The Use of a Computer-Assisted Personalized Approach in a Large-Enrolment General Chemistry Course

PAPER

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The CAPA© system[1,2] (a computer-assisted personalized approach) has been used in general chemistry courses at Michigan State University since January 1993. This networked software system is a tool that enables instructors to write and distribute personalized problem sets, quizzes, and examinations for their students and includes an array of course management and statistical functions. Advantages of the system include

- Encouragement of a continual rather than sporadic effort by students in the learning process.
- Immediate feedback of a student's responses at any time.
- Individual problem sets for students that permit and encourage collaborative study.
- A shift in effort for instructors from grading and course management to teaching and course development.
- Support for the design and coding of both conceptual and algorithmic problems.
- A shift in role for the instructor from examiner to tutor and teacher.

Introduction

Michigan State University is a large public university with an undergraduate student population of approximately 32,250. Of these, about 8650 are in the freshman class. Almost all physical science, biological science, and engineering students are required to take at least one semester of chemistry – in most cases the 4-credit general chemistry course CEM 141. This results in an annual enrolment in CEM 141 in excess of 3000 students of which 2000 take the course in the Fall semester.

Students in CEM 141 have widely different backgrounds in chemistry and mathematics. Many, but by no means all, have experienced one year of chemistry in high school. Their mathematics backgrounds, often the more reliable predictor of success, vary from little or no knowledge of algebra to some experience with calculus. Enrolment in the course requires no prior knowledge of chemistry but does require at least concurrent enrolment in algebra I. The academic level of CEM 141 approximates that of A-level chemistry or a pre-degree general chemistry course in the UK. Chemistry, biochemistry, and chemical engineering majors do not take CEM 141.

Our intent in CEM 141 is to provide for the student a thorough basis in the fundamental properties and behaviour of matter that subsequently will be of some use to them in their major programme. The syllabus is fairly typical of traditional general chemistry courses in the US – the topics covered are listed in Table 1. Only 33% of the CEM 141 enrolment go on to take the second semester (CEM 142).

Chemistry 141 is taught by a traditional lecture-recitation method and the aim is to encourage conceptual understanding of the principles rather than to focus on the memorization of facts and the algorithmic solving of problems[3]. Thus the aim is to emphasise the higher order aspects of Bloom's taxonomy of educational objectives[4] and this is done as much as possible in the spirit of the lighting of a fire rather than the filling of a pail[5].

To achieve success, students need to develop two habits. The first and more important is a regular (preferably daily) active study of the material. The second, which helps a student enormously, is collaboration, cooperation, and discussion of the subject with other students[6,7]. In addition, students benefit from rapid formative feedback of their progress. Given the number of students involved (as many as 2000 per semester) these needs raised significant logistical concerns. One problem is that it is easy for students to get lost in the crowd and considerable care has to be taken to cater for the needs of the individual. For the instructors, the administration of examinations and problem sets can be almost overwhelming; the manual grading of the latter places an onerous burden on teaching assistants and it is impossible for them to provide results rapidly enough for effective feedback. A computer-based learning support system is the only realistic way to meet these demands.

Table 1: Syllabus for CEM 141

- Classification of matter
- Formulas, equations, stoichiometry & the mole concept
- Types of reactions; redox and acids and bases; aqueous solutions
- Solution stoichiometry
- Energy and reactions; first law of thermodynamics
- Atomic structure; electronic configurations; periodicity
- Bonding and molecular structure
- States of matter, gases and solids
- Second law of thermodynamics; entropy and free energy
- Changes of state; phase diagrams
- Solutions
- Kinetics and equilibria
- Aqueous equilibria

There are many web-based educational tools available today that can be used in a variety of ways. Some merely assist in the management of traditional lecture courses, supplement the presentation of some of the material (for example, Authorware-based visualization[8]), provide question management and test construction (for example, Question Mark Designer[9]), or enable instructor-student conferencing on line (for example Alta Vista Forum[10] which has previously been used with considerable success in the Physics Department here at Michigan State University[11]). Other tools enable entire web-based courses for either local or distance learning (for example WebCT[12–14] –a development system that includes management and administration, material presentation, study guides, quiz and examination modules, online help, bulletin boards, chat rooms, and email).

The CAPA system described here proved to be the ideal solution for our students in CEM 141. This system is a specialized single component rather than a complete web-based program. It can be used in conjunction with other web-based tools, such as conferencing utilities or material presentation modules, to provide an entirely online program, or, as in our case, it can be used in conjunction with lectures and recitations in a more traditional course. The CAPA system is a sophisticated component[15] consisting of three parts: 'QUIZZER' is used to create questions and prepare personalized problem sets or examinations, 'GRADER' is used to record student responses and scores, and 'MANAGER' is used to create class reports and compile various statistical information. What distinguishes the CAPA system from many other computer-based generators of problem sets[16] is the variety and sophistication of question types that can be designed and coded. In addition to the more easily coded algorithm-based numerical questions[17] it is particularly well-suited to the design and coding of conceptual questions[18], with the inclusion of pictures, diagrams, and animations[19]. A key feature of the CAPA system is that it includes templates and tools which make it easy to generate hundreds (or thousands) of different questions from the same code[11,15]. Thus each coded question has many variants of which one is selected at random whenever that coded question is assigned. This ability to generate hundreds of similar random questions from a single code is essential in permitting open formative assessment problem sets[20].

A detailed description of the CAPA system is available elsewhere[1,2,11,18,21], and its use in a smaller enrolment chemistry course has also been described[22]. The system is under continual development and is available under licence from Michigan State University[23]. It is used in chemistry courses at several universities in North America (US and Canada) and to a larger extent in many physics departments.

The system used by our department is served by a Digital Alpha 433a workstation (433MHz) with 256MB RAM and two 9GB ultra-wide SCSI drives. Printing of the problem sets is done on an HP 8100 duplex laser printer. In this department, the CAPA system has been used in both semesters of general chemistry (CEM 141 & 142), in the first year laboratory classes and subsequent sophomore analytical and senior level analytical-physical laboratory classes, and in junior level physical chemistry courses for non-majors. Although this report concerns only the large-enrolment CEM 141 course, the benefits of the system in the encouragement of student activity and learning apply equally as well to classes of 20 as to classes of 2000 students.

Methods

Writing the Questions

The aim was to create a bank of coded questions from which an individual problem set of 10 would be distributed to each student during every week in which there was no examination. This is a total of eleven sets, or 110 questions. In any given week each student would receive the same set of coded questions, but the set would be unique to the student because of the random assignment of question variants.

The question bank now includes over 400 coded questions classified by topic. The questions are of four types and an example of each type is shown in Figure 1.

- TYPE I: Straightforward numerical questions that can be solved by the application of an algorithm or formula (which could be supplied by a friend or in an internet chat room). The inclusion of such questions in the question bank is useful because almost all the students benefit from practising such routine items. Furthermore these comparatively easy questions successfully encourage the poorer students in the class to try the more difficult ones, and the better students feel good about getting the answers correct quickly.
- TYPE II: More thought provoking numerical questions that require the student to think more deeply about the theory behind the calculation.
- TYPE III: Non-numeric questions that cannot be solved by applying an algorithm but are essentially tests of knowledge.
- TYPE IV: Problems testing conceptual understanding, often through the use of diagrams.

The Appendix provides descriptions of how large numbers of variants can be generated and randomly selected for each coded question.

Using the System

Each week in which there is no examination, the course instructor selects from the bank of coded questions a set of 10 which are at an appropriate level for that stage of the course and which includes an appropriate mix of the four types of questions. This constitutes the *problem set* for the week. The CAPA system then creates a unique version of the problem set for each student and prints the student's name and other course information at the top. The problem set is made available both online through the web and as a printed copy at lectures at least a week before the deadline. The deadline for the submission of answers was chosen to be the Friday of each week at 8:00 am. The CAPA system provides for an unlimited number and duration of logins at any time of the day. Upon login, students can try the current set, participate in discussion online, look at the answers to previous problem sets, or access their record. When trying the current problem

Figure 1: The four basic types of question

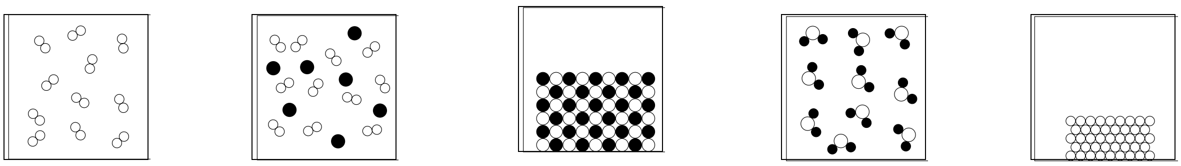
Type I What is the molar mass (atomic mass) of an element if 1.010 moles of atoms of the element have a mass of 119.897 grams?

Type II Suppose that the atomic mass unit (amu) had been defined as one-twentieth of the average mass of an atom of fluorine, instead of one-twelfth of the mass of an atom of carbon-12. What would the average atomic mass of magnesium be on this new scale? What would the value of Avogadro's number be using this new scale?

Type III Decide if the statements written are always true, sometimes true, or not true. Select A – always true, S – sometimes true, and N – not true. For example, if the first statement is always true, and the remaining questions are never true, enter ANNNNNN.

1 Compounds are molecules
2 A substance is pure matter
3 Elements exist as molecules
4 All molecules are diatomic
5 Molecules are made of atoms
6 Mercury is an element
7 Substances are either elements or compounds

Type IV Answer the following questions referring to the figures shown. The circles in the pictures represent atoms; different coloured circles represent different elements. Enter your answer as a series of five letters. For example, if the answer to all is A, then enter AAAAA.



A B C D E

Which figure represents a view, at the particulate level, of
1. Water vapour
2. A mixture of hydrogen and neon at room temperature
3. Nickel metal at room temperature
4. Chlorine gas
5. Crystalline sodium chloride

set they are expected to make mistakes and are allowed multiple attempts. The number of tries allowed for a question is a global or question-dependent variable set by the instructor (usually 10 or 15). The instant feedback and the opportunity to correct wrong answers immediately without penalty encourage the students to learn the principles of chemistry. The possibility of attaining a perfect score is highly motivating and students work hard to achieve it. The advantage of providing students with immediate knowledge of their progress is that they can do something about it, rather than waiting one or two weeks for the return of a manually-graded problem set, by which time it is too late.

The course is graded on a fixed and published scale. The accumulated score on the CAPA problem sets typically contributes 22% to the grade. The rest of the marks come from the recitation (8%), three mid-term exams (15% each) and the final exam (25%). Although the marks from the CAPA problem sets contribute to the total for the final grade, this summative component is intended primarily as a formative assessment tool– "a testing method without academic penalty that reveals shortcomings in students' understanding while allowing them to take responsibility for their own learning"[24].

Clearly the system relies on networked computer technology: students login to the server over the internet using a web browser, or telnet, and enter their responses remotely to verify their answers. The great majority of students (>80%) now use the web.

Results

Figure 2 shows the numbers of students for two Fall semesters (1998-1999) who obtained a given cumulative score from all 11 CAPA problem sets. It shows that approximately 25% of a typical course enrolment achieve a perfect score of 220. This reflects considerably greater effort than observed previously for manually-graded homework sets: 60% of students spent more (37%), or much more (23%), time doing CAPA problem sets compared to manually-graded assignments[22]. Figure 3 illustrates the hours during the day when students most frequently login to the system. The data show average figures over a three week period during mid-semester (weeks 5, 6, and 7) in the Fall of 1999 – a total of 113,233 logins. The most popular hours are from 7 to 11 in the evening with a maximum observed rate during this three-week period of 2395 logins/hour, a rate of more than one login per student per hour. Login rates increase as the deadlines approach.

Figure 4 shows the individual CAPA scores plotted against the final grade for the CEM 141 course in the Fall of 1998. It shows that it is rare for a student to obtain a grade of 3.0 or better without obtaining a CAPA score of at least 75% (165 marks). The CAPA results do not discriminate between the better students in the class; discrimination between the different grades results primarily from examinations. At grades of 2.5 and below, a few students obtain scores below 50%, though a similar number of students in these grades continue to score near-perfect scores. It is only in the failing grade (0.0)

Figure 2: CAPA Final Scores for CEM 141 Fall 1998 and Fall 1999

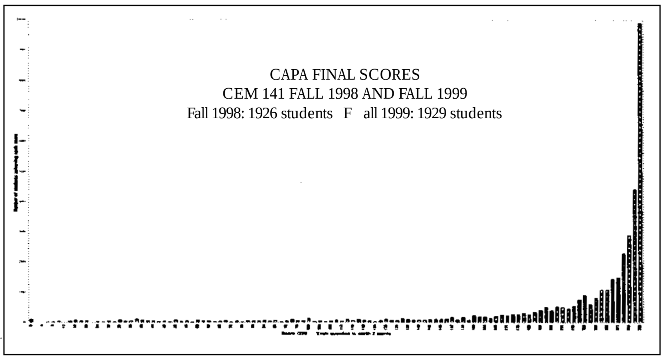


Figure 3: Distribution of logins over a 24 hour period

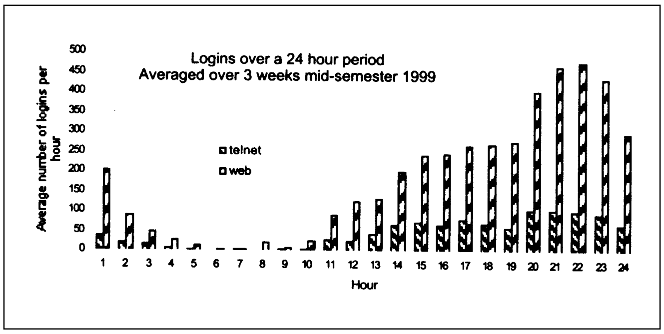
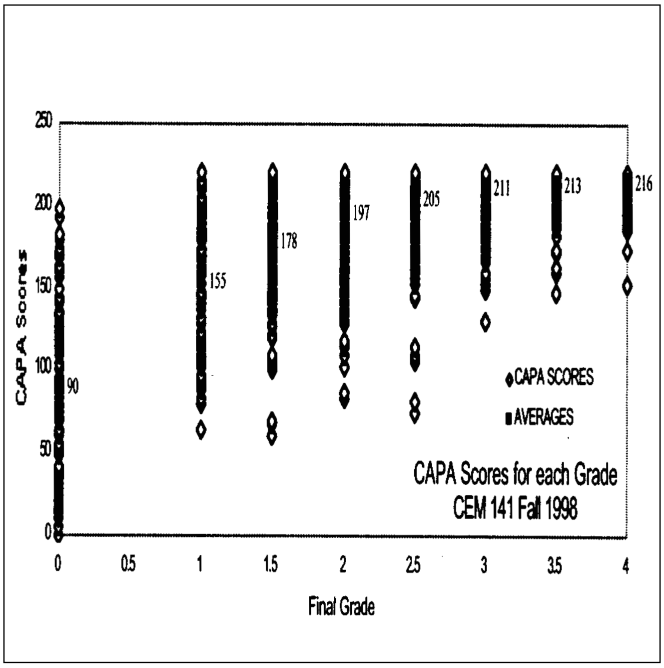


Figure 4: Correlation of Final CAPA scores and Final Grades



that the mean CAPA score falls below 50% (110), and even in this grade a number of students score nearly 90% in the CAPA tests. Thus, although there is a relationship between the *mean* CAPA score and the final grade, the lack of a tight relationship coupled with the high scores is good evidence that the CAPA problem sets encourage students across the ability range to engage actively with the subject throughout the course

Figure 5: The range of degrees of difficulty for ten questions on a set

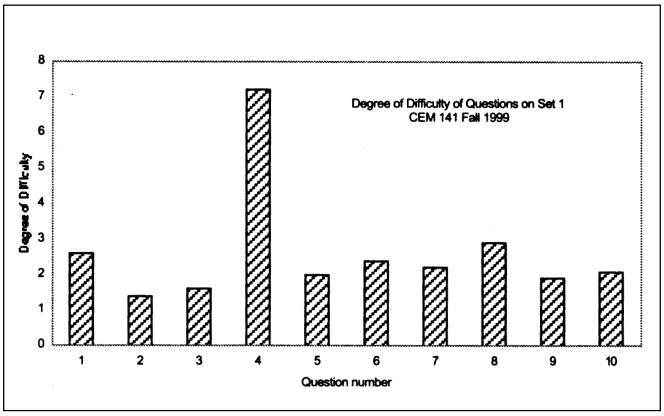
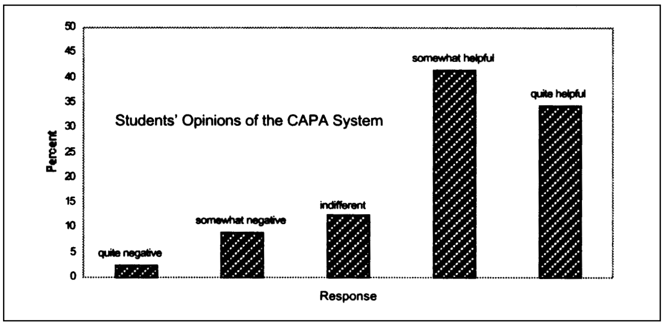


Figure 6: Students' opinions of the CAPA system



and that the CAPA problem sets are better characterised as incentive rather than assessment.

One of the many analytical features of the CAPA Manager is the determination of the degree of difficulty of a question equal to the ratio of the number of attempts to the number of successful responses. A typical range of degrees of difficulty is illustrated in Figure 5. An unusually high degree of difficulty has one of several causes: the question may involve material that was not, or has not yet been, discussed; the material may have been explained inadequately; the question may indeed be more difficult; or perhaps it is too easy for students to make random but incorrect guesses. Question 4 in Figure 5 generated considerably more attempts than other questions – almost certainly due to some early incorrect guessing. This question is a non-numeric TYPE III question (reproduced in Figure 1). Question 1 in Figure 5 is a simple numeric TYPE I problem with a slightly higher than average number of attempts; it asked for a calculation of a volume in cubic meters when length, width and height are all given in feet and inches. Invariably many students neglect to cube the conversion factor after calculating the volume in cubic feet or cubic inches. The value of the statistical and analytical functions of the CAPA Manager lies in the easy discovery of unrealised problem areas and possible misconceptions that students have of the subject matter.

Asked for their opinion of the CAPA system, students responded as illustrated in Figure 6 (mid-semester Fall 1999).

76% of the enrolment responded that the system was helpful, 13% were indifferent, and 11% were negative in their response.

The most common favourable written comments were "...helps me understand the material better.", "It makes me sit down and study the material.", "...forces me to keep up.", "...a way to make sure that I understand the key concepts.", "...doesn't punish you for getting the wrong answer.", "...can't think of a better way to submit homework for such a large group of students.", "...a great idea.", "...helps my grade.", "I prefer it to other forms of homework."

The few more negative comments were "CAPA questions should be more like those on the examinations.", "...tedious...frantic to find the answer rather than evaluating the problem.", "...doesn't prepare me for the examinations.", "...need more tries.", "CAPA stands for computer-assisted pain in the...but it encourages me to study the material.", "...takes too much time...one a week is too much."

In general, students' responses were overwhelmingly positive. Even those students who did not like doing the CAPA problems appreciated the satisfaction and reward of getting the answers correct.

Discussion

Student Study Patterns

The application of CAPA described here was intended to encourage the students to develop a regular study habit and to engage in co-operative discussions with other students. The number of logins and the overall CAPA scores show that the majority of students regarded the weekly tests as sufficiently important for them to work at them regularly–thus ensuring that the first objective was met. Furthermore informal feedback from the students revealed that during the most recent semester (Fall 1999) study groups have formed spontaneously in almost all the residence halls on campus. These study groups typically meet during the evenings once or twice each week. It seems likely that the students are encouraged to meet and study together because a favourable environment for collaborative work has been established[6,25]. As Ward and Bodner state: "*Students should never be rewarded because others fail. Nor should they fail because others succeed. It is possible to create an environment where students work together so that everyone who is willing to work can succeed*". In this case the co-operative environment is created by removing any competition to obtain the best grades (through the fixed grading scale and the opportunity for multiple attempts at each question) and by the varied style of question which encourages a range of intellectual activity.

Question Design

The question design is a key factor in determining whether the habit of regular study that is encouraged by the weekly problem sets actually results in effective learning. Thus the effectiveness of the CAPA system depends heavily upon the effort devoted to the design of questions and problems. This is perhaps more important for those students who are taking chemistry because they have to rather than because they want to. If a student's motivation is simply to get the correct answer, then the more the question compels the student to think and understand, instead of just using an algorithm or formula supplied by a friend or on an internet chat room, the more effective the question is in encouraging study. It is fairly easy to write and code questions that are straightforward algorithmic TYPE I problems and some of these are often useful–indeed they are included in our problem sets. However, as indicated in the Appendix, the CAPA system allows the generation of hundreds or thousands of variants of each coded question so that even with this most basic kind of question students cannot copy their answer from a friend, though they can often obtain the correct algorithm for calculating the answer in this way.

It is important to write TYPE II numerical questions that compel more thought by students. Figure 1 allows a comparison of this sort of question with a simple algorithmic TYPE I question on the same topic–the application of the mole concept. The TYPE II question, intended to be the more thought provoking, is in two parts; it requires consideration of how Avogadro's number is defined and what a mole is. As in the simple TYPE I equivalent, the question can be varied sufficiently to yield 2000 randomly different versions by randomly choosing the fraction, the first element, and the second element. When a problem has two required answers like this, it can be written as two separate but linked questions or as a single question requiring two answers, both of which must be correct. The increased thought provoked by this type of question is shown by the increased email traffic with instructors, increased student visits to the chemistry tutoring (help) room, increased postings on the student internet chat room, and the higher degree of difficulty revealed by item analysis: (Difficulty: TYPE I: 1.3; TYPE II: part 1: 3.0 and part 2: 3.2).

Non-numeric TYPE III questions designed to test knowledge are useful and are always included in our problem sets. Chemistry, at least to our freshman students, is a foreign language. As such, its vocabulary and syntax must be learned and practised–this is the lowest level, but a necessary one, in Bloom's hierarchy of educational objectives[4]. Non-numeric questions are included to encourage this learning.

Conceptual TYPE IV problems are often pictorial although they need not be–the ability to imagine the behaviour of matter at the particulate level implies an understanding of how and why things happen.

Overall View of the CAPA System

The use of the CAPA system in General Chemistry at Michigan State University has been a very positive experience. From the student's view, the immediate feedback, the possibility of retrying the problem if necessary, and the impact that success makes on his/her grade, all contribute to the positive feeling about the program. It has increased the amount of time and energy devoted to chemistry by the students and it has encouraged them to collaborate in their learning. The system requires an active study of the material–the fact that each student has a unique problem set requires each student to solve their own set while allowing co-operation and discussion between students. Students have to become responsible for their own learning and they are motivated by the fact that they can indeed ultimately get all the questions correct with no penalty for the number of their attempts. The weekly required completion of a problem set of ten questions keeps the student on track and up-to-date.

From an instructor's point of view the increased study done by the students, and the timeliness and regularity of their study, is rewarding. Furthermore it is now possible to monitor the progress of individual students and provide early warning of possible problems and potential failure on an up-to-the-minute basis.

Acknowledgements

The CAPA system has since its inception been developed under the leadership of Ed Kashy in the Department of Physics and Astronomy and the National Superconducting Laboratory at MSU. The work of Wendy Whitford and Steve Poulios of the General Chemistry Office in the day-to-day operation of CAPA is invaluable, as is the support of Guy Albertelli and Felicia Berryman, system coordinators of CAPA at MSU. This paper was presented in part at a conference at Michigan State University February 1999[26].

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27. Readers interested are encouraged to contact the author for the code for questions illustrated in this paper. Readers may also visit http://capa2.nscl.msu.edu/homepage/VariousProblems.html to try a problem set in chemistry

Appendix A Question Design and Coding

As described in the body of the paper, we characterise questions as one of four basic types:

- TYPE I Straightforward algorithmic
- TYPE II Thought provoking numeric
- TYPE III Non-numeric tests of knowledge
- TYPE IV Conceptual

Random and choose functions for numeric or string variables allow great flexibility in the design of questions[27]. A general strategy, for example, is:

/LET indx = random(1,4,1) //chooses a random value for indx from 1 to 4 in integer steps

/LET diatomic = choose (indx, "hydrogen", "chlorine", "nitrogen", "oxygen")

In principle it is the application of these functions that makes it easy to generate a great many individual questions from the same stem.

The code for a type I question, such as that shown in Figure 1, includes ranges of numbers from which other numbers are calculated. In all such cases the numbers are varied so that each student is provided with a numerical problem quite different from others in the class. For example, in the question illustrated in Figure 1, the value 1.010 is chosen at random from a range of 85 possible values and the number 119.897 is chosen from a range of 25 values. For a Type II question such as that shown in Figure 1, many versions can be generated by varying the identity of the two elements shown in the example as fluorine and magnesium. Other Type II questions do not involve the use of strings. An example is

Consider the reaction of nitric oxide NO with oxygen O_2 to form nitrogen dioxide NO_2:

$$2NO(g) + O_2(g) \text{ Æ } 2NO_2(g)$$

Suppose that a 3.0 liter vessel contains NO gas at 3.0 atm pressure. Suppose that a second vessel, 4.0 liters in volume, contains O_2 at 2.0 atm pressure. Now suppose that the two vessels are connected by a pipe of negligible volume and the two gases mix and react to form as much NO_2 as possible. Assume that the gases behave ideally and that the temperature is the same at the end as at the beginning. What is the pressure inside the apparatus at the end of the reaction?

This question requires a clear understanding of the principles involved. It invariably causes some anguish amongst students, requiring as it does not only their understanding of the relationship between the relative number of moles of a gas and its partial pressure but also their recall of the principles of stoichiometry and limiting reactants. The degree of difficulty (Fall 1999) was 5.8–the highest on the set. Algorithms can be written for the solution to numerical questions such as this (they are coded in the question). However, they are sufficiently complex to discourage their formulation by students.

In general, the sharing of algorithms by students may be circumvented by coding a sufficient number of random permutations of the question–altering the question stem, the variable to be evaluated, as well as the random values assigned to other variables – so that no single algorithm is available. For example, if a question tests the stoichiometry of a reaction then one of a series of similar but sufficiently different reactions can be chosen at random.

Other requirements and features are also coded in the questions, for example: the accuracy and precision required in the answer, the number of tries allowed on the question, the point value for the question, a hint provided if the student's first (or other number assigned by the instructor) response is incorrect, and an explanation of the answer made available after the closing date. These and other features of the code and the formatting of the problem sets using LaTeX are described in the CAPA User's Manual[15].

Type III non-numeric questions such as that illustrated in Figure 1 invariably involve a mapping function that scrambles sets of variables based upon a randomly generated seed, thus ensuring that a large number of individual questions can be created from the same stem.

A Type IV pictorial problem is illustrated in Figure 1. It provides views at the particulate level of substances and mixtures in different states and the student is required to match the pictures with the appropriate description. The CAPA system facilitates the coding of questions such as these. In this question, the five diagrams are chosen from eleven possible, the names of the substances involved are chosen at random, and the order of the pictures and questions is randomly mapped–giving rise to hundreds of quite different versions of the question. The task for the instructor is only to draw a sufficient number of pictures and write a sufficient number of possible examples to match. The incorporation of figures and diagrams as eps files in CAPA questions is straightforward – some other examples are shown on the CAPA web site[27].