New Tools to Improve Student Success in Problem Solving

Bert Ramsay
President, *Chemical Concepts Corporation*
32 North Washington St., Suite 9-B
Ypsilanti, Michigan 48197-2662
Bert@chemicalc.com

And
Emeritus Professor of Chemistry
Eastern Michigan University
Ypsilanti, Michigan

Abstract

This paper will discuss how the Chemical Calculator (U.S. patents 5,265,029; 5,604,859; and patents pending) can be used as a learning tool to improve students' basic problem solving skills. The chemical calculator is designed to function as an "electronic" tablet on which the student can write the solution to a problem, and then complete and display the calculation result (with units). In addition, practice in the development of paper-and-pencil problem solving skills is provided to the student via the *Personal Tutor* mode. The *Personal Tutor* provides suggestions for correcting both unanticipated-, and commonly encountered incorrect answers. The *Personal Tutor* can also help with a step-by-step solution to problems. The *Learning Curve Monitor* tracking of 1) the number and type of incorrect answers, 2) the amount and type of help received, and 3) the time spent on the problem virtually guarantees (*) student success. (**Caveat*:: the student must still do the work, and take responsibility for their success!)

How this paper is organized: The main body of this paper is found in this page as summarized in the table of contents. As you proceed through the topics you will find links to other sections that illustrate some of the applications and uses of the chemical calculator. These illustrations will, I hope, serve to support some of the conclusions I make about the value of the software tools I have developed. (See Section XI.)

Table of Contents

I. Introduction

It may be safe to say that one of the most important goals of chemistry teachers is the development of the problem solving skills of students.

"Chemistry teachers would like their students to become excellent problem solvers. Yet most students find problem solving one of the most frustrating aspects of their introductory chemistry courses. Lack of success in solving problems probably discourages many students from taking any chemistry courses after their first." (Gabel, 1989)

"We now turn to more specific considerations of learning that are important in chemistry. We begin with problem solving because it represents the ultimate goal of chemistry education." (Herron, 1996)

Although much research has been done to identify the reasons for the lack of success in developing problem solving skills, strategies proposed, software and multimedia products created, we have yet to see the kind of tools that would support and facilitate student learning.

The purpose of this paper is to discuss how the chemical calculator and its companion *Personal Tutor* might fill this need. Since the introduction of the chemical calculator in 1990, like the calculator in the 1970's, has met with some opposition from chemistry teachers as to the legitimacy of its use by students I think it worthwhile to give some background to the invention.

II. Background of the Invention of the Chemical Calculator

A. Some Biographical Information:

Until my retirement in 1995, I had been a member of the Department of Chemistry at Eastern Michigan University since 1965. My teaching and research interests have focused in the areas of organic chemistry, the teaching of chemical information retrieval, and the history of chemistry. My earlier contributions in chemical education research have focused on the use of media technology for the teaching of chemical information retrieval.

B. Background to the Invention:

The concept of a chemical calculator was conceived while attending the national meeting of the American Chemical Society in Dallas, Texas in the spring of 1989. (Some of you who attended that meeting may recall the "basketball court" presentation by Stanley Pons of "cold fusion"! It was an exciting moment in history - the significance of which remains to be seen.) The idea: Wouldn't it be nice if you could carry around a periodic table-calculator with which you perform chemical calculations - for example, by writing a chemical reaction, balance the equation, and complete stoichiometric computations. This would be a "chemist's calculator".

I was able to locate a programmer to develop the program to "reduce the idea to practice". Since the requirements for producing this in a hand-held form were financially prohibitive, the program was created as a DOS application with a connection to a touchpad containing the periodic table, numeric- and unit keys. The touchpad served as the model for the hand-held device. The touchpad interface proved impratical and was replaced in 1993 with an onscreen periodic table and numeric- and units keypad that could be "touched" by a mouse click. The current version of the chemical calculator software has eight calculation modes. (We will see later how four of these modes are used for solving problems.)

C. Patent Application:

An application for a U.S. patent was filed in 1990, and issued in November 23, 1993 as **U.S. patent 5,265,029**. (European applications have been filed as well.) A related patent (U.S. 5,604,859) was issued on 2/18/97. Other patent applications are pending. Suffice it to say, it was not long after the patent was issued that objections were raised to this patent. An article, and letters, published in *Chemical & Engineering News* in 1994 summarizes some of the issues..

D. Commercialization Activities:

Most academics involved in the creation of intellectual property (e.g. laboratory research discoveries, textbooks) do not concern themselves with the commercial value or use of their property. In the case of textbook, for example, the commercialization is left in the hands of a publisher. Multimedia creations have often been handled the same way, or marketed by not-for-profit organizations.

I mention this only to point out that after I had filed the first patent application, I decided that I would try to market and sell my invention myself. The chemical calculator (with trade name: CHEMiCALC) was introduced in August of 1990 as part of the Exposition at the national meeting of the American Chemical Society in Washington, DC. Suffice it to say, after over 9 years in this entreprenurial venture, I have yet to make my first dollar, much less million. I would probably not repeat this way of "testing" the value of my invention. I hope the discussion that follows will reflect what I have learned from this experience. (I might mention that a proposal, submitted as a Phase II National Science Foundation Small Business Innovation Research Award, to evaluate the educational use of the handheld chemical calculator was not recommended for support.)

III. Solving Problems vs. Exercises

Almost immediately after the introduction of the chemical calculator (as "**CHEMiCALC: The** *Chemist's* **Calculator***!* "), I encountered chemistry teachers who expressed their concern about letting their students use this tool which they believed would "do the calculations" for them. They were also concerned that students would never learn how to solve problems on their own. Similar reactions have been emcountered, for example, in the acceptance of the use of *MathCad* (published by MathSoft) and Dave Brooks' *Stoichiometer* program. (Brooks, 1995)

A key question:" How would the use of this tool by students affect the development of their problem-solving skills, compared to the development of their exercise-solving skills? It is not always clear what type of skill development we are encouraging in the classroom. A review of some definitions is in order.

A. Defining Problems and Exercises

1. **Problems**: Most reserchers who have studied problem solving have adopted one, or both of the following definitions:

" 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, 1980)

"What you do, when you don't know what to do." (Whetley, 1984)

2. **Exercises**: An exercise (*algorithm*) may be defined:

"Rules for calculating something that can be followed more or less automatically by a reasonably intelligent system, such as a computer." (Ehrlich, 1980)

"Problems exist along a continuum, from well-defined to ill defined, and along another continuum, from routine to nonroutine. *Routine problems* are those that we frequently encounter, and we develop well-defined procedures for solving them. We refer to routine, well-defined problems as *exercises*, and we refer to nonroutine, ill-defined problems as *problems*." (Herron, 1996)

B. Logical Consequences of these Definitions:

"If you accept these definitions, there is a fundamental difference between an exercise and a problem. We all routinely encounter questions or tasks for which we don't know the answer, but we feel confident that we know how to obtain to obtain the answer. When this happens, when we know the sequence of steps needed to cross the gap between where we are and where we want to be, we are faced with an exercise not a problem." (Bodner, 1991)

We might argue that just as a standard calculator is accepted as a useful tool for solving exercises, we should view the chemical calculator in the same way when used to solve exercises. I believe that its use will facilitate the development of problem solving skills as well since the chemical calculator, unlike a standard calculator, provides additional help in the setup, and completion of the many routine calculations that comprise the components of a successful solution to a problem.

IV. Barriers to Developing Problem Solving Skills

A review of the research on problem solving reveals that there are many barriers to developing novice students as successful problem (or exercise) solvers. The conclusions of some of these studies are summarized in parts IV and V below. (The documentation for the sources is found in the References section of this paper.

A. Cognitive Skill Development and Attitudes

1. **Chem- and Math Anxiety**: It seems many students come into chemistry courses with many anxieties about their ability to be successful problem solvers.

2. **Math Skill Development and Background.**

3. **Concrete vs. Formal Reasoning skills.**

4. **Selecting an Appropriate Strategy:** What is an approriate strategy? Factor-Label (Dimensional Analysis), Proportional reasoning, algorithms, concept maps.

5. **Conceptual vs. Algorithmic Problem Solvers:** Are there different kinds of problem solvers and/or different kinds of problems?

6. **Short-term (working) Memory Overload:** Does the initial complexity of a problem overly burden novice problem solvers?

7. **Active vs. Passive Learning Environments:** Is our passive "lecture" format for teaching so pervasive that it is difficult for students to get into an acitve mode until they take a test?

8. **Educational Messages:** Is our educational system set up to point out the students' limitations and failures? (Is the message: "You "failed" the test with 60% incorrect answers!" Or "You had 40% correct answers. What can be done to increase that percentage?" **Successful problem solvers believe they can solve problems; unsuccessful problem solvers do not believe that they can solve the problem and often give up. Need to maximize the chances of early success, rather than failures.**

B. Understanding and Representing Problems

1. **Problem Presentation:** How does one respond to Gabel's suggestion? "Student difficulties with chemistry problems may result in part from the way problems are presented. Educators must take care to write problems that are clear and unambiguous, drawing on available information about the differences between expert and novice problem soling." The fact is that it is very difficult to be clear in the problem presentation when you are dealing with students who may not be to handle the inherent level of the problem's complexity.

2. **Working on Problems and Exercises:** "Solutions to textbook problems are archistic - that is, they show the logical sequences of steps that are strung together in a linear fashion [as used to solve an exercise].

3. **Do we teach Problem Solving?:** "We do not tell students how we solved the problem, but rather the process used to solve the exercise."

4. **Learning from Examples:** "Research has shown that the **least effective strategy for teaching students** to solve problems is working examples for the learner - the strategy typically used in introductory texts and classroom presentations, [and most tutorial programs]."

5. **Pace of concept development:** Many types of problems are presented in a relatively short period of time - before the student has had time to develop some basic problem solving skills. For example, by the middle of the first semester of introductory chemistry, the student is asked to solve reaction stoichiometric problems - which many instructors agree is one of the most difficult concepts to grasp.

6. **Herron and others stress some of the ways novice students approach problem solving:**

- Often focus on inaaproriate aspects of a problem.
- May change the problem representation during problem solving.
- Sometimes apply procedures rigidly and inappropriately.
- Let their beliefs guide their approach to problem solving.

- Often systematically distort the problem to be consistent with prior knowledge.
- Have difficulty in breaking down a complex problem into sub-problems.
- Have difficulty seeing the explicit steps taken by experts to solve problems.
- Misunderstand or change the goal of the problem.
- Do not fully understand the conditions placed on a problem.
- May include unessary assumptions.
- May not spend much time on analyzing the problem.
- Have difficulty seeing the problem as a "whole".
- May not spend much time on verification: Students who have no confidence in their problem solving ability often see little point in spending additional time checking their work.

C. Reading and Working Problems

1. **Manipulation and understanding of symbols:** "The instructor [the successful problem solver] writes symbols which represent a physical reality. All too often, students [unsucessful problem solvers] write letters and numbers and lines, which have no physical meaning to them." (Bodner)
2. **Using the appropriate algorithms:** It is not always clear which type of algorithm is appropriate for solving a particular problem. Is this a "mathematical" problem - for which you can use a mathematical formula? Or is this a "conversion factor" problem - which can be solved without a mathematical formula? In fact, however, most introductory chemistry problems can be solved with both kinds of algorithms. The more complex problems may require both.
3. **Uncoupling of Conceptual understanding from the mathematical maipulations required to solve problems:** See the next category.
4. **Reading Errors:** Getting a good start on the solution to a problem can be side-tracked by "reading" errors. For example, if you started a problem with "25g" when the problem stated "25kg".
5. **Calculation Errors:** The variety of errors that are commonly made while working through a problem may well account for the high level of frustration experienced by many novice problem solvers. Let us look at them as a separate topic.

V. Types of Calculation Errors

Calculation Errors: The variety of errors that are commonly made while working through a problem may well account for the high level of frustration experienced by many novice problem solvers. The two types of calculation errors that result in an incorrect answer are either anticipated or unanticipated. A student may make any number and types of errors while working through a set of problems. Hierarchies of errors are also encountered as the complexity of the problem increases. (Take a break, and complete this sentence: "Every morning is the dawn of a new [?]"

A. Unanticipated Errors:

(The first two types of unanticipated errors described below could not, of course, be considered as the result of a calculation error.)

- **Unit labels:** An answer was submitted with no, or an incorrect unit label. (For example, the answer

"25.5" or "25.5kg" was submitted instead of the correct answer.)

- **Non-unit labels:** An answer was submitted without an indication of the identity of the substance.
- **"Magnitude" Calculation Errors**: These types of calculation errors are quite common, and are difficult to identify and correct.

B. Anticipated Errors:

You do not have to have been a chemistry teacher or tutor for long to notice the frequency of certain kinds of mistakes and errors made by students working on chemistry problems. In fact some kinds of mistakes are so common that they find there way into the incorrect answers inserted in multiple choice questions. An important objective in converting the novice problem solver to an expert is to find ways for the novice to recognize them and avoid making them again. The difficulty for the novice to achive this objective (while working on their own) is that each problem may generate its own unique set of mistakes. It is not always easy to locate the mistake and/or understand what might be done to correct it. After spending what seems an inordinate amount of time trying to find and correct the error, many students soon lose patience and give up. Some conclude that their frustration indicates that they will never become effective problem solvers. (How many times have you heard students tell you: "I'm not smart enough to solve these problems"?) As the course progresses very rapidly to introduce new concepts before older ones have been assimilated and understood, the frustration level among many students increases.

C. Hierarchies of Errors

As a student moves through an introductory chemistry course, not only do the problems become more complex, but the number of possible errors and mistakes that could be made increase as well. Think of how many of these types of errors were made by your students in a test, or in tutorial conversations.

1. **Input and Reading Errors**

Beginning students encounter these kinds of errors even before they use a calculator. For example, the digits, 0.25, 5.2, or 3.5 might have been entered in the calculator instead of the correct value of 2.5. These input-errors may have arisen from a simple "decimal point" error, dyslexia, or the wrong punch of a calculator key.

2. **Transcription Errors**

The solution to a problem may require you to locate, correctly copy some data, and then enter the digits into the calculator. Unlike a simple input error, if you copy the data incorrectly, a "check" of the calculation result by repeating the calculation would produce the same result.

3. **Computational Errors**

In a multistep calculation, one simple error in the choice of an arithmetic operation (multiply, divide, add, substract) is not easy to catch since there is no record of what you did in each step.

4. **"Mathematical Formula" (Algorithmic) Setup Errors**

The use of a formula or equation as the algorithm to solve a problem requires the correct rearangement for the calculation of the unknown. When this is done in haste, you may encountersome of the terms inverted or improperly assigned. For example, a novice problem solver wishing to determine the mass of a substance, given its density and volume, may end up calculating the mass = D/V or V/D.

5. **Chemical Formula Errors**

A variety of "chemical formula" errors are possible for any problem involving mole conversions.

a) **Reading the formula:** When looking at a chemical formula, was the formula copied as written? Did the formula show a subscript of "2" or "3"?

b) **Formula/Name conversions:** A common error in working on problems that involve mole conversions arises when an incorrect chemical formula is written based on the name given in the problem. For example, the student asked to use the molar mass of "calcium chloride" in a mole conversion, might calculate the molar mass based using "CaCl" as its formula.

c) **Constituent Element Counting:** A frequent error arises from not properly counting all of the elements inside the parentheses. (Example: The constituent element count for "calcium hydroxde" is given as: 1 Ca, 1 O, 2 H.)

d) **Molar mass calculations:** There are many other areas for calculation errors. Should also consider how the molar mass conversion factor is used in the setup (use: "18g/mol" or "1 mol/18g")?

6. **Stoichiometric Relationship Errors**

There is a lot to keep track of by the time you have started to work on reaction stoichiometric problems:

a) You must write the correct formulas of all of the reactants and products.

b) You may have to calculate the correct formula weights (molar masses) of the reactants and products.

c) You must balance the equation.

d) You may have to carry out a series of mass -> mole -> mole -> mass calculations, while keeping track of which stoichiometric factors should be used.

VI. Developing Problem Solving Skills: Two Assumptions

I believe that the chemical calculator and *Personal Tutor* are two tools that can help students develop their problem solving skills. I would start by making two assumptions:

Assumption #1:

Students that possess basic problem-solving skills should be provided with the kinds of calculation tools that would eliminate (or at least minimize) errors, save time, and reinforce their understanding of their solution to the problem.

I would, however, offer the opinion that once these tools are in the hands of the beginning students, they may well find that they will quickly learn how to demonstrate that they qualify as the possessors of basic problem solving skills.

The next section of this paper shows how the chemical calculator fufills the expectations of this assumption.

Assumption #2:

Beginning students should be able to demonstrate their understanding of how to solve problems in a traditional manner (i.e. paper and pencil and/or calculator) before being allowed to use the "advanced" calculation tools.

The *Personal Tutor* mode of the chemical calculator is designed to fullfill the expectations of this assumption.

VII. Solving Problems with the Chemical Calculator

A. A Model for Problem Solving

George Bodner (1991) has provided a model for problem solving that underlies the design and use of the chemical calculator as a unique tool. May I paraphrase as follows:

We really don't understand a problem until we have an answer to the problem.

Keep in mind that a student still might not get the correct answer because of their lack of content knowledge, cognitive skills, etc. or understand it in a way that compliments you. (Bodner has proposed a simple 16-step "anarchistic model of problem solving" that has been rejected by some of his colleagues who argue "that we can't expect students to approach problem solving in the same way" we do in research.

B. The Chemical Calculator Model for Problem Solving

The chemical calculator is designed to help the student successfully complete problems in such a way that they also understand how the solved the problems.

Some of the ways this design can assist in the successful solution of a problem, as well as its understanding of how the problem was solved:

- **Build Understanding with the "Electronic" Workpad:** By including both the setup and the calculator in one place, the student constantly encouraged to examine how the problem was solved. The inclusion of units with the values, and unit tracking allows you to check for many setup errors
- **Assess Understanding:** "Assessment of student performance should focus on the student's ability to justify and explain what they know." (Ward and Bodner, 1993) This means we would expect the novice problem solver to be able to not only write out the setup, but also explain why it was setup that way. (This is an expansion of expectation for receiving "partial credit" for including the setup even if the answer is given.)
- **Increase Student Responsibility:** The responsibility for the correct answer to the problem depends on what each student does. (WYSIWYC: What You See Is What YOU Calculated!) This builds up student confidence and removes the fear that the calculator is solving problems for them.
- **Reduce Errors:** Many calculation or input errors can be immediately spotted and corrrected with the UNDO function. Computational errors are minimized. (Example: the time spent, and the errors made in completing a routine molar mass calculation are virtually eliminated.) You can save time on the many routine calculations that interfere with your "what If" explorations. (Look at problem #3.)

Design Limitations:

Conceptual misunderstandings are not automatically identified or explained. (For example: the chemical calculator will not tell you if you have written a correct chemical formula, how to balance an equation, or why the equation you have written can not be balanced. The chemical calculator may not help you eliminate the errors that led to one of your anticipated incorrect answers. The *Personal Tutor* takes care of most of these problems. (Section VIII below.)

C. Sample Problems

Let's look at the how the chemical calculator may be used to solve three typical types of problems:

1. A density calculation problem.
2. A mole conversion problem.

3. A reaction stoichiometry problem.

It is recognized, however, that a student just beginning the study of chemistry may not have enough background to use this tool efficiently. The *Personal Tutor* mode was designed to help this student.

VIII. Developing Problem Solving Skills with a *Personal Tutor*

A. Why a *Personal Tutor* Mode?

As soon as I introduced the chemical calculator in 1990, I encountered opposition from many teachers to allowing their students to use it. After a demonstration of the chemical calculator to several high school chemistry teachers in Michigan, one of the participants said:

"Several teachers from the Midland school system were quite vocal, saying that this would keep kids from having to go through the mechanics of doing the calculations and thinking things out more thoroughly.:

Suffice it to say, I believe that many viewed the chemical calculator as a kind of "black box" that did the calculations automatically for the students. The word "calculator" was given a meaning that suggested that the student had someone doing the work for him. No matter how many demonstrations I gave in the next several years (as provided above), I was successful in changing the perceptions of only a very small percent of these teachers. A solution to to this dilemna only gradually emerged as I began to ponder how the chemical calculator could be used to respond to the following scenario. How many of you have encountered the student coming into you office with the following complaint?

I spent hours studying for this exam! I don't understand why I missed so many of the questions!

Now I am sure most of you have found that not only had they not spent the time necessary to properly prepare for the exam, but that the way in which they used the time was not productive. This would be quickly pointed out with the following question:

"Now look at this exam question you missed. There are at least 6 homework problems like this. Did you work through all of them?

Here is a likely scenario that describes what the student might have done on these homework problems. (Compare this model for novice problem solvers to the anarchistic model used by expert problem solvers.)

1. Reads the problem.
2. Writes something.
3. Does something - perhaps a calculation.
4. Opens the *Solutions Guide* in which the solution to the problem is shown.
5. Identifies a mistake or error, or perhaps confirms that his/her "mental setup" was the same as shown in the *Solutions Guide*.
6. Looks in the *Solutions Guide* at the setups for rest of the problems.
7. Says to him/herself: "*Now I know how to solve these problems without repeating that mistake*".
8. Goes out for a beer or orders a pizza.

So in perhaps 5 or 10 minitues had been spent working in this way on the 6 homework problems.

Now there are at least two reasons why the student was not prepared for the exam:

1. **Learning from our own mistakes:** Most of us learn by making our own mistakes. Only a few of us learn from seeing how others solve a problem, or others make mistakes.

2. **Understanding the variety of mistakes we make:** Every time you work a problem, you may make a different mistake for which the Solutions Guide may not give you any help.

B. Using the *Personal Tutor*

Of course, you as a teacher could sit with the student as they work the problems and help them identify the where they are having problems. But, of course, you have not the time to do this with every student. Hiring, or using peer tutors, may solve some of the limitations of personalized help. But there are not enough tutors available to help all of the students that need them and when [1 a.m. the night before the exam!] they need them. The *Personal Tutor* mode was created to respond to this need.

Imagine a *Personal Tutor* sitting next to every student who will:

- **Check** the answers they have calculated for a homework problem and suggest some things to do to their setup that might remedy the incorrect answer.

- Help **setup** up the solution to the problem.

- Monitor the student's progress in developing their problem solving skills

Let's look at how this *Personal Tutor* is able to help develop students' problem solving skills on two of the three problems we worked on earlier using the chemical calculator. When you have finished this tour, come back here and check out one more thing the *Personal Tutor* can do to virtually guarantee the students success!

IX. Tracking Student's Learning: the *Learning Curve Monitor*

How many problems should a student work on before they can be confident of their problem solving skills? I think most of us would say that it is not simply the number of problems worked by the student that is crucial, but the number of things learned, and remembered, while working the problems that would help them become more efficient problem solvers. What you would like to have is a record kept of the kinds of errors you made while working on the problems. The *Learning Curve Monitor* provides this progress report for the student.

- The *Learning Curve Monitor* keeps track of the **Number** and **Types of Incorrect Answers** made while working through the problem.

- The *Learning Curve Monitor* keeps track of the **Amount** and **Type of Help** requested from the *Personal Tutor* while working through the problem.

- The *Learning Curve Monitor* keeps track of the **Time** spent (completed and incomplete) while working through the problem.

Let's look at some examples to see how this works for two of the three problems we solved using the chemical calculator. When you have finished looking at these examples, I'd like to conclude by showing you how the teacher can customize the *Personal Tutor*-linked problem sets.

X. Defining and Customizing Problems linked to *Personal Tutor*

Every teacher can now customize and link the problems to *Personal Tutor*. No programming ability is needed. You can do this with the specific textbook- or homework problem sets assigned to the student, or test questions. I'll show you how the density calculation and mole conversion problems were created, defined and linked to the *Personal Tutor*.

XI. Implications for the Teaching and Learning of Problem Solving Skills

I believe that the main barrier to the development of problem solving skills is the frustration experienced by students unable to identify and correct computational and conceptual errors. Two tools have been developed to overcome this barrier.

1. **Chemical Calculator:** With this tool students will save time, reduce errors, and facilitate their understanding of chemistry problem solving.
2. *Personal Tutor***:** The improvement of beginning students basic paper and pencil problem solving skills can be virtually guaranteed (*) when they use the *Personal Tutor* mode in conjunction with the *Learning Curve Monitor* to keep track of their progress toward this goal. (* *Caveat*: The student still has to do the work, and take responsibility for their success.)

End of Semester Party

Hey, just checking to see if you got this far in the paper. Or did you get here from the table of contents before reading the rest of the stuff?

© 1999, Bert Ramsay, Chemical Concepts Corporation

Contents