for a single failure followed by two correct answers, I ignore the failure. For those who fail at one and success at the other at one level, just be consistent: I would give them that level. Note also: check the number sequences above to check if any sequence of numbers has any pattern in your cultural setting (like a radio wavelength, a car registration code or whatever...)

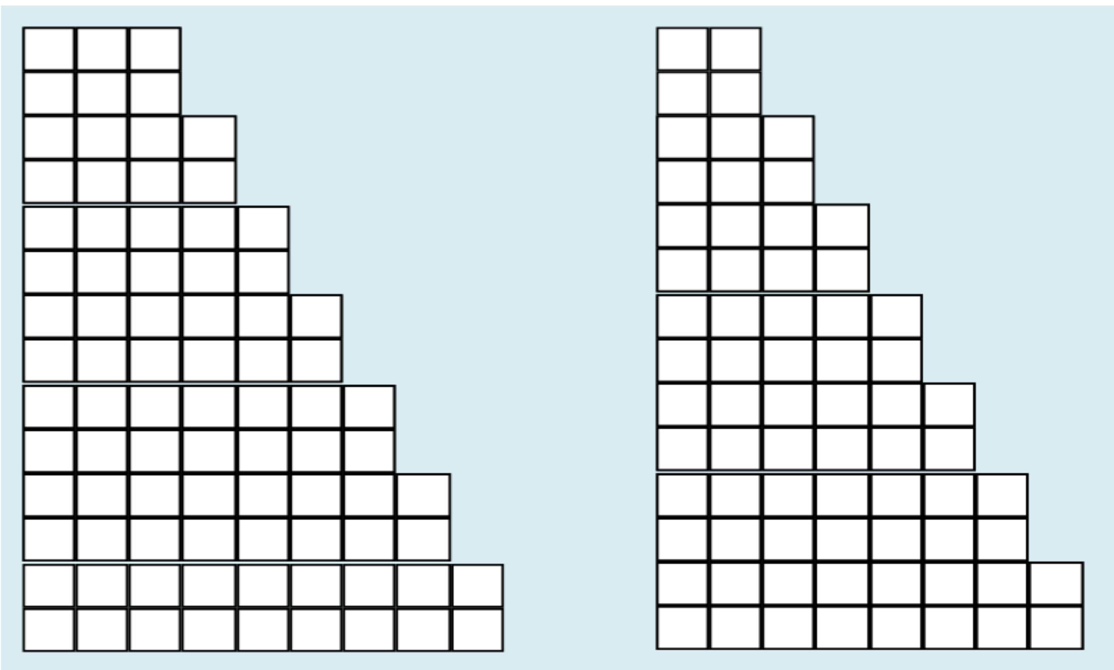
(9) The student answer sheet will look something like:

Student Answer Sheet

Your name: ....

Write the numbers in the boxes below

Digit Forwards **Digit Backwards Test**



Appendix 4: Attitude Questionnaire

Name:

Please answer the following questions by marking a box according to your preference.

The initials in each box correspond to: Strongly Agree, Agree, Neutral, Agree, Strongly Agree.

Questions 1-5 begin with, I find chemistry:							
1	Challenging	**SA**	**A**	**N**	**A**	**SA**	Easy
2	Varied	**SA**	**A**	**N**	**A**	**SA**	Repetitive
3	Interesting	**SA**	**A**	**N**	**A**	**SA**	Boring
4	Satisfying	**SA**	**A**	**N**	**A**	**SA**	Unsatisfying
5	Exciting	**SA**	**A**	**N**	**A**	**SA**	Tedious
Questions 6-16 about problem solving in chemistry:							
6	I am good at problem solving.	**SA**	**A**	**N**	**A**	**SA**	I am poor at problem solving.
7	I usually have enough time to complete a set problem.	**SA**	**A**	**N**	**A**	**SA**	I usually struggle to complete a set problem in time.
8	I have an effective strategy for tackling unfamiliar problems.	**SA**	**A**	**N**	**A**	**SA**	I have not found an effective strategy for tackling unfamiliar problems.
9	Open ended problems enhance my understanding of the subject.	**SA**	**A**	**N**	**A**	**SA**	Open ended problems don’t affect my understanding of the subject.
10	Problem solving is a useful skill to acquire.	**SA**	**A**	**N**	**A**	**SA**	Acquiring the skill of problem solving is a waste of time.
11	I find problem solving interesting.	**SA**	**A**	**N**	**A**	**SA**	I find problem solving tedious.
12	I find problem solving too demanding.	**SA**	**A**	**N**	**A**	**SA**	I find problem solving too easy.
13	It is important that chemistry problems relate to real life contexts.	**SA**	**A**	**N**	**A**	**SA**	There is no advantage in chemistry problems that relate to real life contexts.
14	I find chemistry problems that relate to real life contexts enjoyable.	**SA**	**A**	**N**	**A**	**SA**	I don’t find chemistry problems that relate to real life contexts enjoyable.
15	I find chemistry problems without real life contexts enjoyable.	**SA**	**A**	**N**	**A**	**SA**	I don’t find chemistry problems without real life contexts enjoyable.
16	It is useful to solve problems similar to those that are found in the workplace.	**SA**	**A**	**N**	**A**	**SA**	There is no advantage in solving problems similar to those that are found in the workplace.

Appendix 5: Responses to interview questions

Student 1

1. How did the problems compare to problems that you've done before on your course? *Tricky question. Very different, very much open-ended problems. Like we kept getting told "there's no right or wrong answer."*
2. Did you find them more or less challenging than conventional problems? *More challenging, more interesting as well.* Why? *You had to look at different ways to solve the problem. You get a normal chemistry problem and you use an equation to solve it or something like that. Different ways you had to think about doing it.*
3. Did you find them more or less enjoyable than conventional problems? *Oh yeah they were fun, they were definitely fun.* Why? *The group problems we got to, say argue, we weren't really arguing but decide which was the best route to take to solve the problem.*
4. In groups, how did you go about tackling a difficult problem? *Which was the worst one? The worst one I think we found was No. 5. We spent quite a while on this one trying to figure out different ways of solving it. It took a while, we went through several methods which we could use and discounted all of them basically.* Did you have a starting point? *With that one which was pretty tough there wasn't really any definite starting point.*
5. Was it more or less challenging tackling them individually compared to in a group? *The individual problem was less challenging.* Why? *It was quite an easy one to figure out.* If you tackled the harder problem do you think working on your own would be easier? *It kind of depends who you're working with really. If you've got a good group and they put some good ideas forward then it can make it easier but if everybody's always conflicting it makes it tougher to solve.*
6. What skills do you think these problems help you develop? *Listening to others in*

your group, that was a big thing. Skills, I hate that word. I'm useless at English I can never think how to word things. Problem solving skills, looking at different ways to approach the problem.

7. Would these skills be useful in your future career? *I suppose so yeah, I might come across some problem one day*
8. Would you be prepared to have a go at more problems to help us with this research? E.g. on blackboard *Yes, they're great fun*

Student 2

1. How did the problems compare to problems that you've done before on your course? *You can probably know the answer or the range of the answer. Unpredictable. You can get all sorts of results.* Anything else you found different? *Quite interesting. You use your knowledge to apply to real life.*
2. Did you find them more or less challenging than conventional problems? Why? *Different types, you can think about anything, during a lecture you've got a particular direction to learn the things or something.* Would you say it was more challenging as you said because there wasn't a right answer, you didn't really know what you was working to? *More challenging cos it's different.*
3. Did you find them more or less enjoyable than conventional problems? Why? *More enjoyable. I like enjoying thinking about things. Rather than manual work or listening.*
4. In groups, how did you go about tackling a difficult problem? *For me, I give myself a little time, say three minutes to think about the question first. Then discuss with the group.* How did you then go about it? Did you have a starting point? Did you just put ideas in? *I think we all put ideas in and give a little bit of extra information to help each other.*
5. Was it more or less challenging tackling them individually compared to in a

group? *I like to do individual.* Why? *I've got more time to think about it. I don't have to know the answer before I think through. Sometimes when I discuss with other people if they think too fast to compare with them.*

6. What skills do you think these problems help you develop? *Communication skills, gave me some more confidence.* Confidence about team working and your own knowledge? *Yes and also speaking English*
7. Would these skills be useful in your future career? *Yes, definitely.* Why? *We are learning all the chemistry it's for the future, for example for the company to do all the group things, if they come they give you a problem you have to solve it.*
8. Would you be prepared to have a go at more problems to help us with this research? E.g. on blackboard. *Yes*

Student 3

1. How did the problems compare to problems that you've done before on your course? *Harder than previous ones. First time doing the group thing, really enjoyed it. Good to get help from other group members.*
2. Did you find them more or less challenging than conventional problems? Why? *More challenging, not simple question. A range of different things to analyse. No single right answer. Made you think more.*
3. Did you find them more or less enjoyable than conventional problems? *Yes. I couldn't answer all of them but they were good.* Why? *Exploring a range of answers and knowledge of chemistry.*
4. In groups, how did you go about tackling a difficult problem? *I'm not English so it wasn't easy for me explaining what I want to say because before I had to think. But it helped when my fellow students work together and let me think about it and explain what I wanted to say easily.*
5. Was it more or less challenging tackling them individually compared to in a

group? Why? *I think for me the individual one was more challenging. I enjoyed it, especially the group ones. I really liked the group ones.*

6. What skills do you think these problems help you develop? *Thinking skills and how to work out, not just a solution but a possible way to arrive at a solution.*
7. Would these skills be useful in your future career? *In a certain sense yeah, it can help you sometimes, let's say in an interview, they say a question to you, help you to find a way, even if you don't know the answer to give a good estimation and say something about it not just work around the question at least say something about it.*
8. Would you be prepared to have a go at more problems to help us with this research? *Yeah, why not.*

Student 4

1. How did the problems compare to problems that you've done before on your course? *Harder. In 1^{st} yr follows a set method. These problems meant you first had to decide what to do. More grounded in reality.*
2. Did you find them more or less challenging than conventional problems? Why? *More challenging, had to find a method. Probably in line with being a 2^{nd} year.*
3. Did you find them more or less enjoyable than conventional problems? Why? *More. Personally prefer more abstract problems. Like context-based problems.*
4. In groups, how did you go about tackling a difficult problem? *One or two would start to solve problems, others would chip in ideas (some would not). No attempt to agree on a method first.*
5. Was it more or less challenging tackling them individually compared to in a group? Why? *More challenging individually. Tend to doubt yourself when alone. No-one to bounce ideas off. Realised how useful it was to be in a group.*
6. What skills do you think these problems help you develop? *Encourage others to*

participate. Application of theory to real world problems. To ask for help.

7. Would these skills be useful in your future career? *Yes. I plan to work in chemical industry. Probably skills that would be useful anywhere.*
8. Would you be prepared to have a go at more problems to help us with this research? E.g. on blackboard *Yes. But though feedback on blackboard sounds ok, wouldn't the problems on blackboard mean that some would just look things up? Isn't the idea to "think on your feet"?*

Student 5

1. How did the problems compare to problems that you've done before on your course? *"Different". Didn't have all the information. Had to use estimation. Range of possible results but none of them necessarily wrong. Less pressure because there was more than one correct answer, you just had to be "in the ball park". Less information meant you had to work harder to choose a method.*
2. Did you find them more or less challenging than conventional problems? Why? *More challenging, had to think about what method to use instead of just using the method given. Had to use brain "in a better way".*
3. Did you find them more or less enjoyable than conventional problems? Why? *More. "different" "more exciting" Not another standard problem can relate it to life, something you would see around you. Better to have questions in context.*
4. In groups, how did you go about tackling a difficult problem? *Went through question together. Explain to those who didn't understand question. Suggested method they favoured individually. Agreed on one method then followed it.*
5. Was it more or less challenging tackling them individually compared to in a group? Why? *More challenging individually. Others offer other viewpoints. Can help each other. Have doubts if you are working alone. Can get information from others. Doing group questions helped doing a question alone.*

6. What skills do you think these problems help you develop? *Communication. Team work. Considering other points of view. Better preparation for real life.*
7. Would these skills be useful in your future career? *Yes. I plan to remain in chemistry research.*
8. Would you be prepared to have a go at more problems to help us with this research? E.g. on blackboard *Yes. Enjoyed whole experience. Exercised mind.*

Student 6

1. How did the problems compare to problems that you've done before on your course? *We had to actually think about. It involved knowledge of our chemistry background. Encouraged teamwork, I really enjoyed them to be honest. I thought they were a lot better.*
2. Did you find them more or less challenging than conventional problems? Why? *More, it made you think outside of the box. In a team of four we wouldn't have been able to do it without that team of four. Everyone had their own little snippets of ideas to chuck into the equation. We got one really well done it was the one about the Krugerrand. One person knew what a Krugerrand was. One person knew the weight of a Krugerrand. And we could work it out from there. From a sentence we could work out the amount of gold nanoparticles you could get from a Krugerrand.*
3. Did you find them more or less enjoyable than conventional problems? Why? *More. Because it made you think. It wasn't the normal boring, "here's some problems go ahead and solve them" type exercise it actually made you think got you stimulated.*
4. In groups, how did you go about tackling a difficult problem? *First off we found somewhere to start then brainstormed for the first part of the time limit. Second part we actually got down to solving the problem the best we could.* How did you

find your starting point? Group decision or did somebody just offer something? *Generally somebody just offered something and kick-started us and the rest just built from that knowledge.* Did you find it was the same person each time? *Usually two of four.*

5. Was it more or less challenging tackling them individually compared to in a group? Why? *More challenging individually. Didn't have the input from the rest of the group. Four heads are better than one, you know.* Did you go about the individual ones a different way? *Once again you had to revert to your chemistry knowledge which was good. But it was a bit hard trying to blow the cobwebs away from last year. I know it's in there somewhere.*
6. What skills do you think these problems help you develop? *Team building. Using your initiative. Basic chemical knowledge.*
7. Would these skills be useful in your future career? *Depends what my future careers was. In something like management I assume it would, definitely.* Why do you think for management? *Brainstorming sort of ideas you have to do in management I suppose and working in a team yeah.*
8. Would you be prepared to have a go at more problems to help us with this research? E.g. on blackboard. *Yeah, I found it very enjoyable.*

Appendix 6: Observations and notes from the qualitative study of approaches to open-ended problem-solving

Student A

Curry

From script

- Mainly microwave based

From recording

- Microwave
- Estimates time, allows for defrost
- Estimates wattage
- Oven time, gas mark, cost per unit
- Focus on cost of energy
- Assumes 100W = 6kJ/h
- All context focused
- Unwilling to get to grips with the problem
- Avoiding the science and maths

Student B

Curry

From script

- E = Watts x time
- Thrown by open-ended nature of problem
- Also lack of data and method

From recording

- Microwave
- Difficulty interpreting question
- Not sure how to start

- Microwave energy in watts
- Distracted by microwave settings
- Asks for formula for energy from watts
- Doesn’t know what a Watt is
- Looks for help
- Gives up
- Heat = energy when prompted
- Dismisses problem as physics
- Phased by lack of data, lack of formula
- Lack of data prevents her from having a go
- Chooses some data after prompting and then uses it
- Guesses units

<u>Hair</u>

From script

- Rate of growth

From recording

- Clarifies question ok
- Trouble estimating rate of hair growth
- Prompted to draw amino acid
- Discusses structures of proteins/strands/stacking
- Knew some amino-acid chemistry, α-helix
- Bogged down with detail of protein chain
- Wants more info/data/numbers
- Needed prompting often
- Gets nowhere

River

From script

- Not distracted by context or data
- Totally chemical approach

From recording

- Picks out surface area – not sure why – rejects it
- Goes to benzene & carbon "reaction"
- Assumes chemical reaction
- Gets nowhere

Student C:

Curry

From script

- Starts with microwave energy
- Switches to specific heat capacity
- Logical approach
- Misses mass from the equation but knows he needs it

From recording

- Microwave energy x time
- Identifies the need for information about microwave specifications
- Knows what data he needs
- New strategy: Switches to energy needed
- Identifies mass and temperature change
- Struggles to remember equation
- Realises that energy is proportional to SHC
- Works out SHC is energy per unit of mass per degree through logic
- Realises SHC of ice is different and estimates that

- Developed and equation, through reasoning, to work out the answer

Hair

From script

- Worked in length rather than volume
- Some trouble with unit conversion
- Some trouble with assumption but v. happy once numbers generated

From recording

- Doesn't understand question straight away
- Tries to clarify question
- Doesn't want to do the problem
- Possible language barrier
- Estimates rate of hair growth
- Assumes linear protein structure
- Reasons out amino acid structure
- Sensible estimates of size of amino acid unit
- Not put off by context – needed a bit of prompting with amino acids
- Developed/drew model
- Stuck on assumptions & conceptual knowledge but good with maths

River

From script

- Context only approach

From recording

- Evaluate data in table
- Surface area of river – context
- Some logical reasoning
- Context focused solution

Student D:

<u>Curry</u>

From script

- Energy of microwaves
- $E = hc/\lambda$
- Assumed 1 photon per molecule

From recording

- Took long time to get started
- Focus on heating time
- Long gaps/silence
- Thought about energy use during working day
- Can't identify what she needs to know
- Trouble getting started

<u>Hair</u>

From script

- Poor assumptions – context based

From recording

- Can't get started
- Doesn't understand question
- Assumes hair composed of α-keratin
- Assumes mass of one strand of hair
- Uses 5g hair
- Some poor assumptions/distracted by context
- Gets nowhere without prodding

Student E:

<u>Curry</u>

From script

- Identified data needed e.g. microwaves, SHC
- Calculates using SHC for 20 moles water
- Not quite right on units

From recording

- Microwave, wavelength, heating water only, temperature change
- SHC water
- Good estimation of moles of water
- Brings in concept of calories and relates to SHC, good reasoning
- Uses moles rather than grams
- Final units wrong
- Methodical/logical
- No mention of context

<u>Hair</u>

From script

- Rate constants for formation of hair
- Can't get past context, lack of prior knowledge
- Distracted by terminology

From recording

- Wants to know what keratin is
- Difficulty stating rate = rate equations/constants
- Focus on hair restorer – context
- Can't get started, can't get past keratin and rate constants for reactions
- Distracted by context
- Looked at phys chemistry first
- Distracted by wording

- Distracted prior knowledge

River

From script

- N/A

From recording

- Chooses C to use least amount – logical
- Check whether "real" scenario
- Calculates surface area of river & divides by surface area of charcoal
- Distracted by context but logical approach
- Got some numbers to work with?
- Decided on using carbon with smaller surface area as it will use less
- Logical but distracted by context

Student F:

Curry

From script

- Remembered mass from a packet
- Focus on energy input
- Uses SHC

From recording

- Uses SHC
- Energy needed over time
- Estimates SHC of water
- Includes time in equation
- Focus on heating up food
- Thinks about units
- Needed some prompting

Hair

From script

- Assumptions; hair growth, area/volume of hair, vol of protein
- Good approach

From recording

- Assume just protein
- How long to grow a length & how much amino acid in that volume
- Clear strategy/logical/structured
- Happy to make sensible estimations
- Considers variables
- Confident about how to do it

Student G:

Curry

From script

- Calculated water content
- Used water content for calc
- SHC

From recording

- Based on water
- Estimated water content
- Remembered SHC of water
- Calculated heat from -5 > 0°C then 0 > 50°C
- Worked answer out per gram
- Correct units

Hair

From script

- Trouble getting started
- Worries about lack of prior knowledge

From recording

- Clarifies problem
- No prior knowledge
- Assumed structure of amino acid – model
- Rate of hair growth
- Makes sensible assumptions about size
- Started to develop strategy
- after slow start used models & assumptions
- logical
- good estimations

<u>River</u>

From script

- Correct strategy
- Adsorption to activated carbon
- Didn’t get distracted by other data
- Linked benzene & carbon & coverage

From recording

- Links benzene to activated carbon
- Sensible assumptions
- Identifies adsorption to C
- Surface area
- logical

Student H:

<u>Curry</u>

From script

- Latent heat of fusion and evaporation
- Energy proportional to heat

From recording

- Look at pack for minutes in microwave
- Use wattage x time = energy to heat the curry
- Looked from point of view of cooking
- Distracted by rice, didn't know if it would be needed to calculate rice separately.
- Didn't realise watt is related to energy
- Assumes curry is equal to water
- Assumes all curries are different
- Use water as a model, heat for 1 min, measure ΔT
- Realises this will be inaccurate
- Tries to remove inaccuracy, resample, water content of curry, use standard, blank, repeats
- Developed scientific method for experiment
- Can't get from ΔT to energy
- Not keen to put numbers in
- Not comfortable with estimates & assumptions
- Stuck on context
- Developed method
- Approached scientifically but less structured

<u>Hair</u>

From script

- no attempt to calculate answer
- proposed MS-HALDI

- stayed in comfort zone

From recording

- stayed in comfort zone
- proposes MS to analyse amino acids
- distracted by context
- describes keratin, helix
- distracted by hair product
- distracted by sampling
- develops over complex sampling method
- wants to devise an experiment
- focus on validity of experiment
- focus on physically measuring amino acid molecules
- bogged down with identity of amino acids
- not comfortable making estimates or doing anything without data
- chose new method when prompted to estimate

<u>River</u>

From script

- uses surface area
- distracted context and data
- unwilling to commit because of lack of data

From recording

- straight into calculating no of moles of carbon in benzene
- interested in context
- distracted by data
- distracted by properties of carbon

- not linking carbon with spill
- draws on prior knowledge of activated carbon and reasons how it might work
- distracted again by data
- out of comfort zone
- no risk taking
- distracted by carbon chemistry
- reasoning through a bit
- reflection “I’ve a feeling we’ve been doing this wrong
- likes comfort zone
- Context
- Prior knowledge

Student I:

Curry

From script

- Defined problem in terms of oven/cooking
- Estimated oven capacity, cooking temp

From recording

- Defined walking to freezer, reading label
- Acting off, how, when
- How long to cook, how large
- Need to know – instructions, size, temperature to eat/cook, capacity of oven, time
- Don’t know – defrost?, equipment, implements
- Heat 1g over 1 hour
- How many joules
- Bond energy = 45kJ

- Microwave attacks water
- Latent heat of melting – to defrost curry 500kJ/g water
- 150 000kJ/curry to defrost – accepts answer as ok
- Temp connected to time
- Assume defrost energy same as cooking energy
- Writes down info he knows/doesn't know rather than try to understand problem.
- Defined problem in terms of context
- looking all at context first →then scientific

Hair

From script

- problems with context, prior knowledge, estimations macro→micro

From recording

- doesn't understand question
- states prior knowledge
- restates problem with focus on context gets to problem statement
- length time of hair growth
- wants composition of hair
- focus on restorer – context
- can't link hair growth with amino acid production
- knows what he has difficulty with
- knows what he wants to know
- finds it difficult to commit to estimates
- can't put it all together
- reflective
- won't commit himself

- can't go from macro →micro
- Distracted by context at first
- Then decides to look at hair growth ∞ rate of amino acid incorporation
- Has strategy but unsure about estimations
- Reflective, knows what he's struggling with
- Struggling making estimations
- Trying to apply what he knows to this problem

River

From script

- N/A

From recording

- Difficulty defining problem
- Troubled by table of data
- Assumes chemical reaction
- Doesn't know what activated carbon is
- Logical ideas about solution to problem
- Looking at it as organic problem
- Context
- prior knowledge

Student J:

Curry

From script

- Defined problem in terms of SHC
- Made sensible estimations
- Identified equation
- Estimated data to put in

From recording

- Temp of freezer
- Temp to eat
- ΔT converts to Kelvin
- Estimate volume of curry – more difficult
- Specific heat
- Knows equation, understands it
- Sensible estimation of SHC based on water
- Correct units
- Reflects on quality of answer
- Defines problem in terms of science

<u>Hair</u>

From script

- Sensible estimations for cm/s
- context

From recording

- solid start, estimate hair growth
- limited by poor knowledge of chemistry
- uses model of amino acid as a sphere
- calculates area and volume of spheres
- good estimate of size of amino acid
- some problems converting: m, cm, nm
- reflects on value obtained for no of molecules
- good strategy but uses area rather than volume
- logical, successful, good estimations

<u>River</u>

From script

- N/A

From recording

- Clarifies problem
- Data doesn’t help him at outset
- Assuming chemical reaction
- Thrown by data table
- Knows some organic chemistry
- Assuming chemical reaction
- Draws organic reaction
- nowhere

Student K:

- made estimations
- used appropriate equations
- understand concepts
- sensible approach
- small problem with unit
- mental arithmetic
- good strategy
- not put off by lack of knowledge

Student L:

- defines the problem
- makes estimates
- good strategy
- mental arithmetic

- distracted by context due to lack of knowledge

Student M:

- struggling
- focus on microwave – context
- looking for equations & known method rather than developing a strategy
- inconsistent
- focus on prior knowledge
- not estimations
- distracted by prior knowledge
- tried to identify unnecessary information longer problem
- distracted by context

Student N:

- sensible assumptions
- logical strategy
- not distracted by prior knowledge
- overcomplicates assumptions/model
- distracted by context & personal experience
- stopped by lack of prior knowledge

Student O:

- draws analogue with prior knowledge
- identified data needed
- focus on context
- distracted by context
- can’t make estimates
- wants data

- logical approach
- looking for equation
- *2nd problem*
- distracted by prior knowledge
- not looked at whole problem
- can’t define problem