TEACHING SCIENCE, CHEMISTRY AND BIOLOGY AT THE COLLEGE/UNIVERSITY LEVEL

Michael F. Shaughnessy, Juchao Yan, William Cooper

Eastern New Mexico University,
Portales, New Mexico, ***USA***

ABSTRACT

When college students arrive in science classes, some are woefully unprepared, some are minimally prepared, and some, while well educated in high school have forgotten many of the basics in terms of basic science, basic scientific reasoning, and basic scientific procedures. This paper examines some of these issues, reviews some of the main areas of concern and delves into issues of formative evaluation and the issue of pre-requisite courses.

Keywords: *teaching, science, chemistry, biology*

INTRODUCTION

All too often, there is a presumption at the college and university level that students are adequately prepared for college and university classes. In some instances, students have been minimally trained in scientific procedures, some have only been minimally trained in terminology, and other lack scientific reasoning skills needed to conduct scientific experiments with rigor. This paper will review some of the main tenets of science, and discuss constructs and realms imperative to success in college science, biology, chemistry and other scientific realms.

TERMINOLOGY

Many students have only a vague inkling of basic scientific terms, definitions and words and phrases. The students often need to have a refresher on terms such as independent variable (that which is measured) and dependent variable (the variable acted upon) and even simple terms such as treatment are often misunderstood. The "treatment" in many experiments can be heat, cold, a liquid, a solid, or the passage of time. The treatment can be as simple as vitamin C or ascorbic acid or water. Students may have difficulty operationally defining these terms or a clear, exact, precise definition needs to be provided to them, and for them, and in some instances reviewed. Students also need to work on precision of thought, thinking and specifying terms.

Some advanced science classes have their own sets of terminology---

Chemistry is often called the central science, and uses experimentation (or measurements) to study the composition, structure, properties, and change of matter.

In measurements, we try to determine our measurement data, which is the number of standard units of a property inherent in an object or system. When expressing a measurement quantity, more often than not, students make mistakes for both the number and the units. As far as the number is concerned, students rarely consider the resolution of their measuring tools (i.e., the smallest, detectable change in the measurement quantity) or the number of significant figures (i.e., all the measured digits plus the last uncertain one) in their measured value. In terms of the units, students sometimes omit the units or use wrong units. When plugging several measured values into an equation to get their desired information, students often get confused on how to determine the propagation of uncertainty. That is, which measured value plays the most important role in determining the final answer's uncertainty?

In choosing a method for their chemical analysis, students often have a difficult time in differentiating absolute methods from relative methods. Absolute methods do not rely on calibration with chemical standards to determine the amount or concentration of an analyte (i.e., the compound of interest) in a sample. Relative methods, however, require some type of calibration with chemical standards. Calibration here refers to the determination of the relationship between the analytical response and the analyte concentration.

In evaluating/assessing their methods or instruments, students often cannot clearly differentiate the following pairs of figures of merit (i.e., a numerical value derived from an experiment that provides quantitative information about some performance criteria for an instrument or method): accuracy and precision, duplicate and replicate, error and uncertainty, limit of detection and limit of quantitation, repeatability and reproducibility, robustness and ruggedness, sensitivity and selectivity, and to name a few.

THE HYPOTHESIS

Sadly, some students did not learn the basics of formulating a hypothesis in purely scientific terms. They have a hunch or a guess, or some vague, nebulous idea about causality- but they have never been asked nay, forced to write down a clear, specific, hypothesis with an alternative hypothesis, nor have they ever put on paper the scientific terms for these statements. Further they have never hypothesized an increase or a decrease due to some other factor or variable. In a sense, the hypothesis is the beginning of any rigorous experiment in that it lays the foundation for the rest of the experiment. It provides some students with a framework, with a structure, that some of them sorely lack. For some students, they know the hypothesis but they need to take the time to write it down for the record, or for part of the experiment for future or later reference. The "null" hypothesis needs to be clearly differentiated from the alternative hypothesis and hopefully the student clearly understand what they are trying to prove, and at what level of statistical confidence they are looking at. For some students that may not have taken statistics, this is again, a problem as a quick refresher course in statistics and the mean, median and mode or even percentages is needed.

THE SCIENTIFIC METHOD

There IS is a method to the scientific madness that often occurs. It may begin with observation, it may begin with a review of the past literature, or it may begin with some vague, nebulous idea stemming from something that they have learned in the past or watched on television. The scientific method requires a certain focus of thinking, a certain rigor of thinking, in some instances a certain clarity and specificity of thought- that not all students possess. There is a clear sequential process and procedure that needs to be followed in experimentation, and not all students have the attention span to focus and attend to the steps and procedures as well as the very exact, specific, processes that need to be followed. Some know the processes but fail to adequately document the steps in the experiment, and fail to follow the results in an orderly fashion. Kuhn, Amsel, O'Loughlin, Schauble, Leeadbeater and Yotive (1988) have investigated the development of scientific thinking and reasoning skills. This is an area with which instructors should be aware and sensitive in terms of their students and their thinking skills and abilities.

STATISTICS

In the old days, numbers, data, and results were often computed by hand, and students could see the mean, median, and mode, and then were left to computer the standard deviation using a hand held calculator. There are many subtle nuances to the realm of statistics- computing the numbers, reporting the numbers and understanding the numbers. Some students may have had algebra in high school, followed by geometry, but they may not as yet have had a formal course in statistics, thus are left to their own devices, or are reliant on SPSS or SAS or BIMED or some other package for computation of calculations.

Computing the numbers is one aspect of the scientific procedure- but understanding the results in terms of the impact of the independent variable on the dependent variable is still another aspect. Reading past results of studies also requires a certain amount of statistic acumen that not all students have. They may not have a grasp of t-tests or ANOVA procedures. They may not understand post hoc (or after the fact tests). Thus, they are woefully unprepared for multiple experiments in which one experiment clearly follows the results of the previous one based on the statistics. Some students may not be aware of the free software on line for computational purposes.

PROCEDURES IN EXPERIMENTATION

While some students may have been minimally exposed to some very simplistic experiment in high school, they are less well equipped to conduct college level experiments, many of which contain multiple variables. They are simply not prepared to conduct multiple experiments wherein the outcome of one depends on another or the next. They are thinking univariate in a multivariate world and not yet prepared to think in terms of the possibility of more than one variable being relevant or salient.

There needs to be a high degree of specificity in terms of what is done first, second, third and so forth in all experimentation. In a college or university lab, there is no room for sloppy, careless procedures, and in fact meticulous attention to detail is the order of the day. This is a skill that not all student have, and even not all doctoral level practitioners have!

Generally speaking, there are seven consecutive steps to follow for any scientific experimentation: 1) define the problem, 2) collect and prepare the sample, 3) run the assay or analysis, 4) process the data, 5) do statistical analysis, 6) obtain solution in problem, and 7) refine the method if necessary.

Kuhn, Iordanou, Pease, and Wirkala (2008) have examined this realm and have indicated that certain specific skills need to be developed in order to achieve skilled scientific thinking. While controlling variables is certainly part and parcel of this realm, there are other aspects- such as understanding the functions of science, and being able to engage in discussion, debate and argument about the findings of scientific experimentation.

KEEPING DATA

The essence of most scientific experimentation is the realm of data. Students need to be cognizant of the fact that results are contingent upon accurate, specific, exact, precise data. This data has to be kept over the course of the experiment, and with computers and Microsoft Excel, it seems easy for students to be able to keep data on their flash drives and store their data. Hopefully, they will not lose their flash drives during some evening event at some dorm.

SAFETY

In certain realms of chemistry, and other scientific endeavors, it is imperative that safety procedures be followed, particularly in terms of chemistry, chemicals and hazardous materials. Instructors may have to teach safety procedures and how to handle certain materials. Procedures should also be taught regarding the handling of certain substances, and the disposal of waste materials. Latex gloves, and eyeware to protect the eyes is often needed.

SCIENTIFIC THINKING.

As the student progresses along their journey, they need to be employing scientific thinking and examine and explore all facets of each experiment. Constant vigilance is often needed, and not all students have the acumen for this part of the experiment. Constant observation, constant recording, constant note talking is imperative in certain longitudinal experiments so as to isolate the factors needed for future or further investigation. In some instances, visual observation is just as important as the analysis of the data- as some microscopic events may yield interesting observations and lead to a future experiment. Kuhn (2002) has written on this topic of scientific thinking and it's development. Further research into the current cohort of students is sorely needed. Further, Kuhn and Dean (2004) have delved into the aspect of connecting scientific reasoning and causal inference.

SAMPLE SIZE

While some students comprehend the importance of "sample size", not all students understand the need for an adequate number for statistical power. At the college level, certainly there is an expectation that we are simply exposing students to the scientific method and experimentation. However, there are caveats that need to be stated. Sample size is often linked to statistics, and again, it is not always as comprehensively reviewed there as it needs to be. But basically, inferences, or conclusions cannot be drawn from small sample sizes, and those inferences that are drawn have to be seen with caution, and those concerns clearly indicated in the final report. It is imperative that students understand the very real limits of small sample sizes and generalizability.

USING THE INTERNET

In some experiments, it is generally sound practice to review what has been done in the past by other eminent scientists and thinkers. Students should be encouraged to use the library and the Internet to procure at least preliminary information as to what research has already been conducted, and what the results have been. Unfortunately, the Internet does not always contain reliable, dependable information and students do not adequately search thoroughly. Browsing through the stacks is a skill that not all students have. They are not always able to separate the "wheat from the chaff " so to speak. Instructors need to provide some guidance in these areas. Some specific realms of science have very specific sites that they can direct students to so as to expedite the learning process.

WRITING SCIENTIFICALLY

Sadly, many students arrive at colleges and universities woefully unprepared to write clear, cogent, concise, summaries of scientific experiments and the results of said experiments. Instructors may need to provide adequate templates, or examples for students to emulate. Students need to understand that they may need to write, polish, edit and re-examine their work and possibly have a graduate student review their work before submission. Obviously adequate time is needed for this, so students have to allocate their time accordingly and plan for revising their work.

In each scientific domain, there are certain procedures and protocals protocols. Microbiology is different than micro-chemistry, which is different than physics and so forth. Each discipline, while having commonalities, also have certain ways to writing, specific to their discipline. Formatting is important, and needs to be emphasized.

Being a sub-discipline of chemistry, Analytical Chemistry is "the science of obtaining, processing and communicating information about the composition and structure of matter."

(http://www.acs.org/content/acs/en/careers/college-to-career/areas-of-chemistry/analytical-chemistry.html)

That is, Analytical Chemistry is the art and science of chemical analysis. In chemical analysis, our goals are to identify, quantify, detect and separate compounds of interest.

To teach students how to write professionally in Analytical Chemistry, an instructor should start to develop their writing skills in the introductory course of Quantitative Analysis. In Quantitative Analysis Laboratory, students learn how to quantify their unknowns precisely and accurately. Each student is required to have a bound (but not spiral) lab notebook. The purpose of the lab notebook is two-fold. First, it should be the only guide students need to do experiments in the lab. They should therefore come to class with a pre-lab write-up already done (see below). Secondly, the lab notebook should keep a record of exactly what they did in the lab, what might have gone wrong, and all calculations necessary to get their results. The most important thing about the lab notebook is its completeness.

Pages in the notebook should be numbered and the date when the data were taken should be written on every page. Enter data in ink as soon as taken. Never copy numbers from loose sheets of paper. Cancel out errors and reject data by drawing a single line through the spurious entries. Never try to erase or obliterate entries or remove pages.

The following six entries should be put in the pre-lab write-up: the name of the experiment, the date when the experiment will be carried out, the purpose of the experiment, a reagent table, the procedure to be followed in performing the experiment, and prepared tables to fill in with data to be collected during lab. The reagent table should include the names of all chemicals to be used in the lab, any data about the compounds relevant to the calculations, and hazard information about the chemicals to be used. The procedure should be complete enough to allow them to perform the experiment without looking at the manual, and written in a column on the left half of the page to allow them to write observations on the right side during the experiment.

While performing the experiment in the lab, students should record all observations in the column beside the procedure, all data in the data tables, and any errors which might throw off a result.

After the lab, students should include all calculations, graphs and printouts from the instruments and computer in the notebook. Based on their data processing and result discussion, they should draw a concise and scientifically sound conclusion, which should be included in their lab notebook as the last component of their reports. Kuhn (2007) has suggested that the reasoning about multiple variables, while important, is not the only challenge being faced by instructors and students learning about scientific reasoning. Certainly, as Kuhn (2016) has suggested, young scientists need to learn much about variables, including their operational definition and measurement as well as their impact on the processes and procedures in science

WORKING IN GROUPS

In order to provide instruction effectively and efficiently and expediently, some college instructors provide instruction in groups. There are pros and cons to this type of approach. In some instances, one student may do all of the work, and in other instances, the entire group may be clueless and flounder. The instructor has to monitor and mentor each group to ensure that all know safety and all are able to follow procedures and to ensure that no one person is doing the majority of the work. It is imperative that students understand that data and records must be carefully kept and that there must be meticulous attention to detail.

Instrumental Analysis deals with the fundamental principles of an instrumental method and its general theory, and is the upper division course in Analytical Chemistry. Focusing on hands-on training with modern instruments, Instrumental Analysis Laboratory consists of selected experiments in electroanalytical chemistry, spectroscopy, and chromatography.

It is very common that each academic institution owns only one big-ticket instrument, such as a high-field Nuclear Magnetic Resonance spectrometer. For an effective instruction, the instructor should group the class together for a demo, ensuring that all students understand the theory and know how to operate the instrument. Then, ask each student to focus on a specific task on their own. And finally, regroup the class together, with each student sharing their experience and interpreting their own data. It has been found that authentic, research-based laboratory truly benefits the students in small class sizes. It increases significantly the post laboratory student-instructor interactions, and provides an excellent opportunity for students to apply their learning as well as to improve their skills in experimental design, observation or manipulation of materials and equipment.

Sadly, in some of these groups, there their attention is more focused on their cell phone and texting than on the experiment at hand.

YOU TUBE

It must be noted that instructor time is valuable and there are many demands on the faculty member's time. There are committees, meetings and other administrative things of concern. If specific You Tube videos can be located and sent to students via e-mail attachment, this would save some instructors a good deal of time, effort and energy.

INTRODUCTORY AND ADVANCED COURSES

While some students may have taken a lower level science class, there is no guarantee that they are thinking, behaving, writing, and observing like a good scientist. Often, there is an element of formative evaluation that has to be done, in order to ensure that students have a firm foundation and grounding in the basics in order to master upper division courses.

Formative evaluation can be done in many ways- either by an informal test- or by simply asking students to report verbally their level of skills in various domains. Kuhn and Dean (2005) have suggested that scientific reasoning is more than learning about how to control variables. In introductory courses, the control of certain variables is quite simple. In advanced courses, where students are forced to look at combinations and the impact that certain variables have on each other, scientific reasoning becomes more complex and intricate

THE ISSUES OF REMEDIATION

There are several deficiencies that lower-level students have when entering an upper-level chemistry lab. Students entering an upper-level chemistry lab should know the nomenclature of common glassware and their uses. These would include Buchner funnel, separatory funnel, watchglass, and Erlenmeyer flask. All too often, students do not have the precision of language, terminology, and the specific names of various components and aspects utilized in the science of chemistry. While they may have some vague familiarity with the periodic table of the elements, their memory fails in other realms.

Another common deficiency is mechanical dexterity. A common experimental setup in Organic Chemistry 1 Lab is vacuum filtration. This requires a certain amount of mechanical dexterity. A side-arm Erlenmeyer flask is clamped with a three-prong clamp to a ring stand. The side-arm is then connected to a rubber hose which is connect at the other end to a chemical trap. The trap is connected by rubber hose to the vacuum line. In the Erlenmeyer an O-ring is placed and inside the O-ring is placed the Buchner funnel with filter paper. This setup requires the student to understand some mechanical flexibility along with dexterity which is lacking in lower-level chemistry students. Many students also lack the visual motor coordination or they lack eye hand coordination which acts as a hindrance to their success in classes.

Finally, students entering an upper-level chemistry lab lack the ability to develop a flow chart. For example, if Compound A is to be separated from Compounds B and C by solvent extraction then a flow chart is required to follow the separation procedures. If Compound A contains a basic functional group, then it is acidified and the resulting salt will be transferred to the aqueous phase. Once in the aqueous phase, Compound A will be basicified back into its neutral form and precipitated out.

Likewise, if Compound be contains an acidic functional group, it can be basicified to form a soluble salt that is transferred to the aqueous phase. There the compound is acidified back into it neutral form with acid and yield a precipitate. Thus, Compounds A, B, and C can be separated by pH solvent extraction. Thus, these steps cannot be followed by a lower-level chemistry student entering the upper-level chemistry lab. Therefore, lower-level chemistry students come to upper-level chemistry labs ill-equipped. Further, many students lack familiarity with some basic charting, graphing and pictoral representations. A Venn diagram is a relatively simply concept, yet many students lack the cognitive capacity to understand or grasp the essential nature of the overlap in a Venn diagram.

Teachers continually ponder what basic frames of reference are being given in high school science classes, as students often seem baffled and befuddled in undergraduate science classes. Lehrer, Schauble & Petrosino (2001) have suggested that we reconsider the role of experiments and experimentation in science education.

SUMMARY AND CONCLUSIONS

This paper has cursorily addressed the realm of science teaching, and some of the skills, abilities, and understandings that students require in order to be competent, effective, efficient scientists, able to engage in the scientific method in their university and college classes. There are undoubtedly other venues that need to be explored in various subdomains of science, but it is hoped that this cursory general overall introduction will provide some assistance for instructors. It would seem plausible- but empirical evidence is still called for and needed in this realm to insure productive, competent scientists in the future.

REFERENCES

1) Kuhn, D., Amsel, E., O'Loughlin, M., Schauble, L., Leadbeater, B., Yotive, W. (1988) The development of scientific thinking skills. San Diego, CA., US; Academic Press
2) Kuhn, D. (2007) Reasoning about multiple variables: Control of variables is not the only challenge. Science Education, 91 (5) 710-716.
3) Kuhn, D. (2002) What is scientific thinking and how does it develop? In U. Goswami (Ed.) Handbook of childhood cognitive development. Oxford, England: Blackwell.
4) Kuhn, D. & Dean, D. (2004) Connecting scientific reasoning and causal inference. Journal of Cognition and Development. 5. 261-288
5) Kuhn, D. & Dean, D. (2005) Is developing scientific thinking all about learning to control variables? Psychological Science, 16, 866-870.
6) Kuhn, D. Iordanoi, K., Pease, M., & Wirkala, C. (2008) Beyond control of variables: What needs to develop to achieve skilled scientific thinking? Cognitive Development 23 435-451.
7) Kuhn, D. (2016) What Do Young Science Students Need to Learn About Variables? Science Education 100(2) 392-402.
8) Lehrer, R., Schauble, L., & Petrosino, A.J. (2001) Reconsidering the role of experiment in science education. In K. Crowley, C. Schunn, & T. Okada (Eds), Designing for science: Implications from everyday, classroom and professional settings (pp.251-277) Mahwah, NF: Lawrence Erlbaum Associated.