Electrochemical Based Enzymatic Determination of Glucose in Beverages

A laboratory for quantitative determination by selective electrochemistry

This laboratory seeks to quantitatively determine glucose concentration in common beverages. The method employed is enzyme catalyzed oxidation of glucose, quantified by chronoamperometry. With an inexpensive patterned electrode and low cost glucose oxidase enzyme, an electrochemical sensor is constructed to selectively measure glucose in complicated beverages which can present as analytically challenging matrices. This lab briefly discusses conceptual information about sugars used to sweeten common beverages, enzyme-substrate interactions, glucose mutarotation, enzyme kinetics, and electroanalysis.

Introduction

Bioanalytical chemistry, a subdiscipline of analytical chemistry, uses quantitative and qualitative methods of analysis to evaluate biological based chemical species. These biological species are commonly found in complicated matrices such as blood and may include proteins, drug metabolites, and sugars.

In a complicated matrix such as blood, it is difficult to quantitatively determine the presence and concentration of target analytes. Therefore, the matrix is often simplified by chemical separations (e.g. HPLC, GC, electrophoresis), prior to quantitative determination.

Another manner to quantify an analyte among several interferents is by increasing selectivity. Many enzymes and substrates function as a lock and key gateway. The enzyme catalyzes a reaction only when a very specific substrate binds to its active site.

Such is the case for glucose oxidase and its substrate, \( \beta \)-D-glucose. Therefore despite a complicated matrix of chemical species, an assay based on glucose oxidase will only have an analytical signal from \( \beta \)-D-glucose (Figure 2).

**Figure 1.** Example of US Nutrition Facts on Edible Consumer Goods.

**Figure 2.** Diagram of Glucose Oxidase Enzyme with its Substrate \( \beta \)-D-glucose and Product \( H_2O_2 \).

Electrochemical methods are highly sensitive. Use of electrochemistry with enzymes as described above adds selectivity. Therefore, in complicated matrices (such as common soft drinks, which could contain caffeine, sugars, preservatives, water, colorings, acids, and other chemicals), electrochemical determination of the extent of an enzymatic reaction is a sensitive
and selective method by which to determine glucose concentration.

The assay described here uses glucose oxidase to catalyze the oxidation of \( \beta\)-D-glucose to gluconolactone (GNL), with hydrogen peroxide \( (H_2O_2) \) as a byproduct (Figure 2). The hydrogen peroxide is electrochemically detected at a platinum electrode. The current from hydrogen peroxide oxidation is calibrated against standard glucose solutions to construct a calibration curve and determine the unknown glucose concentration.

---

**Biochemistry Background**

The United States Food and Drug Administration (FDA) does not have stringent policies on nutritional label reporting of sugars (Figure 1) [1]. On a nutritional label, the entry for “Sugars” under Total Carbohydrate may include any of the following naturally occurring or artificially added sugars: fructose, glucose, sucrose, and dextrose and in one of several forms (crystalline as in sugar crystals or liquid as in high fructose corn syrup). Any sugars added to the product must be stated on the ingredients list. While a general consumer is made aware of added sugars and total mass of sugar per serving, the customer does not know the concentration or ratios of the sugars present [2].

**A. Types of Sugars**

**Fructose** (Figure 3) is also called “fruit sugar” as it is the predominant natural sugar found in plant products such as berries, flowers, and root vegetables. For use in processed foods, fructose is commonly obtained from sugar cane and sugar beets [2, 3, 5].

**Glucose** (Figure 3) is also a monosaccharide and is the primary source of cellular energy in plants and animals. Commercially, glucose added to foods is most often sourced from grains, corn being used most often. Glucose enters the bloodstream after processing through the gut and liver [2, 3, 5].

**Sucrose** (Figure 3), more commonly known as table sugar, is a disaccharide consisting of a molecule of fructose bound to a molecule of glucose. When the singular word “sugar” appears in FDA approved food labeling (ingredients or nutritional information), it exclusively refers to sucrose. Sucrose is most often obtained from plant sources, namely sugar cane and sugar beets.

**B. High Fructose Corn Syrup**

In recent years, processed food manufacturers use high fructose corn syrup (HFCS) in lieu of sucrose as a sweetener. Both consist of glucose and fructose, but HFCS is less costly due to governmental corn subsidies. In humans, sucrose is broken down to glucose and fructose which are processed as monosaccharides [2, 3, 5].

HFCS is a mixture of the monosaccharide sugars glucose and fructose. Often, HFCS is used in processed foods because it is less expensive than sucrose. Commonly, perceived sweetness of sugars is based relative to sucrose. Sucrose has a rating of 1 on the “sweetness scale,” while glucose and fructose are rated 0.74 – 0.8 and 1.17 to 1.75, respectively [4].

HFCS formulations are prepared and named based on their content of fructose. A common blend of HFCS used in soft drinks is HFCS55, which means it contains 55% fructose and 42% glucose in water. Based on relative sweetness, HFCS55 provides sweetness similar to pure sucrose.

Consider the sugar content of a cola carbonated beverage. The label states that a can with volume 355 mL contains 39 g sugar. According to the ingredient label, the sugars are from HFCS. Therefore, the effective glucose concentration in such a can would be 16.4 g \((0.42 \times 39 = 16.4)\).

For quantification of glucose, it is important to realize that the sugar content listed on a can of carbonated beverage sweetened with HFCS55 is not solely due to glucose. In this lab, only glucose, and more specifically only \( \beta\)-D-glucose...
(the substrate for the enzyme glucose oxidase) is the analyte of interest.

C. Glucose Mutarotation

Two stereoisomers of glucose are D-glucose and L-glucose. The D or L designation with glucose refers to the asymmetric carbon farthest from the aldehyde or keto group. Most naturally occurring sugars are D isomers. D and L sugars are mirror images of one another. D-glucose is the isomer found in nature and in nutritive sweeteners. D-glucose can exist in an open chain and closed chain form, the former being thermodynamically unstable.

When a solution of D-glucose is prepared in water, there is a dynamic equilibrium between the open chain and closed chain forms α-D-glucose and β-D-glucose [4]. The cyclic forms of carbohydrates can exist in two forms, α- and β-based on the position of the substituent (OH-) at the anomeric center. The α- and β- forms are sometimes described as anomers since they are isomers at the anomeric center.

Because the open chain is not thermodynamically stable, an equilibrium mixture between the α-D-glucose and β-D-glucose will result given enough time. At room temperature, mutarotation reaches equilibrium in several hours resulting in a mixture of 36% α-D-glucose and 64% β-D-glucose.

![Figure 4. Mutarotation Equilibrium Reaction of D-glucose.](image)

It is important to account for glucose mutarotation when using freshly prepared solutions of glucose. After preparation, solutions must be equilibrated at room temperature for at least twelve hours before use; otherwise, the ratio of β-D-glucose and α-D-glucose will be unpredictable and contribute to erroneous measurements [4].

D. Glucose Oxidase

Glucose oxidase (GOx) is an enzyme that selectively catalyzes the oxidation of β-D-glucose to β-D-gluconolactone (GNL) with hydrogen peroxide as a byproduct. GOx is a highly selective enzyme. Even in the presence of nearly identical α-D-glucose, only β-D-glucose is a substrate for GOx. Enzyme | substrate interactions act like a lock and key. β-D-glucose is like the key while GOx is like the lock as depicted in the illustration in Figure 1.

Overall, the general reaction of interest shows a 1:1 molar relationship between β-D-glucose and hydrogen peroxide.

\[
\beta-D\text{glucose} + H_2O + O_2 \xrightarrow{\text{GOx}} \text{GNL} + H_2O_2
\]

The bioanalytical assay described here indirectly quantifies glucose by measuring the molar concentration of H₂O₂. H₂O₂ is an electrochemically active chemical species and can be monitored using electrochemical techniques such as chronoamperometry.

E. Enzyme Kinetics

The Michaelis-Menten model of enzyme kinetics is perhaps the most straightforward and well known model used in biochemistry. The model is based on a general kinetic approach for the steps of an enzyme reaction (Equation 2) [5].

\[
E + S \rightleftharpoons ES \rightarrow P + E
\]

Enzyme (E), which acts as a catalyst, combines with substrate (S) to form an enzyme-substrate complex, (ES). This is a reversible equilibrium step with associated forward (\(k_f\)) and reverse (\(k_b\)) rate constants. The ES complex then catalytically reacts to produce product (P) plus enzyme at a specific rate (\(k_{cat}\)).

From the general reaction in Equation 2, application of typical first order kinetics shows that the overall reaction rate is equal to the rate of appearance of product. The work of Michaelis and Menten is most recognizable by the reaction rate model

\[
\dot{\bar{v}} = \frac{d[P]}{dt} = \frac{V_m[S]}{K_m + [S]} \tag{3}
\]

Where \(\dot{\bar{v}}\) = reaction rate, \([P]\) = concentration of enzyme product, \(t\) = time, \([S]\) = substrate concentration, \(V_m\) = maximum rate at saturating concentration of substrate, and \(K_m\) = [S] when at
The reaction rate increases with increasing substrate concentration, asymptotically approaching its maximum rate, attained when all enzyme is bound to substrate.

The maximum kinetic rate achieved by the system at maximum (saturating) substrate concentrations is called \( V_{\text{max}} \). The Michaelis constant is the substrate concentration at which the reaction rate is at half-maximum. \( K_m \) is inversely related to the affinity of the substrate for the enzyme. The value of the Michaelis constant is dependent on enzyme, substrate, and environmental conditions such as temperature and pH [5].

The discussion on enzyme kinetics presented above is brief. It is important to be aware that the reactions of interest in this laboratory are not simple reactions driven only by thermodynamic control.

### Electrochemical Background

Enzyme mediated quantification of glucose by chronocoulometry requires a basic knowledge of the theory and instrumentation (tools). A wealth of knowledge exists for both topics. Here, only a brief overview, sufficient to understand the methods employed, is given.

#### A. Chronoamperometry

This lab will use an electrochemical experiment called chronoamperometry. As the name implies, current is measured as a function of time while the cell potential is held constant. Current at a given time, \( i(t) \) (in Amps) is directly proportional to concentration, as shown by the Cottrell Equation (Equation 4)

\[
i(t) = \frac{nFAD_0^{1/2}C_0^*}{\pi^{1/2}q^{1/2}}
\]

where \( n \) = number of electrons transferred, \( F \) = Faraday’s Constant (96485 C/mol), \( A \) = working electrode area (in \( cm^2 \)), \( D_0 \) = diffusion coefficient (in \( cm^2/s \)), \( C_0 \) = concentration (in \( mol/cm^3 \)), and \( t \) = time (in s).

In general, the working electrode is first held at a constant potential where no reaction occurs (no current). Then, the cell potential is rapidly changed (stepped) to a value that induces faradaic current. The current corresponds to electrons gained or lost during electrolysis (oxidation or reduction). The value of potential at which the electrolysis occurs is specific to the chemical system under study.

For each mole of \( \beta \)-D-glucose in a sample, oxidation of the GOx enzyme produces one mole of gluconolactone and one mole of \( H_2O_2 \).

Electrochemically, the \( H_2O_2 \) can undergo a two electron oxidation to form \( O_2 \) and \( H^+ \) as shown in Equation 5. \( H_2O_2 \) can be detected at a platinum electrode via oxidation to \( O_2 \). Therefore, after the GOx has catalyzed the conversion of \( \beta \)-D-glucose, the \( H_2O_2 \) produced will be electrochemically oxidized. The extent of oxidation (magnitude of current) will be measured by chronoamperometry and compared against a calibration of several standard solutions to determine the unknown concentration of \( \beta \)-D-glucose in the sample.

\[
H_2O_2 \rightarrow O_2 + 2H^+ + 2e
\] (5)

Chronoamperometry is explained in the context of Equation 5. \( H_2O_2 \) is oxidized to \( O_2 \) between 600 to 700 mV vs. an Ag/AgCl reference electrode. To oxidize hydrogen peroxide produced by the action of glucose oxidase, the cell potential is stepped from an initial resting potential (where neither reaction occurs nor electrons flow) to a potential more positive than 600 to 700 mV. At 900 mV, any \( H_2O_2 \) near the electrode surface will be oxidized. For each mole of \( H_2O_2 \) oxidized, two electrons will flow into the external circuit (measured as current in the potentiostat). After a specified amount of time, current is measured and verified against a calibration curve to determine the concentration of \( \beta \)-D-glucose in the sample. The detection scheme is shown in Figure 5, where \( \beta \)-D-glucose is converted to gluconolactone and peroxide by glucose oxidase. The peroxide generated is oxidized at the platinum electrode (slant lines). Current is monitored and related to calibration.
B. Electrochemical Instrumentation

There are two main components of the electrochemical instrumentation used in this experiment: the potentiostat and the electrodes.

- WaveNow™ USB Potentiostat with AfterMath™ Data Organizer Software
- Compact Voltammetry Cell
- Patterned Platinum Electrodes

Electrodes used in this experiment are called the working, counter, and reference electrodes. The electrochemical reaction of interest occurs at the working electrode. The working electrode is an inert material that is a sink for electron transfer. The reference electrode has its own fixed redox potential and serves as a standard reference for cell potential. Current should not pass through a reference electrode, thus the counter electrode (or auxiliary electrode) is the third electrode in the system. Current passes through the counter electrode to balance a change in cell potential due to the reaction at the working electrode.

For this experiment, the platinum patterned electrode conveniently contains all three electrodes as shown in Figure 6.

1.0 M Sodium Acetate Buffer (100 mL)

Sodium acetate is abbreviated NaOAc. To prepare this solution, you will need sodium acetate (CH₃COONa, MW = 82.03 g/mol), concentrated hydrochloric acid (HCl, 36.5% - 38% v/v), and water.

Hydrochloric acid is extremely corrosive. Avoid contact with skin. If acid contacts the skin, rinse profusely with copious amounts of water.

In a 100 mL volumetric flask, dissolve 8.2 g of sodium acetate in about 70 mL of water. Add 4.2 mL HCl. Stir completely and dilute to the mark with water. Label the solution as 1M NaOAc Buffer.

50 mM Sodium Acetate (500 mL)

For this solution, prepare as a 1M NaOAc Buffer dilution.

In a 500 mL volumetric flask, add 25 mL of the 1M NaOAc Buffer and dilute to the mark with water. Label the solution as 50 mM NaOAc Buffer.

100 IU/mL Glucose Oxidase Solution (500 mL)

Dissolve 50 kU (one thousand IU) of glucose oxidase in 500 mL of the previously prepared 50 mM NaOAc Buffer. Stir gently with a glass rod to avoid creating bubbles. Keep refrigerated for storage and warm to room temperature before use. Label this solution as Glucose Oxidase Stock.

Enzyme concentrations are often expressed in units of IU (International Units). One IU is the amount of enzyme that will produce 1 μmol of product per minute, (or that will consume 1 μmol of reactant per minute). Prepare this solution based on the concentration stated on the bottle.

100 mM Glucose Stock Solution (100 mL)

For this solution, you will need D-(+)-glucose (MW = 180.16 g/mol) and the 50 mM NaOAc Buffer previously prepared.

In a 100 mL volumetric flask, dissolve 1.8 g of D-(+)-glucose in the 50 mM NaOAc Buffer and dilute to the mark with the 50 mM NaOAc Buffer.
Prepare this solution at least 12 hours in advance. This allows mutarotation of the α and β optical isomers of glucose to reach equilibrium. Remember, only β-D-glucose is a substrate for the enzyme glucose oxidase.

Beverage Sample Stock Solution (10 mL each)

Prepare a stock beverage sample. Select any glucose containing beverage. Beverage selection may affect results. Some sweetened beverages contain little glucose despite having a high “sugars” listed on the nutritional label. Record the nutritional label data and ingredients list for each beverage sample into a notebook.

If the beverage is carbonated, decarbonate it prior to use (i.e. remove all gas bubbles). This is accomplished by placing the soft drink in a plastic bottle and sealing the cap, shaking for 20-25 seconds, and then slowly opening the cap to release CO₂. Repeat this procedure until no observable carbonation is present.

Mix 0.8 mL pure beverage with 0.5 mL 1M NaOAc Buffer and 8.7 mL water. Label this solution as Beverage Stock Solution.

Beverage Sample Test Solution (10 mL each)

Test beverage samples should be analyzed immediately after prepared. The preparation for the beverage solution tested will be given in the experimental section.

<table>
<thead>
<tr>
<th>Standard #</th>
<th>[Glucose] (mM)</th>
<th>100 mM Glucose Stock (mL)</th>
<th>50 mM NaOAc Buffer (mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0.0</td>
<td>5.0</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>0.5</td>
<td>4.5</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>1.0</td>
<td>4.0</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>1.5</td>
<td>3.5</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>2.0</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Table 1. Glucose Standard Preparations.

Glucose Calibration Standards (5 mL each)

Prepare a series of at least five glucose standards. These should be prepared from previously made solutions, 100 mM Glucose Stock Solution and 50 mM NaOAc Buffer as shown in Table 1. It will be easiest to prepare each sample in separate 20 mL scintillation vials (which fit the compact voltammetry cell cap). Label any standards prepared.

Experimental

In this lab, the concentration of glucose in a beverage sample will be obtained by oxidizing an enzymatic byproduct of glucose oxidase, hydrogen peroxide.

After you have made the solutions, proceed to the instrumental setup. The analysis portion involves construction of a calibration curve from glucose standards and the analysis of a beverage sample as compared to the calibration. Read through the experimental section completely before proceeding.

A. Setup

The following instrumentation supplies will be needed to perform this experiment: the Pine Research Instrumentation WaveNow potentiostat, USB cable, platinum screen printed electrode, compact voltammetry cell, and the solutions previously prepared. A stopwatch must also be used to accurately ensure all samples have reacted with enzyme for the same time.

1. Turn on the potentiostat and connect it to a personal computer using a USB cable. Use the AfterMath™ software application to control the potentiostat (Figure 7).

2. Connect the cell cable to the potentiostat using the end terminated with an HD-15 connector. The other end of the cable should be a mini-USB connector.

3. Obtain one platinum patterned electrode. This patterned electrode has a working
electrode in the center which has a 2.0 mm diameter (Figure 5). Compute the surface area of the working electrode (in cm²) and make a note of your result in your lab notebook.

4. From the Experiments menu in AfterMath, select “Chronoamperometry (CA)...” Notice, this will create a new Experiment Node in the archive structure on the left panel of the screen (e.g. CA Parameters) (Figure 8).

5. Select the appropriate potentiostat from the drop down menu at the top of the parameter entry screen (e.g. Pine WaveNow).

6. Enter the parameters as shown in Figure 9.

B. Glucose Calibration

The enzyme-glucose reaction is kinetically limited; therefore, it is important to prepare and analyze each standard before moving on to another.

![Figure 8. Chronoamperometry Selection in AfterMath.](image)

![Figure 9. Chronoamperometry Parameters.](image)

Work systematically and in sequence, from lowest to highest concentration of glucose. Analyze each of at least five standard glucose samples, given in Table 1, in the following manner:

1. Rinse the electrode with DI water and dab dry with a delicate wipe. Set aside.
2. Obtain a standard sample (5 mL of solution in a 20 mL threaded vial).
3. Add the 5 mL Glucose Oxidase Solution to the test solution. Shake well, and immediately start a timer.
4. Allow the enzyme to react for 5 minutes.
5. After 5 minutes, insert the platinum patterned electrode into the hand grip (Figure 10).
6. Screw the beige compact voltammetry cell cap onto the vial (Figure 10).
7. Insert the hand grip, which is connected to the electrode, into the cap (Figure 10).
Figure 10. Assembly of the Compact Voltammetry Cell.

8. Connect the USB cell cable. The correct connector is to the LEFT of the electrode face of the patterned electrode card (Figure 10).

9. In AfterMath, highlight the CA Parameters icon in the tree structure on the left (that you created above). Click the “Perform” button to begin the chronoamperometry experiment (Figure 11).

Figure 11. Selection of Existing CA Parameters in AfterMath.

10. After the experiment completes, right click the experiment node in the left panel of AfterMath (e.g. CA Experiment [00##]) and rename it to indicate the glucose concentration used.

Remove the grip and cap from the vial. Dispose of the waste appropriately. Repeat these steps for each calibration standard until you have obtained data for all five standards.

For comparison, Figure 12 shows an overlay of amperograms obtained from different glucose standards, each of different concentration.

Figure 12. Overlay of Chronoamperograms.

C. Beverage Analysis

To a clean 20 mL threaded vial, add 5 mL Beverage Sample Stock Solution and 5 mL of the Glucose Oxidase Stock. Mix well, and start a timer.

Allow the enzyme to react for 5 minutes. Perform Chronoamperometry on the sample as with the glucose calibration. The measurement can be made in triplicate for statistical validation of the data.

Data Analysis

The resultant data from a chronoamperometry experiment, called a chronoamperogram, is a plot of current vs. time. The current arises from the electrochemical oxidation of \( \text{H}_2\text{O}_2 \), (Equation 5). From Equation 4, the measured current is proportional to the concentration of peroxide. From the overall enzyme reaction (Equation 1), one mole of glucose is oxidized for every mole of peroxide produced and subsequently electrochemically oxidized.

A. Calibration Curve Construction

For each glucose standard, review the corresponding chronoamperogram in AfterMath.

1. Expand the appropriate experiment node and select the “Current” node (Figure 13).

2. In the graphical data window in the right panel of AfterMath, right click the data trace.

3. From the menu, select Add tool and then Crosshair.
4. A large plus sign will lock to the data trace. The crosshair tool will report the x and y values for a certain point on the data, as time (x-intercept), current (y-intercept). With the mouse, move the crosshair to the data point at \( t = 8 \) seconds.

5. Record the current at 8 seconds.

6. Repeat this analysis for each glucose standard.

![Crosshair Tool in AfterMath.](image)

To maintain assumptions for the Michaelis-Menten model of enzyme kinetics (discussed in most biochemistry textbooks [5]), a common enzyme assay is to vary substrate concentration and measure the reaction rate. In this lab, current is a direct measure of the kinetic rate.

The calibration data is only useful if linear in the target range. A Lineweaver-Burke plot can linearize data and extract the kinetic parameters \( V_{\text{max}} \) and \( K_m \). From the raw current vs. [glucose] data obtained from glucose standard analysis, generate values for the Lineweaver-Burke plot (also called a double reciprocal plot). Take the reciprocal of current and reciprocal of [glucose] and plot 1/current vs. 1/[glucose]. Plot data as points. Perform a regression fit to the data and record the linear equation.

The reciprocal of Equation 3 is the linear representation by which to create the Lineweaver-Burke plot (Equation 6, Figure 15).

\[
\frac{1}{\bar{v}} = \frac{K_m}{V_{\text{max}}[S]} + \frac{1}{m}
\]

![Lineweaver-Burke (Double Reciprocal) Plot of Standard Data.](image)

As discussed in the Biochemistry Background, the data in the calibration plot should not be linear across the range tested. Lack of linearity is due to the two limiting factors of the glucose oxidase enzyme system; 1) the amount of substrate (β-D-glucose) available and 2) the maximum turnover rate of the glucose oxidase enzyme.
B. **Determination of Glucose Concentration in Beverages**

For each beverage sample, find the current at 8 seconds as with the glucose calibration chronoamperograms. With the linear regression equation from the calibration (as in Figure 15), determine the glucose concentration of the beverage sample.

Remember to take into account that the linear calibration used reciprocal values and the sample analyzed was diluted two times. Calculate the concentration of glucose in the beverage sample.

**Questions**

**Question 1:** Compare glucose concentration as determined by this method to the nutritional label on the beverage. Do the values agree? Why or why not? Are there clues in the ingredient list that support your observations?

**Question 2:** If a current measurement by chronoamperometry was taken immediately after glucose oxidase was added to the sample, how would that affect the concentration measured by chronoamperometry?

**Question 3:** Why are all solutions in this lab in a buffered NaOAc solution? (Hint: consider general properties of enzymes).

**Question 4:** How should current vary with peroxide oxidation?

**Question 5:** This experiment used a 2 mm disk electrode. If a working electrode with a 5 mm radius was used instead for the glucose calibration, discuss the change expected in current response. What is the proportionality between electrode area and current?

**Question 6:** State the values of \( V_m \) and \( K_m \), with the appropriate units. Show the calculation of \( V_m \) and \( K_m \) from the linear calibration data.
References


Reprints

Reprints of this document are available upon request from:

Pine Research Instrumentation
2741 Campus Walk Ave, Building 100
Durham, NC 27705

http://www.pineinst.com/echem

Instructor Resources

Please email the sales department at: pinewire@pineinst.com for instructor resources, solutions to questions, and general discussion on this laboratory.