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The Random Questionnaire Generator, a suite of programs designed to produce randomised multiple-choice tests for assessment of a first year chemistry class, has now been in use at Aberdeen University for three years. It has proved popular with students and staff and gives a much more reliable mark for each student than the previous system. The Creator program has also been used to generate tests for use in continuous assessment tests for students at Level 2.

Introduction

At Aberdeen University, as at many of the other older Scottish Universities, a large proportion of B.Sc. students take the Level 1 Chemistry course. There is no separation of intending chemists from other science students. All students taking the first year course follow the same laboratory course, which requires attendance at one 3-hour class each week. Several set experiments run on each lab day, and students rotate around these according to a pre-defined rota.

Students make records of their work in their laboratory manual during the laboratory class. The records include calculations, graphs, data analysis and answers to questions. Until three years ago all laboratory manuals were checked and marked by a member of staff before the student was permitted to leave the laboratory. The increase in student numbers during the 1990s meant that there could be up to 120 students in the lab during any lab session. This overloaded the system, caused unacceptable queuing and resulted in some students stopping lab work early so as to get to the front of the queue (a practice which was quickly copied by others).

Staff identified the following problems with the marking process:

- It was impossible to award a meaningful and consistent mark in the time available to assess each student (less than 2 minutes) and as a result the marks did not discriminate between able and less able, or even between conscientious and careless students.
- Opportunities to teach through interaction with students at the bench were significantly reduced by the time spent on marking.
- Student time spent on laboratory work was unacceptably reduced not only by the need to queue, but also by the tendency to stop work early.

In considering how to reorganise marking procedures to alleviate these problems we concluded that a computer-based test offered the

most promising way forward. We identified the following characteristics of a satisfactory assessment procedure:

- Each student would be provided with an individualised test to be completed by the end of the laboratory session; this individualisation would both prevent simple copying of answers and allow the test to take account of the fact that in many experiments students are given different samples to analyse.
- The questions would be worded in a friendly way so that students would recognise the test as a valuable learning experience.
- Questions would attempt to ensure that the information provided in the laboratory manual is read and understood (preferably in advance of the class) and would consolidate the theoretical background by asking about new terms and definitions introduced in the experiment, and understanding of general information related to the experiment.
- The test would be designed to provide a mark for the recording of observations made during the experimental work (e.g. the colour of a precipitate formed at a particular point), for the quality of the results obtained and would give practice in calculations with dummy data.
- When dealing with observations and results, it should be possible to award fractional marks.
- As far as possible the test would be marked automatically using an optical mark reader.

Our Department has been using multiple-choice testing in examinations since the early 1960s and has followed with interest the literature on the requirements for the design of effective questions. This has been revisited in recent years as a result of the increase in popularity of computer-based assessment.^{1, 2} Also, we have noted since we started our project that other institutions have reported the introduction of computer-based pre-lab and post-lab tests.^{3, 4} However none of the published work appears to have been concerned with the provision of a single test based on a particular laboratory class in which individual questions are designed to

be completed at different times throughout the class. We looked at other testing systems that include randomised selection of questions (for example Turton⁵), and at commercial systems such as Question Mark Designer,⁶ but found that these were designed for computer delivery of tests, and did not offer any possibility of customisation to meet all our needs. We therefore decided that the best option was to design our own style of test.

The system we designed has now been in operation for three years.^{7,8}

Methods

Creating the questions

The first year laboratory course consists of 20 sessions in each of which each student completes a different experiment. Before leaving the laboratory each student completes a test of 20 questions and hands in a coded answer sheet. Each test paper is unique to the student concerned and is generated on paper for each student from a bank of multiple-choice questions. Students collect their test papers at the start of each laboratory session, and answer the questions at appropriate points during and at the end of the experimental procedures. Because all the tests are different, we are able to allow students to discuss the answers to questions. Students are also encouraged to seek help from demonstrators with questions they find difficult.

The answers to the test questions are entered directly onto a copy of the University's standard, machine-readable form for marking by an optical mark reader; this form simply lists the question number and offers the choice of five boxes corresponding to the alternative responses provided (five boxes are always provided even though some questions are only provided with three or four responses). Individual test papers, each of which is prepared as a Microsoft Word document, are created by the computer from the bank of questions. Typically the question bank for each experiment consists of 24 different basic questions, but the variety is considerably increased because many of these basic questions have a number of variants (2–8). Variants are generated in several different ways. Sometimes it was possible to devise equivalent questions that were totally different, or (in the case of dummy calculations) to provide different data for the same calculation. Sometimes it was possible to use a fixed set of responses, but different question stems, one corresponding to each response. However, in some cases, the only acceptable variation was to change the order of the possible responses. With such questions, it is obviously easier for students to collaborate, but we were satisfied that they would at least have to read the question and its responses carefully — it would not be possible just to find out from a neighbour that the answer to question 3 was B.

The provision of a machine-readable test of observations made and of results was tackled in two ways. The first is used in experiments where all students should in theory obtain the same answer. The style of question used here is:

- **From the calibration graph, in which of the following ranges was the concentration of potassium ions in the riverwater?**
- A **Less than 8mg l⁻¹**
- B **8–9 mg l⁻¹**
- C **9–10 mg l⁻¹**
- D **10–11 mg l⁻¹**
- E **More than 11mg l⁻¹**

We tried here to avoid making the middle response the correct one, so that students could not use our ranges to guess the answer that we were expecting. The evidence we have from student queries is that they are very keen to code their results correctly, rather than attempt to cheat the system. The correct response is awarded a full 1 mark, but other responses may be awarded partial marks, based on our knowledge of the errors of the experiment.

The second method is required for experiments where students are expected to get different results, and where the mark is to be awarded for aspects of experimental work that involve human judgement. For these questions, the student is informed what the marks are awarded for but is instructed not to provide an answer. Instead, responses to be coded on the machine-readable answer sheets are decided by demonstrators after examining the laboratory manual and checking calculations where necessary. This is done throughout the class and does not usually cause delays. Examples of these questions are:

- Has the mass of the iron compound been recorded correctly?**
- Are the titration volumes in good agreement?**
- Has the percentage yield been calculated correctly?**
- Has the graph been drawn neatly and correctly?**

Demonstrators have a key for each experiment, which details the appropriate response for these questions, which we define as 'demonstrator-marked'. For each question, the key provides a letter that corresponds to the full mark of 1; the other letters correspond to fractions of a mark. Thus, if the key letter is C, students awarded response C receive a mark of 1, but other responses receive 0.75, 0.5, 0.25, or 0. The letters corresponding to the correct result are different for the different experiments, are kept secret from the students, and are changed from time to time. Amongst other characteristics of student work, these demonstrator-marked questions require demonstrators to check calculations, to examine

graphs for neatness and correct plotting, and to examine the appearance of organic products. Marking guidelines leave as little room as possible for personal interpretation so that postgraduate demonstrators are able to assist the staff with marking. Demonstrator-marked questions are included in the same format and in the same place on all the test papers for a particular experiment. They are therefore designated as 'fixed'.

Questions dealing with other aspects of the experiment (for example, calculations with dummy data, and questions dealing with background theory) are of a more conventional style. For the purposes of creating test papers these questions are designated as 'fixed' (one of the variants appears in every test paper, always in the set position), 'compulsory' (one of the variants appears in every test paper, but in any available position) or as 'optional' (a question which need not be selected).

Depending on the experiment, a test paper will contain 3–20 fixed questions, 0–10 compulsory questions, and 17–20 optional questions selected from a bank of up to 30 (basic questions) with a total of up to 80 variants.

Creating the test papers

The test papers are created from the question banks and the corresponding Questionnaire Definition Files, by using the Creator program, which is written in *Delphi* (like the others in the suite). The program reads a set of daily *Excel* spreadsheets (giving lists of student names, laboratory numbers, and class codes), another spreadsheet giving the rota of experiments (which relates student laboratory numbers with experiments for each week), and a file, which defines all the experiments. The program uses the student's laboratory number together with a 'day code' defining the day of the week and the week number to set the rules by which the algorithm selects the questions for each student in a manner that appears to be random. Each test will include all the fixed questions, in their defined positions, along with the Compulsory questions and enough Optional questions to give a total of 20; the positions of the "c" and "o" questions are different for each different test. The algorithm also determines which of the optional questions are selected and (for questions with variants) it also determines which variant is selected.

To simplify the handling and distribution, the font size and margins for the questionnaire are set to

permit each test to be printed on a single sheet of paper. An example of a test is shown in Figure 1. Once the student names are available, laboratory numbers have been allocated, and the daily *Excel* spreadsheets prepared, questionnaires are simple to produce. Normally they are generated for all students for a given day and week number in a single batch (although if necessary a single form can be printed). This is repeated for other days and week numbers. The limiting factor in the process is the printer — but with a fast printer, tests for 20 lab sessions (for 5 weeks, with 4 lab classes each week; up to 3000 tests) can be printed in a single day.

Marking program

The laboratory technicians scan the completed machine-readable forms by using a Scanmark 2000 (<http://www.scantron.com/scan/sm2000.htm>) optical mark reader (omr). The machine is set to reject forms if marks are missing or not dark enough to be readable; it can also reject some invalid codes. Any rejected form is returned at once to the student, with advice to make marks darker, or insert or amend codes and then the form is rescanned. We bought our own reader for this project, but use the University's standard printed forms. The omr software writes the data to an ASCII text file.

Each week, the four daily files are processed by the Marker program, which uses the same algorithm as the Creator program to determine, for each student, which questions have to be marked. It then checks the answers in the answer file, and awards the appropriate mark. It has not proved possible to make the marking process fully automatic, because students sometimes make errors in entering their laboratory numbers and/or day codes, but the program attempts to flag these, and the flagged entries are corrected manually. When all corrections have been made, the program is instructed to insert the marks into the *Excel* spreadsheet, which also serves as the register for the class. At the time of marking, the responses are recorded in a text file for later analysis, if desired, for example to calculate the fraction of the class with the correct answer to every variant of every question (the facility value).

A special arrangement had to be made for the "Unknown Samples" that students have to identify in the Inorganic part of the laboratory class. There are 47 different samples, so it was not considered necessary to generate fully randomised tests.

- 2071 JOHN SMITH Cations part 2 Day code: 0321
- Q1.** The colour of the solid and the stock solution of compound T is?
 A Colourless / white B Pink / red C Green D Blue
- Q2.** With which of the following pairs of cations are the colours of the solid and stock solution of compound T compatible?
 A Cu^{2+} and Cr^{3+} B Cu^{2+} and Fe^{2+} C Cr^{3+} and Co^{2+} D Ni^{2+} and Fe^{2+}
- Q3.** On heating the precipitate a change in colour was noted. What was the final colour observed?
 A Blue B White/colourless C Green D Black
- Q4.** Which of the following is the only cation to fit the result obtained when sodium hydroxide solution (dilute then excess) was added to the compound?
 A Ni^{2+} B Cu^{2+} C Cr^{3+} D Fe^{2+}
- Q5.** Unknown T was copper sulphate 5-hydrate. Which of the following is the formula for this compound.
 A $(\text{CuSO}_4)_5 \cdot \text{H}_2\text{O}$ B $\text{Cu}(\text{SO}_4)_2 \cdot 5\text{H}_2\text{O}$ C $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ D $\text{Cu}_2\text{SO}_4 \cdot \text{H}_2\text{O}$
- Q6.** Which of the equations below represents the formation of the precipitate of copper hydroxide?
 A $\text{Cu}^{2+}(\text{aq}) + 2\text{OH}^-(\text{aq}) \rightarrow \text{Cu}(\text{OH})_2(\text{s})$ B $2\text{Cu}^{2+}(\text{aq}) + \text{OH}^-(\text{aq}) \rightarrow \text{Cu}_2\text{OH}(\text{s})$
 C $\text{Cu}^{2+}(\text{aq}) + \text{OH}^-(\text{aq}) \rightarrow \text{CuOH}(\text{s})$ D $\text{Cu}^{2+}(\text{aq}) + 2\text{OH}^-(\text{aq}) \rightarrow \text{CuOH}_2(\text{s})$
- Q7.** What is the formula of the compound formed on heating copper hydroxide?
 A CuS B CuO C CuOH D $\text{Cu}(\text{NO}_3)_2$
- Q8.** The precipitate redissolved on adding excess ammonia solution owing to the formation of a complex. Is the complex
 A An anion B A cation C A neutral molecule
- Q9.** What is the name given to this type of complex?
 A Hydroxo B Ammine C Amine D Hydrate
- Q10.** Which of the following equations represents the formation of the copper complex ?
 A $\text{Cu}^{2+}(\text{aq}) + 6\text{NH}_3(\text{aq}) \rightarrow [\text{Cu}(\text{NH}_3)_6]^{2+}(\text{aq})$ B $\text{Cu}^{2+}(\text{aq}) + 4\text{NH}_3(\text{aq}) \rightarrow [\text{Cu}(\text{NH}_3)_4]^{2+}(\text{aq})$
 C $\text{Cu}^{2+}(\text{aq}) + 4\text{NH}_3(\text{aq}) \rightarrow [\text{Cu}(\text{NH}_3)_4]^{4+}(\text{aq})$ D $\text{Cu}^{2+}(\text{aq}) + 6\text{NH}_3(\text{aq}) \rightarrow [\text{Cu}(\text{NH}_3)_6]^{6+}(\text{aq})$
- Q11.** On addition of excess of concentrated hydrochloric acid to a solution of unknown T a colour change was observed. Which of the following changes in colour best fits your observation?
 A Blue to greenish yellow B Blue to violet C Blue to red D Green to blue
- Q12.** The change in colour is due to the formation of a complex. Is the complex
 A An anion B A cation C A neutral molecule
- Q13.** What is the name given to the type of complex formed with hydrochloric acid?
 A Hydroxo B Chloro C Amine D Hydrate
- Q14.** Which of the following represents the formula of the complex formed?
 A $[\text{CuCl}]^-$ B $[\text{Cu}_2\text{Cl}]^{2+}$ C $[\text{CuCl}_4]^{2-}$ D $[\text{Cu}_2\text{Cl}_4]^{2-}$
- Q15.** Which of the following is the correct formula for the precipitate formed when sodium sulphide was added to T?
 A CuS_2 B Cu_2S C CuS D Cu_2S_2
- Q16.** From the colour of compound U and its solution, which of the following groups of cations can you say are definitely not present in the compound?
 A Mg^{2+} , Ca^{2+} , Sr^{2+} , Ba^{2+} , Cd^{2+} B Cr^{3+} , Fe^{3+} , Co^{2+} , Ni^{2+} , Cu^{2+}
 C Zn^{2+} , Al^{3+} , Pb^{2+} , Sn^{2+} , Sn^{4+} D Cd^{2+} , Mn^{2+} , Fe^{2+} , Ag^+
- Q17.** Which of the following groups of cations is compatible with the result from the reaction between compound U and sodium hydroxide solution?
 A Mg^{2+} , Ca^{2+} , Sr^{2+} , Ba^{2+} , Cd^{2+} B Cr^{3+} , Fe^{3+} , Co^{2+} , Ni^{2+} , Cu^{2+}
 C Zn^{2+} , Al^{3+} , Pb^{2+} , Sn^{2+} , Sn^{4+} D Cd^{2+} , Mn^{2+} , Fe^{2+} , Ag^+
- Q18.** Which one of the following cations can be eliminated because it would have given a precipitate if the solid was tested with nitric and sulphuric acids?
 A Ca^{2+} B Mg^{2+} C Cd^{2+} D None
- Q19.** Unknown U was magnesium sulphate 7-hydrate. Which of the following is the formula for this compound?
 A $(\text{MgSO}_4)_7 \cdot \text{H}_2\text{O}$ B $\text{Mg}(\text{SO}_4)_2 \cdot 7\text{H}_2\text{O}$ C $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ D $\text{Mg}_2\text{SO}_4 \cdot 7\text{H}_2\text{O}$
- Q20.** Which of the following is the formula for the precipitate formed when sodium hydroxide was added to a solution of U?
 A $\text{Mg}(\text{OH})_2$ B $\text{Mg}_2(\text{OH})_3$ C MgOH D Mg_2OH

Figure 1. An example of a questionnaire

Instead, a limited number of tests were prepared for each of the samples used. The pre-prepared questionnaires are associated with the samples rather than with individual students. These tests are identified to the Marker program by special codes printed on the test forms in place of the normal day codes. Different students complete different numbers of unknown samples, so all the marks achieved by one student are summed in a single spreadsheet cell.

Providing students with feedback

Feedback to the students is provided in two ways. In the first, marks are made available by the Laboratory Mark Reader program, which runs on two low-specification computers in the laboratory. This program reads copies of the main Excel spreadsheets, and allows students to see the mark achieved in the previous week(s), and also to find out the numbers of the questions they have answered incorrectly. Students are advised to retain their questionnaires so that they can review these questions; they are advised to consult a demonstrator if they do not understand their error.

The second form of feedback is provided only to students who get marks below a given threshold (usually 12 out of 20). These students are offered a printed report showing their incorrect responses and they are particularly recommended to consult a demonstrator for advice about their errors. The printouts include the full text of questions answered incorrectly, but questions related to the student's experimental data are normally labelled in the answer file so that they are excluded from these reports. (The same applies to the first form of feedback.)

Results

The facility value calculated for each question (and each variant) provides evidence that no questions appear to be either so easy or so difficult that they provide no useful discrimination between students. Typically, the facility values fall between 0.6 and 0.8, which we regard as satisfactory here. In a normal exam, an 'ideal' question would have a value of 0.5, because half the class got the question correct; but a test should include a range of facility values in order to discriminate across a range of student abilities (1).

Furthermore, the facility values for variants of the same basic question are essentially the same. These results provide reassuring evidence that the tests are discriminating effectively. A point of particular interest arises from our examination of the facility values for questions, which differed only in the order of the distractors. We observed considerable variation in the numbers choosing the various wrong answers, but we found only two for which the correct answer had a higher facility when the

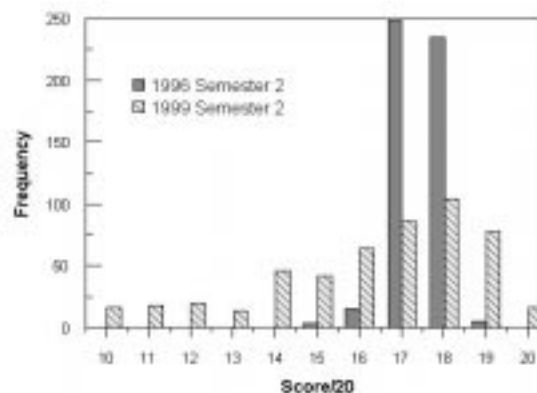


Figure 2. Comparison of laboratory marks awarded by the old and new systems

nearest distractor immediately preceded it. In view of the large number of questions we examined, this was not statistically significant and our observations are therefore inconsistent with the suggestion that the relative locations of the correct answer and 'nearest' distractor can have a significant effect on the facility of questions.⁹ A useful reminder that 'objective testing' is not fully reliable and reproducible was provided by a question with only 3 responses (A, B and C), but for which 6% (1998) and 4% (1999) of students marked response D.

Figure 2 shows a comparison of the marks awarded during a single semester (1999, semester 2) using the new system with those awarded during the last semester in which the old system was used (1996, semester 2). The distribution of marks is still skewed towards the top end of the marking scale, but the new system has resulted in a much fuller use of the total mark scale. Table 1 provides a comparison of the marks obtained in all the semesters since 1996 (2) and shows that 1999(2) is typical of semesters since the introduction of the new system. (Although there is no statistical justification for calculating a standard deviation for data, which are clearly not drawn from a Normal

Semester	96/2 (Old)	97/1	97/2	98/1	98/2	99/1	99/2
Mean	17.7	16.0	15.7	16.0	15.9	16.5	16.2
Standard Deviation	0.5	2.6	1.8	2.5	3.0	3.0	2.7

Table 1. Statistics for Laboratory Marks

Population, it is a convenient way of providing a crude comparison between semesters).

Using the new system, the distribution of marks for laboratory work is similar to the distribution for closed examinations. This is illustrated in Figure 3, which shows a plot of lab marks vs. exam marks for

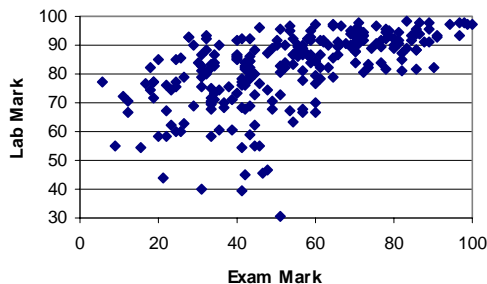


Figure 3. An example of correlation between laboratory and examination marks

semester 1999(2). Almost every student obtained a higher mark for lab work than for the closed examination. However the correlation coefficient is highly significant ($R = 0.57$, $n = 243$, $P < 0.001$).

We are satisfied that the distribution of marks obtained with the new system is a better reflection of our students' performance in the laboratory classes. We find it hard to accept that the data shown in Figure 2 for semester 1996(2) really mean that all our students truly deserve marks in the top quartile of the scale. And we are neither surprised nor concerned that most students achieve a higher mark for lab work than they do in examinations because it is possible in the laboratory to compensate for mistakes or lack of aptitude by perseverance and hard work. Furthermore, we have noted a marked improvement in student attitude to laboratory work since the introduction of the new system; the great majority actively strive to achieve high marks and keen to learn how they have lost marks, to the extent that there have been many requests for the feedback printouts to be made available for all students. In official Student Course Evaluation Forms, over 90% of respondents said that they thought the practical work was well organised. In addition, around 85% said they found the laboratory work interesting (in contrast to Johnstone's report¹⁰ that the majority of young lecturers interviewed by him had, as students, found labs boring).

Staff and demonstrators also report favourably on the new system. The laboratory is now able to close at the advertised closing time. The automation of the recording of attendance and mark has significantly reduced the administrative work associated with the running of the class.

Discussion

There can be no doubt that we achieved our first objective of removing the problem of queues with the consequent advantage that the students do not stop work earlier than is justified by their progress.

There are other advantages. The system for marking and recording of marks operates very efficiently giving demonstrators more time to teach in the laboratory. The use of paper tests means that, for some kinds of experiment, we can completely integrate the tests with the experiments so that they are in-lab rather than post-lab tests. The Master *Excel* spreadsheet allows us to monitor student attendance and take action if necessary. Our comparisons of the new lab marks with old ones and with examination marks have convinced us that we now have a much more reliable mark for the laboratory work than we did in the past so that we now have no worries about the weighting of 20% given for this mark in the end-of-module degree examinations, and indeed we are giving thought to increasing this.

The original version of the Reader program gave only the mark, and comments from students obtained from course evaluation forms resulted in many requests for the feedback printouts to be made available for all students instead of just those who obtained low marks. We take this to be a positive indication of a genuine wish to improve, and to comply with this request, we have very recently introduced the enhanced version of the Reader program, which informs students of the questions that they answered incorrectly.

The suite of programs we have developed is generic in that it can be readily adapted for a variety of uses. This is illustrated by our use of the Questionnaire Generator Program to create homework assignments for level 2 students doing the analytical lab course. Because this is timetabled for the end of the session, students face a conflict between their perceived need to revise and the requirement to prepare lab reports. It was therefore decided to separate the calculations from the experimental work, and issue the calculations early in the semester. We had not felt able to do this previously because of the prevalence of copying when all students receive the same homework tests, but the opportunity to create randomised tests overcame this objection.

For each experiment, six sets of "good" but not perfect data were selected from those obtained by students in previous years, and the Creator program was used to generate randomised tests for each student. There was no intention of using machine marking, so no multiple-choice responses had to be created. The students are no longer required to prepare lab reports at the end of term, because the evidence of their ability to carry out the calculations is measured from their calculations using dummy data, and their actual data is entered into a Visual Basic program which calculates and records the final answers for subsequent assignment

of marks for accuracy. The course evaluation forms show that this is appreciated.

As far as the staff are concerned, there is a considerable saving in workload. Although the marking of the calculations is done manually with the help of a key indicating the data given to each student, this is much faster than marking real laboratory data because the answers are already known. More time is saved by the automated calculation of results even though it requires some human intervention, since there is no need to check the calculation itself. This procedure also serves to prevent students from trying to "fudge" their results.

Our system is an example of the power of computers in teaching with no pretence at being Computer Assisted Learning. We see this as a very positive aspect since we have long observed that the majority of our students are not very enthusiastic about the use of computer-assisted learning.

Acknowledgements

We are grateful to the University Information Services Committee for providing the original funding which allowed us to develop the database of questions and the software, to Dr Simon Heath of CLUES for provision of programming support, and to Aberdeen University Learning Technology Unit for support for recent enhancements to the software.

The programs that make up the Random Questionnaire Generator suite are completely generic in nature, although they do require the user to be running Windows 95/98/NT, together with Microsoft *Word* and *Excel*. We are willing to make them available at a modest price to anyone who is interested in using them.

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