Laser-based liquid prism sucrosemeter: An APCELL experiment.*

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The majority of disciplines in science involve instrumentation to provide meaningful data for a wide range of applications. The automation of many modern instruments means the user can often obtain reliable data easily without requiring an in-depth understanding of the underlying science. Such automation (including computer-interfaced data acquisition) is extremely beneficial to the scientist and researcher, but can actually detract from student learning in a practical sense as it compels the student to rely solely on theoretical knowledge to understand potential limitations and overall reliability of acquired data. Students often have difficulty in achieving this, particularly when core components of an instrument cannot be clearly observed.

While the chemistry involved in this experiment is not challenging (refraction of light as a consequence of refractive index), its main benefit is that it reinforces the importance of critically assessing instrumentation and experimental design when considering data reliability (as opposed to attributing all error to 'experimental error').

The experiment focuses on instrumentation that is entirely transparent and easily controlled by the student. They construct their own analytical instrument that has an observable response signal (visible laser beam diffraction), enabling students to directly recognise the function of each core component. Using their instrument to perform analysis of real samples reveals not only the success of the instrument but also limitations in its applicability. For successful analyses, students consider accuracy and precision of their instrument. This is aided via a comparison of their experimentally obtained data with data obtained from a commercial instrument as well as literature values. For analyses that were not successful, students further explore experimental design by considering modifications to their set-up that could overcome its current limitations.

Educational Template

Section 1 - Summary of the Experiment

1.1 Experiment Title

Laser-Based Liquid Prism Sucrosemeter.

1.2 Description of the Experiment

In this experiment students construct their own sucrosemeter using a He-Ne laser and hollow equilateral prism. Sugar solutions are placed in the prism and the diffraction of a laser beam through these solutions can be monitored as a function of concentration, enabling determination of 'real' unknown solutions (cordial, soft drinks etc.). If available, a commercial refractometer is an ideal addition to the experiment as students can compare the results of their constructed sucrosemeter to the commercial one.

The benefits to student learning in this experiment are more of a general nature than specific to concepts presented by lectures. The fact that real samples are analysed is always a plus to student learning. Technical skills in making standard solutions and drawing results from calibration curves expose the student to core analytical skills.

Constructing their own apparatus which is simple yet yields accurate results reinforces in students that instrumentation and design do not always need to be complicated or expensive. With continued advances in the technology of instrumentation as well as interfaced data acquisition software, it is easy for students to simply 'press a button' to obtain results without considering the chemistry that occurs within a fully enclosed instrument. The simplicity of the experimental set-up as well as the transparency of the response signal (visible laser beam diffraction) in this experiment encourages students to consider 'cause and effect' components of instrumentation. Students critically analyse experimental design by probing both strengths (reliable determination of refractive indices and sucrose concentrations) and limitations of their experimental set-up (analysis of dilute samples and samples of complementary colour to the laser beam cannot be reliably made without modifications to the design and/or sampling). Comparison of direct readings of diffraction angles to calculated angles also encourages students to assess accuracy over simplicity when considering data collection methods (for this experiment, direct readings of deflection angles gives poor accuracy, whereas calculated angles yield great accuracy due to relatively small error propagation).

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* The complete documentation for this experiment is freely available on the APCELL web site [www.apcell.org]. It includes the educational template, a set of student notes, demonstrator notes and technical notes to allow ready implementation into a new laboratory.

1.3 Course Context and Students' Required Knowledge and Skills

This experiment has little direct linkage to general course material in Physical Chemistry, unless a component regarding refraction of light through prisms / solutions, Snell's Law, simple laser chemistry etc. is incorporated. Indirectly, this experiment can enhance a student's confidence in his/her own ability to simplify and comprehend new concepts taught in Physical Chemistry. (New concepts in Physical Chemistry can be difficult for students to grasp if the language and mathematical relationships overwhelm them - this experiment is easily understood, and the associated mathematics is easily applied.)

Minimal prior knowledge is required by students to successfully conclude this experiment. Advantageous skills to have are competency in using volumetric techniques / glassware, basic knowledge of light refraction trends and adeptness in constructing and applying calibration curves.

The experiment as presented here is undertaken by our second year students, however I feel that it is simple enough to be adapted as a first year practical.

1.4 Time Required to Complete

Prior to Lab	30 min - 1 hr (reading)
In Laboratory	2 – 3 hrs
After Laboratory	2 – 3 hrs (plotting data, analysing results, calculations, report writing)

1.5 Acknowledgments

This experiment was adapted from "Narayanan, V.A. & Narayanan, R. *Laser-based Liquid Prism Sucrosemeter – A Precision Optical Method to Find Sugar Concentration*. J. Chem. Ed., 74 (2), 1997".

1.6 Other Comments

In my opinion this experiment is not very challenging when compared to other experiments offered by us at second year level. Despite this, I find it works very well in the laboratory as it incorporates several analytical methodologies common to many experiments. When the students are exposed to the second year laboratories (esp. physical chemistry) for the first time, they are often overwhelmed by the instrumentation, equations involved in analyses and graphing techniques that they have had little prior experience in. This experiment enables students to "re-focus" on many common features of experiments (calculations, using equations, linearity relationships and subsequent calibration curves, error analysis) in a straightforward easy to follow way. I have found that students sometimes gain a better perspective on the subject area as a whole when they are able to "practice" common features (such as graphical analyses) using a protocol that is easy to follow and understand, and has very little prospect of failing to yield reliable results.

As a learning tool this experiment is most effective if it is extended to incorporate scenarios where the design yields accurate and reliable data as well as scenarios where accuracy is not possible without modifying the design and/ or approach. In general, students often attempt to designate poor results to 'experimental error' (error in pipetting, human error in weighing etc.). In many cases such sources of error cannot significantly account for deviations in response signals (for example if the concentration range is beyond an instruments detection limits, or if specified conditions for optimal output are not maintained). It is therefore imperative that students develop the ability to critically assess experimental limitations and distinguish these from sources of error. Addressing limitations in their experimental design and exploring ways to overcome these can precipitate such critical assessment in students.

It is intended to incorporate comparison of student's results to results they obtain when using a commercial refractometer. The attached experimental write-up has not been modified to incorporate this as we are yet to trial the refractometer we have available to us.

On a further note, it is a reliable simple analytical experiment that can be very cheap to set-up and maintain. Commercial sugar and cordials are the only consumable expenses; the He-Ne laser could be replaced with a commercial laser pointer; the hollow prism could be constructed using microscope slides.

Section 2 – Educational Analysis

Learning Outcomes *What will students learn?*	**Process** *How will students learn it?*	**Assessment** *How will staff know students have learnt it?* *How will students know they have learnt it?*

Theoretical and Conceptual Knowledge

The importance of critical appraisal of theories and conceptual applicability.	By observing a) successful outcomes of their experimentation as well as b) limitations in the applicability of their set-up: a) Students use theoretical relationships to calculate refractive index values of samples from experimental measurements. By comparing their results to literature values (and/or measurements from a commercial refractometer), students can see the accuracy of their experimental design. b) By considering and observing scenarios where the experimental design would not be applicable in the current set-up (dilute solutions and complementary coloured solutions to laser beam) encourages students to critically address concepts rather than to simply accept them.	Accuracy of experimentally determined values as compared to theoretically obtained values. Explanations of reasons for observed limitations of the experiment. Discussions of further potential applications of the experimental design (instigated by questions posed in the manual), emphasising consequential limitations and ways to overcome these. These points are assessable via the submission of a written report, as well as oral communication with the demonstrator at the conclusion of the experiment.

Scientific and Practical Skills

Ability to collate, correlate, display, analyse and report observations.	By recording experimentally obtained data and then using this data to determine standard properties of their samples (refractive index, concentration): Students clearly see the response signal they measure (laser beam deflection). They recognise trends in this response signal to sugar concentration (a linear relationship) and can hence use their results to determine sugar concentrations of real samples. By applying experimental data to theoretical relationships (from the measured response signals, deviation angles are calculated which are then used to calculate refractive index values) and comparing values to literature values, students can see further applicability to their experiment design than simple concentration analysis.	Students must collate a written report on their experiment, which is based on a standard format which is clearly outlined in their manual. This is a weekly requirement in our laboratories, so students become aware that they are effectively mastering this requirement as it becomes quicker and easier for them to collate their reports as their experience grows. Assessment is largely biased towards the student's ability to describe the relevance / theory of the experimentation, as well as their ability to discuss the significance of their results. Each practical report is marked by one demonstrator only, so the demonstrator can obtain a general idea of the experiment's success (in lieu of student comprehension as well as accuracy in experimental output) due to repetitive assessment over the course of one semester.

Ability to consider limitations as well as successful applications of experimentation.	As well as any sample a student may choose, they also analyse provided samples that can be reliably analysed using their experimental design (most cordials, soft drinks, etc.). Other samples are also analysed that cannot yield reliable results without modifying their experimental design (e.g. cordial of complementary colour to the laser beam, and solutions that fall outside of the calibration range that can be accommodated by the design). Students therefore directly observe strengths as well as limitations of their experimental design.	By explaining why one sample was unable to be analysed whereas all other samples were successfully analysed. Questions posed in the manual guide students to explain reasons for the experimental limitation they observed (as well as others) and assist students to consider modifications of the experimentation that could overcome limitations. This is assessed via verbal communication as well as discussions presented in the student's written report.
Understanding the operation of instrumentation.	The transparency of the cause and effect response (visible laser beam refraction) being measured as a function of concentration enables the student to see clearly the operation of the instrumentation. Comparing their experimental results to results obtained using a non-transparent commercially obtained refractometer encourages students to translate their direct observations to other instrumentation, realising that the majority contain core components that induce a detectable affect on a sample which can be converted to meaningful data.	As above, orally and via written reports.
Ability to present reports in appropriate formats.	By constructing a written report on conclusion of their experiment, following (if desired) clear guidelines presented in their manual.	Assessment of their written report is based not only on content, but also on appropriate presentation adhering to standard form (e.g. abstract, aim, introduction, experimental, results, discussion, conclusion, references).

Generic Skills

Problem solving: ability to apply problem solving in familiar and unfamiliar situations, and to display the capability of rigorous and independent thinking.	After observing predictable and reliable trends in the response signal to various standard solutions (variation of response is proportional to sugar concentration), students are given an unknown solution to measure in which the response signal cannot be observed. Students are not forewarned of this, and therefore undergo a more complete 'trouble-shooting' process. For some students, this is a quick process as they realise that the conjugate coloured solution absorbs the laser beam. Other students repeat their sampling and measurements of the 'wayward' unknown, double checking procedures used by their partners. After observing a failure to obtain a result after such repetition, students must then critically appraise their experimentation to determine why the initial successful application of their experiment has failed. Most students realise (sooner or later) what is happening with little or no prompting from the demonstrator.	By addressing questions posed in the manual as well as explaining experimental limitations, students will have successfully extended themselves regarding problem identification and solving. Demonstrators will be able to assess this process by observing the student's approach to identifying experimental limitations and ways in which to overcome them (as well as explanations to questions posed in oral communication and the written report).

Working with others: one-to-one and in teams, understanding and responding to the demands of the task and working effectively to achieve a shared goal, coping with set backs.	The experiment is typically undertaken in pairs, with sharing and / or division of tasks being established by the students themselves. When limitations of the experimental design (after obvious success) are encountered, the students work together to discover why, with resolution often being achieved prior to consulting the demonstrator. On occasion, students will question each other's technique before questioning the experimental design or a demonstrator. Teamwork can be enhanced when the students determine that neither they nor their partner have erred.	Teamwork is noticed as being effective during the course of the experiment, by observing the students setting up the equipment, as well as running the experiment and analysing and interpreting data, as well as addressing questions posed in the manual. Poor teamwork can sometimes be noticed if a student does not have all relevant measurements in their written report after the laboratory session (e.g. accurate masses of sugar weighed for preparation of standard solutions). Oral assessment at the conclusion of the experiment is usually performed by the demonstrator on each group rather than individual students. During this time, the demonstrator discusses points of the experiment with each student in the group.
Critical analysis: evaluating relevance and relating knowledge to the real world.	Students critically analyse their experimental set-up by comparing calculated values to theoretical values (and commercial instrumentation if available). They consider the accuracy of their method, and address limitations (both experimentally determined as well as hypothetical situations directly relevant to realistic scenarios). The students measure concentrations of sugar in real 'everyday' samples.	Assessed as per methods already discussed.
Life-Long Learning: the capacity for and commitment to life-long learning.	Students learn this skill as they are directly in control of the entire experimentation themselves (from setting it up to concluding reliable information). They set up their own apparatus and question its application in contexts where success is evident as well as in situations where success requires further modifications.	This is normally evident in the students written report (usually written during the week following the experiment). A student who has mastered this particular skill will normally present a report on successful experimentation, with suggested modifications that would extend its applicability. Students who require further experience in attaining this skill will often report limitations to the experimental design rather than extended modifications to the instrumentation.

Section 3 - Student Learning Experience

3.1 Did this experiment help you to understand the theory and concepts of the topic? If so, how, or if not, why not?

Yes, fairly simple concept. The intro & theory section said everything involved.

3.2 How is this experiment relevant to you in terms of your interests and goals?

It's another good (& simple) example of analytical chemistry. Lasers are always fun.

3.3 Did you find this experiment interesting? If so, what aspects of this experiment did you find of interesting? If not, why not?

Yes. I think analysing unknowns was interesting.

3.4 Can the experiment be completed comfortably in the allocated time? Is there time to reflect on the tasks while performing them?

Yes & yes.

3.5 Does this experiment require teamwork and if so, in what way? Was this aspect of the experiment beneficial?
When taking the angle measurements.

3.6 Did you have the opportunity to take responsibility for your own learning, and to be active as learners?
I guess so, if you mean learning from the intro & theory. Graphing and interpreting is always a satisfying end to an experiment.

3.7 Does this experiment provide for the possibility of a range of student abilities and interests? If so, how?
It's not too challenging (reminiscent of high school physics) – which is nice once in a while.

3.8 Did the laboratory notes, demonstrators' guidance and any other resources help you in learning from this experiment? If so, how?
Lab notes for theory, demonstrator for set up of equipment.

3.9 Are there any other features of this experiment that made it a particularly good or bad learning experience for you?
Good – comparison of measured and calculated values.

3.10 What improvements could be made to this experiment?
None really – maybe just get students to test more unknowns.

3.11 Other Comments
[no responses]

What's in a formula? - Pedagogical content knowledge

Formulas of elements and compounds provide information about the substances that they represent. For example, He refers to a substance that consists of monoatomic molecules, N_2 represents another that consists of diatomic molecules and P_4 is the formula of another that has four atoms in each of its molecules. Why then don't we use S_8 to represent solid sulfur? After all, we use C_6H_6 for benzene, and not CH. But C_∞ for diamond? Maybe the answer lies in balancing complexity and the amount of information provided by the formula.

Sometimes the information in a formula is hidden unless we have an understanding of the nature of the substance. For example, chemists 'know' that He, Na and Si do not all refer to substances that exist as monoatomic molecules. And the formulas SiO_2 and CO_2 may look similar, but they mean vastly different things to the person with a knowledge of structures. To be specific, the formula, SiO_2 for silicon dioxide - a covalent network substance - is taken to mean that in silicon dioxide there are twice as many oxygen atoms in the network as there are silicon atoms. In a sample of carbon dioxide there are twice as many oxygen atoms as carbon atoms, but the formula CO_2 provides the additional information - if you understand carbon dioxide to be a molecular substance - that each molecule of carbon dioxide has one carbon atom and two oxygen atoms. In summary, SiO_2 tells us about relative numbers, but CO_2 tells us about absolute numbers.

Sometimes we use formulas to indicate structural information. For many compounds, there may be various acceptable formulas, each providing a different amount of information. For example, benzaldehyde may be represented by either C_7H_6O or C_6H_5CHO. The first tells us only the composition, while the second provides information about the structure of the molecules.

But then the formula of sulfuric acid is almost always written as H_2SO_4. This formula represents the composition of the molecules accurately, but does it suggest to the novice that the hydrogen atoms are joined to the sulfur atom? Given that each hydrogen atom is bound to an oxygen atom, is $SO_2(OH)_2$ a preferable formula?

An interesting question is how to represent the formula of ammonium iron(II) suIfate-6-water (ferrous ammonium sulfate hexahydrate). The formula most commonly found on the labels of bottles is $FeSO_4.(NH_4)_2SO_4.6H_2O)$ - a typical formula for the 'double salts'. However, this formula almost implies that there are two compounds present: iron sulfate and ammonium sulfate. It suggests that half of the sulfate ions are associated with the iron(II) ions and the other half with the ammonium ions.

A more acceptable view of the structure of this compound is of a lattice containing sulfate anions, and both iron(II) cations and ammonium cations - as though half of the Fe^{2+} ions in an iron(II) sulfate sample have been replaced by twice as many NH_4^+ ions. So a preferred formula might be $Fe(NH_4)_2(SO_4)_2.6H_2O$.

Then again, X-ray diffraction studies on crystals of ammonium iron(II) sulfate indicate that the waters of crystallisation are all bound to the iron(II) ions. So perhaps we should show this in the formula by representation of the hexaquairon(II) complex ion in the

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