Identifying the existence of barriers to students' learning from assessment results

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Introduction

Constructivism is the dominant paradigm in educational psychology at present. According to this theory, learning is an active process of sense-making, which occurs in the mind of the learner as she or he attempts to construct a meaningful representation of new information (Phillips 1995). As a result, instruction aimed at transmitting (intact) a knowledge structure from the instructor to the student will be ineffective. Instead, the learner must build their own structure, or schema, based upon their existing knowledge and understanding (Bodner 1986). There are many different theories of constructivism (Phillips 1995), ranging from the individual-centred radical constructivist position of Von Glasersfeld (1993; 1995) to the group-centred social constructivist position (see Palincsar 1998, for example). However, all such theories share as common features the central position of the learner in sense-making and in building meaningful knowledge schemata.

Scerri (2003) has pointed out that there are important distinctions between a constructivist theory of learning, adopted for teaching purposes in the education community, and a philosophically constructivist theory of scientific knowledge. The former relates to students' learning process, whilst the latter posits that 'the laws of nature as we know them are social constructs – essentially laws that scientists have agreed between themselves and do not have any fundamental significance' (Collins 2001, cited in Scerri 2003; p.469). It is clear that one can believe that the learning process involves knowledge construction whilst simultaneously believing that scientifically accepted laws do have physical significance. It should be noted that only the educational theory of constructivism is being used in the interpretation part of this paper, and no reference to the philosophical position is intended.

The present study is part of a wider investigation of student perception and performance in chemistry examinations, part of which has been reported previously (Read, George, Masters and King 2004a, 2004b). There are several units of study (UOS) in first year chemistry at the University of Sydney which combine both general/inorganic chemistry (hereafter 'inorganic') and organic chemistry, and this paper presents examination performance data for eight such units. It is suggested that assessment results can be used to identify the existence of learning barriers by a purely statistical method, and that the nature of such barriers can then be investigated qualitatively; such a method could readily be applied to investigate units in other subject domains. Finally, whilst explanation in organic chemistry has been discussed in the literature (Goodwin 2003), as has students' development of organic predictive skills (Treagust, Chittleborough and Mamiala 2004), the belief amongst chemists that some students simply do not 'get' organic chemistry remains based on anecdotal evidence. This paper presents empirical data consistent with this belief, and offers a speculative interpretation of the nature of learning barriers faced by students learning organic chemistry.

Method

A comparison of student examination performance has been completed for eight first year chemistry UOS. Data on students' marks, in multiple choice (MC) and short answer (SA) sections across both areas (inorganic and organic), were collected for all students. As a result, all data presented in this paper refer to entire student populations. In addition, a detailed qualitative analysis of the examination scripts from CHEM1405 in 2003 has previously been completed and partially described (Read et al. 2004b). Amongst other things, this analysis provided insights into students' misconceptions, by examining commonalities in student approaches, both correct and incorrect.

Some characteristics of the UOS used in this study are summarised in Table 1. In all cases, the UOS are one-semester-long subjects, each consisting of both general chemistry (equilibrium, thermodynamics, osmosis, acids and bases, redox/electrochemistry and kinetics, etc.), taught in an inorganic context, and organic chemistry. For mainstream science units (CHEM1002, CHEM1102, CHEM1902, and CHEM1904), the principal emphasis in the organic chemistry section is on functional group chemistry, transformations, and spectroscopy. For the life sciences units (CHEM1405, CHEM1611, and CHEM1907/8), the emphasis on simple organic transformations is reduced, and additional material on amino acids, proteins, carbohydrates, and DNA chemistry is presented. Some prior knowledge of chemistry is assumed (to around Higher School Certificate level) for those undertaking the life sciences UOS and students with weaker chemistry backgrounds are strongly encouraged to complete a bridging course prior to commencing the unit. Participation in the bridging course, which covers only introductory general chemistry, has been previously shown to be associated with significantly better overall performance in these UOS (Read et al. 2004a). The mainstream science UOS are taken in the second semester of chemistry study and thus all students in these units will have successfully completed one semester of university-level chemistry.

Table 1. Characteristics of the chemistry units examined in this study

Unit of Study Code	Unit of Study	Semester	N	Number of Lectures (I / O*)	Marks in SA** of exam (I / O*)
CHEM1405	Chemistry 1 for Veterinary Science	1, 2003	93	24 / 28	24 / 27
CHEM1405	Chemistry 1 for Veterinary Science	1, 2004	100	24 / 28	24 / 30
CHEM1611	Chemistry 1 for Pharmacy	1, 2004	207	12 / 27	27 / 45
CHEM1907/8	Chemistry 1 for Life Sciences (Advanced)	1, 2004	178	12 / 27	27 / 38
CHEM1002	Fundamentals of Chemistry 1B	2, 2004	240	19 / 19	25 / 25
CHEM1102	Chemistry 1B	2, 2004	402	19 / 19	26 / 24
CHEM1902	Chemistry 1B (Advanced)	2, 2004	151	19 / 19	25 / 25
CHEM1904	Chemistry 1B (Special Studies)	2, 2004	50	19 / 19	25 / 25

* I / O refers to inorganic chemistry (I) and organic chemistry (O)

** All examinations total 100 marks, and consist of both short answer (SA) and multiple choice (MC) sections

Results and Discussion

The 2003 CHEM1405 examination

The original findings that prompted this investigation arose during the detailed quantitative and qualitative analysis of CHEM1405 in 2003. Analysis of the SA section of this examination, by partitioning the results into inorganic and organic parts, produced evidence of unusual distributions. Figure 1 shows a comparison of the SA sections of this examination. In Figure 1(a), the inorganic mark has been plotted against the organic mark, with a $y = x$ line included for comparison. In Figure 1(b), the distributions of marks have been plotted, grouped by examination grade bands.

Figure 1(a) shows that students' examination performance was much higher in the inorganic section, with the 95% confidence interval (CI) on the mean of the I:O ratio being 1.30 ± 0.08, after exclusion of the outlier (at I:O = 7.88). This shows that, on average, students scored about 30% more marks on the inorganic SA section, compared to the organic SA section. (By contrast, the 95% CI on the MC section I:O ratio was 1.04 ± 0.07, after exclusion of the same outlier.) The grade distributions, Figure 1(b), show an increasing trend in the inorganic section, suggesting that this section of the paper did not effectively discriminate between high achieving students; however, such a shape is consistent with a truncated normal distribution. The unusual 'V' shape seen in the organic SA distribution strongly suggests that the underlying population does not fit a normal distribution.

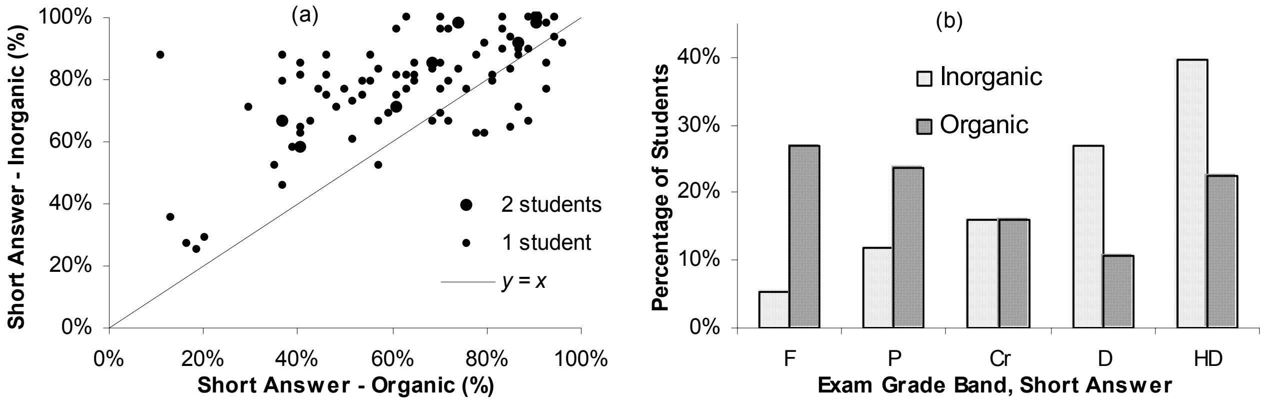

Figure 1. Short answer marks from CHEM1405 in 2003, comparing (a) inorganic and organic performance and (b) distribution of marks for all students, grouped by examination grade bands

To check on this interpretation, the distribution of marks (as a percentage) for each of these sections was plotted, grouped into bands 10% wide. These distributions are shown in Figure 2, along with their best-fit normal distributions. The marks on the inorganic SA section, Figure 2(a), follow a truncated normal distribution. However, a normal distribution is not a good model for the organic SA marks, Figure 2(b), and it is clear that attempting to improve the fit by skewing the model would improve the fit for higher marks, whilst significantly worsening the fit for lower marks.

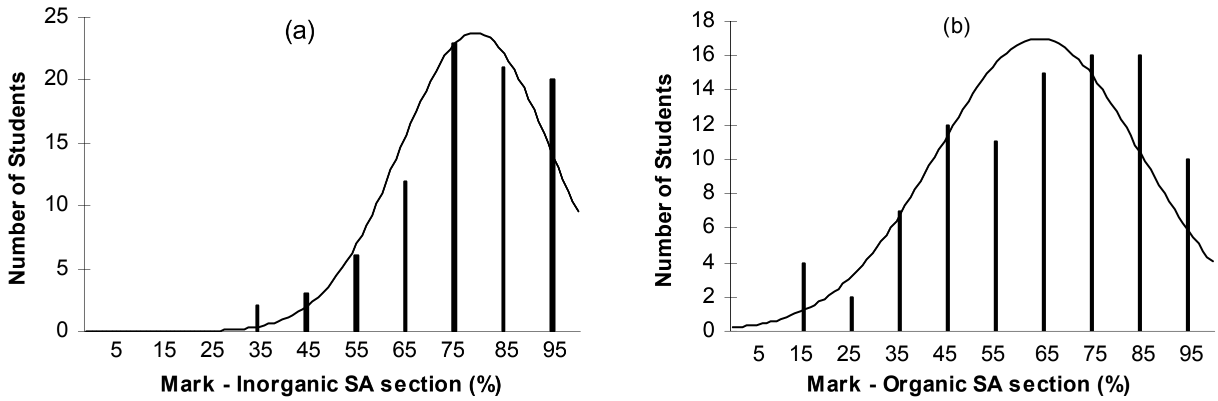

Figure 2. Distribution of marks on the (a) inorganic and (b) organic short answer sections of CHEM1405 in 2003, including best-fit normal distributions

Similar results are seen in all UOS examined from 2004 – a (sometimes truncated or skewed) normal distribution is a good fit for the inorganic SA sections, but not for the organic SA sections. These figures suggest that multiple normal distributions might better fit the organic SA sections. In every case, a tri-normal distribution was found to fit the distributions well, whilst mono-normal or bi-normal models were found to be inadequate. Under a tri-normal model, the number of students, $N(x)$, with a mark of x% is given by the formula:

$$N(x) = \frac{K}{\sqrt{2\pi}}\left(\frac{k_1}{\sigma_1} e^{\frac{-1}{2}\left(\frac{x-\mu_1}{\sigma_1}\right)^2} + \frac{k_2}{\sigma_2} e^{\frac{-1}{2}\left(\frac{x-\mu_2}{\sigma_2}\right)^2} + \frac{1-k_1-k_2}{\sigma_3} e^{\frac{-1}{2}\left(\frac{x-\mu_3}{\sigma_3}\right)^2} \right)$$

where μ_i are the means of each normal population, σ_i are the standard deviations (i = 1, 2, 3), k_1 and k_2 are density factors, included to account for the different sizes of each population, and K is a scaling factor. All variables are positive, and $0 < k_1, k_2 < 1$. Best-fit tri-normal models were obtained by minimisation of the sum of the squared deviations. Figure 3 shows the tri-normal fits for the organic SA section of the CHEM1405 examinations in 2003 and 2004. It is clear that, in each case, the tri-normal model is an excellent fit for the underlying organic SA section mark distribution.

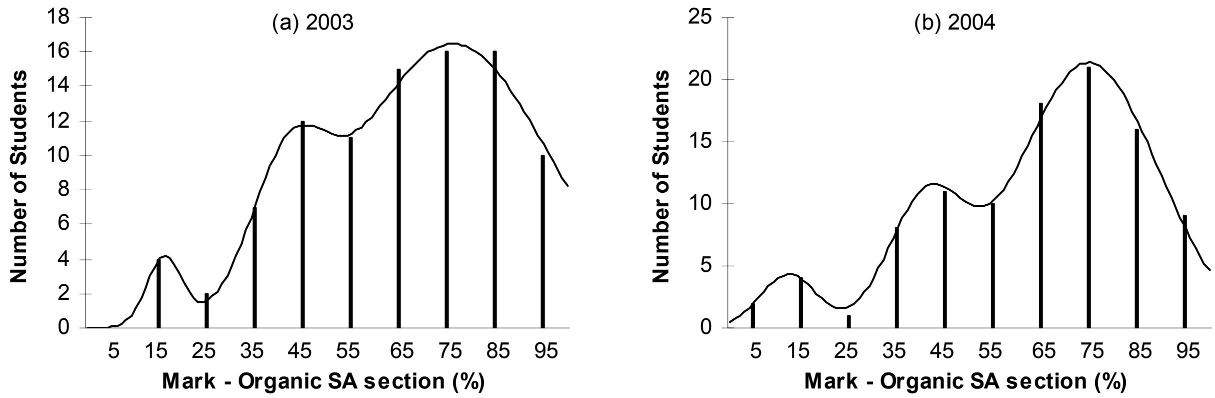

Figure 3. Distributions of marks on organic short answer sections of CHEM1405 for (a) 2003 and (b) 2004. In each case, a best-fit tri-normal model is also shown.

Results from all UOS and goodness-of-fit tests

Table 2 shows a summary of the results found for all UOS. In each case, the inorganic SA section could be simulated by a single (skewed) normal distribution. However, an acceptable fit for the organic SA could not be obtained unless a tri-normal model was used. In each case, the means of the three underlying organic populations were separated by around 30%. Furthermore, in all mainstream chemistry units, and in CHEM1907/8, at least half of the students were not found in the highest group, suggesting that there are learning barriers which these students have yet to overcome.

Table 2. Summary of organic short answer populations for all units studied

Unit of Study Code (Year)	*N*	*Marks in organic SA section / 100*	*Low Group*		*Middle Group*		*High Group*	
			Mean	*Size*	*Mean*	*Size*	*Mean*	*Size*
CHEM1405 (2003)	93	27	15.9%	3.9%	41.7%	15.4%	76.0%	80.7%
CHEM1405 (2004)	100	30	12.0%	7.0%	41.0%	20.0%	75.0%	73.0%
CHEM1611 (2004)	207	45	7.0%	6.0%	32.0%	10.0%	74.0%	84.0%
CHEM1907/8 (2004)	178	38	16.0%	11.0%	40.0%	52.0%	67.0%	37.0%
CHEM1002 (2004)	240	25	16.0%	41.0%	36.0%	38.0%	68.0%	21.0%
CHEM1102 (2004)	402	24	25.0%	15.0%	48.0%	39.0%	76.0%	46.0%
CHEM1902 (2004)	151	25	30.0%	26.7%	57.0%	66.8%	84.0%	6.5%
CHEM1904 (2004)	50	25	27.0%	2.5%	58.0%	47.8%	79.0%	49.7%

The existence of three separate distributions strongly suggests that there exist learning barriers which must be overcome in order to perform well at organic chemistry. Furthermore, the absence of multiple populations in the inorganic sections suggests that these barriers are specifically associated with the learning of organic chemistry – in effect, consistent with the anecdotal notion that some students simply do not ‘get’ organic chemistry. The fact that so many students fail to reach the high performance population, and indeed may be stuck in the low performance population, shows that this phenomenon is worthy of further study, so that the nature of these barriers may be understood, and so that teaching practice may be modified to assist students in overcoming these barriers.

The results in Table 2 were obtained by separating the tri-normal models into their component (overlapping) normal distributions. Individual means were then obtained, and population sizes estimated by comparison of areas. (Since the underlying distributions are not integrable to closed form functions, areas have been estimated from the trapezoidal rule.) Figure 4 shows results from the CHEM1907/8 examination, illustrating these component populations. This result illustrates that the tri-normal model can be used even where there is significant overlap between populations.

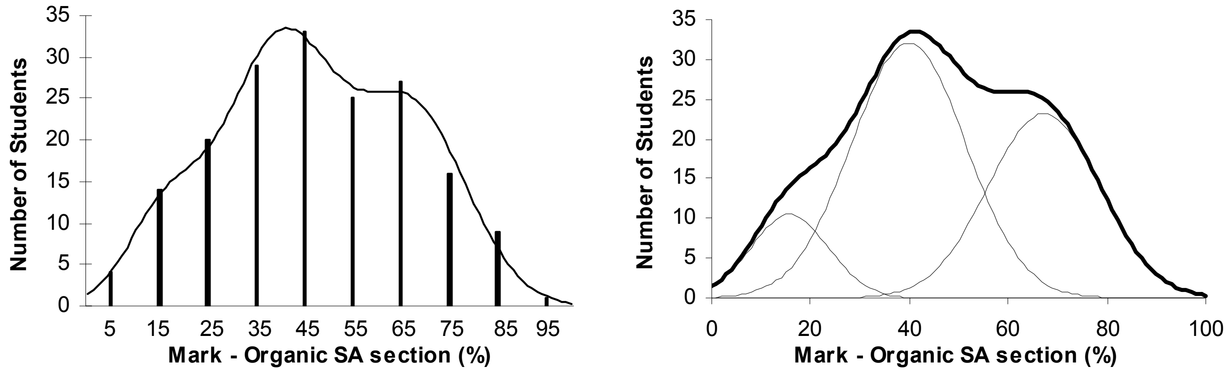

Figure 4. Results for organic short answer section of CHEM1907/8

It is true that, given a sufficiently large number of overlapping normal distributions, any mark distribution could be modelled. For the organic SA sections, the use of three overlapping normal distributions was needed to achieve an acceptable fit. In order to check that these results are not merely a statistical artefact, goodness-of-fit tests (using the chi-squared distribution) have been carried out. Within each unit, every student was assigned to exactly one of fifteen, approximately equally sized, non-overlapping categories. The number of students in each category was then counted, and compared with the number predicted by the models. By using fifteen categories, each test has six degrees of freedom (15 categories minus 8 variables minus 1), providing the test with sufficient sensitivity and power for valid conclusions to be reached. In the event that a tri-normal model did not match the actual mark distribution, a small p-value (less than 0.05) would be produced. Such a result would mean that the hypothesis that the model matches the actual mark distribution was false. As can be seen in Table 3, there are no statistically significant differences between the tri-normal models and the actual distributions for any of the UOS included in this study.

Table 3. Results of χ^2 goodness-of-fit tests of tri-normal models for organic short answer sections

Unit of Study Code	Semester	N	χ_6^2	p – value
CHEM1405	1, 2003	93	6.08	0.41
CHEM1405	1, 2004	100	5.00	0.54
CHEM1611	1, 2004	207	8.94	0.18
CHEM1907/8	1, 2004	178	3.04	0.80
CHEM1002	2, 2004	240	6.72	0.35
CHEM1102	2, 2004	402	7.08	0.31
CHEM1902	2, 2004	151	7.63	0.27
CHEM1904	2, 2004	50*	–	–

* Sample size is too small for valid goodness-of-fit tests to be completed – for 15 categories, a minimum population size of 15 × 5 = 75 is required

Speculative interpretation of the nature of the organic learning barriers

It has been established that all UOS show the presence of separate populations in the organic sections of the final examination paper, and that this result does not occur in the inorganic section. It has been suggested that this indicates the existence of learning barriers which need to be overcome if meaningful understanding of organic chemistry is to result. In order to understand the nature of these barriers, it is necessary to qualitatively examine students' learning of organic chemistry.

Read et al. (2004b) have examined student understanding in CHEM1405 in 2003. One of the organic chemistry questions asked on that examination concerned the amino acid cysteine (Cys) and the Cys-Cys dipeptide. Most (84%) of students could draw the amino acid (when told its side chain in the question), but 47% of these students could not draw the dipeptide. Around half of this latter group offered answers (such as those shown in Figure 5) which did not contain a peptide link, or did not conserve the molecular structure of Cys, or failed to follow bonding rules. Students who were unable to correctly draw Cys either offered no answer to the dipeptide question, or drew molecular fragments. In short, these answers suggest that the misconceptions held by students in the lowest performance group result from fragmentation of knowledge (and hence, dysfunctional schema). Students in the middle performance group seem to have incomplete schema, where critical components (such as the relevance of bonding rules in this context) are missing. As a consequence, it may be hypothesised that these learning barriers may be overcome by teaching aimed at producing internally consistent, coherent, and complete knowledge schemata.

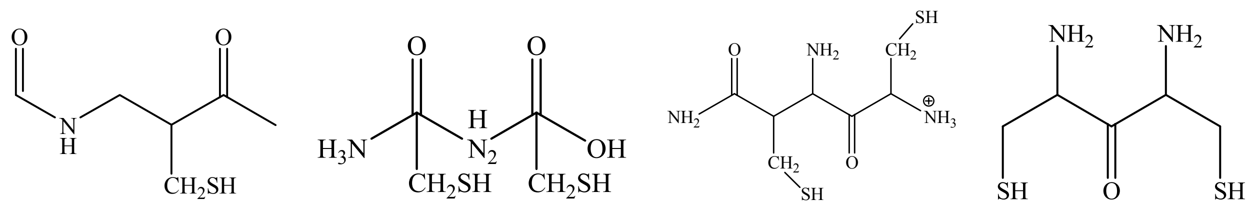

Figure 5. Some of the incorrect structures for Cys-Cys offered by students

Conclusion

This paper shows the existence of three populations of students on the SA organic section, and a single population on the inorganic section, of the examinations in all UOS studied. Further, it has been suggested that the need to use multi-normal models to model a mark distribution suggests the existence of learning barriers, the nature of which is worthy of further qualitative examination. In the case of organic chemistry, these barriers appear to be associated with the formation of coherent and functional schemata. Finally, these results empirically support, and suggest an explanation for, the widely held belief amongst chemists that some students simply do not 'get' organic chemistry.

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