INTRODUCTION TO ION-SELECTIVE ELECTRODES IN THE CLASSROOM AND THEIR APPLICATION TO THE REAL WORLD

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Project Summary

Overview of Project

This module has been designed to enhance interest in engineering and its practical application through the use of ion-selective electrodes in the middle school and high school classroom. These lessons can provide for opportunities in the testing and analyzing of various substances in solution (e.g.; pH, ammonium, potassium, chloride and fluoride). Data which are gathered can be analyzed and a line of best fit or calibration curve created. Students can use that line to extrapolate and/or interpolate between existing data to determine unknown levels of substances in solution. Additionally, working with voltaic cells and ion-selective electrodes can reinforce basic high school chemistry.

Intended Audience

As mentioned earlier, our intended audience will be middle school or high school students. Middle school life-science is usually taught in 7^{th} grade and middle school students could definitely perform these activities with only a minimal chemical and electrical background. The upper level of this module will be formulated for classes such as AP chemistry, AP biology, or even environmental science, which are all usually taught to juniors and/or seniors in high school. Although the equipment used for labs is essentially the same for the varying grade levels, there will be variation in the analysis and application of the data at each level.

Estimated Duration

If the ion-selective electrodes and circuit boards required to conduct the experiment are already produced, then the module could last from 3 days to 2 weeks, depending on the depth of the lesson plans. If the production of the ion-selective electrodes and circuit boards is an intended objective, at least two more weeks should be added to the module.

Introduction

Students have more than likely heard the term “pH” in their everyday lives (i.e.; body chemistry, soil chemistry, food chemistry, water quality). Acid-base chemistry lends itself to teaching information ranging from simple pH numbers to more complex chemical concepts. Charts like Table 1 and Figure 1 can be used to help explain the concept of pH to students.

“Ion-Selective Electrodes (ISEs) are part of a group of relatively simple and inexpensive analytical tools which are commonly referred to as Sensors. The pH electrode is the most well known and simplest member of this group and can be used to illustrate the basic principles of ISEs.” [1] It should be understood that the ISEs are ion specific, each needing its own specific membrane to test for that ion.

The pH electrode is a device for measuring the concentration of hydrogen ions and, therefore, the degree of acidity of a solution. The most essential component of a pH electrode is a special, sensitive membrane which permits the passage of hydrogen ions, but no other ionic species. When the electrode is immersed in a test solution containing hydrogen ions, the external ions diffuse through the membrane causing a build up of charge on the inside of the membrane until it is large enough to resist any further flow of ions across the electrode. This charge can be measured as a change in voltage.

Table 1. Basic pH Table [2]

pH	Conc. H^+	Example	
0	10,000,000	Battery acid	*Most acidic*
1	1,000,000	Hydrochloric acid	
2	100,000	Lemon juice	
3	10,000	Orange juice	
4	1,000	Acid rain	
5	100	Black coffee	
6	10	Saliva	
7	1	Distilled water	*Neutral*
8	0.1	Salt water	
9	0.01	Baking soda	
10	0.001	Milk of magnesia	
11	0.0001	Ammonia solution	
12	0.00001	Soapy water	
13	0.000001	Oven cleaner	
14	0.0000001	Liquid drain cleaner	*Most alkaline*

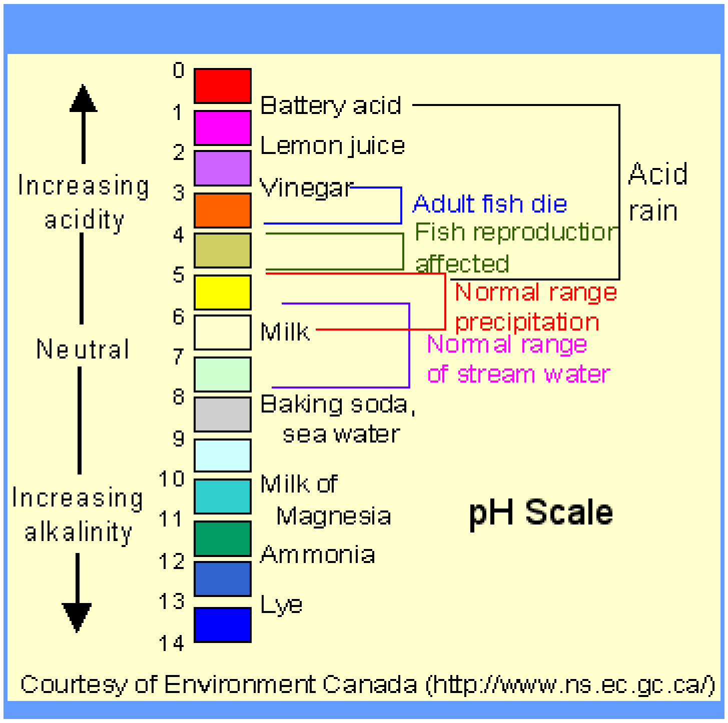


Figure 1. Basic pH Table [3]

This potential difference can only be measured in conjunction with a separate, but unaffected reference system which is also in contact with the test solution. A sensitive multimeter, which can measure milli-volts, must be used to measure this potential difference accurately.

In order to determine the pH of an unknown solution, it is only necessary to measure the potential difference in three standard solutions of known pH, construct a straight line calibration graph by plotting milli-volts versus pH, extrapolate the line from 1-14 to cover all ranges of pH, and then read off the unknown pH in relation to the voltage.

The relationship between the ionic concentration (activity) and the electrode potential is given by the Nernst equation:

$$E = E^0 + \left(\frac{2.303RT}{nF}\right) Log(a_i) \quad [4]$$

where:

E = the total potential (in mV) developed between the sensing and reference electrodes.

E^0 = constant which is characteristic of the particular ISE/reference pair. (It is the sum of all the liquid junction potentials in the electrochemical cell.)

2.303 = the conversion factor from the natural to the base 10 logarithm.

R = the gas constant (8.314 joules/degree Kelvin/mole).

T = the absolute temperature (degree Kelvin).

n = the charge on the ion in gram equivalents (with sign).

F = the Faraday Constant (joules/volt-gram equivalent); and

$Log(a_i)$ = the logarithm of the activity of the measured ion. [3]

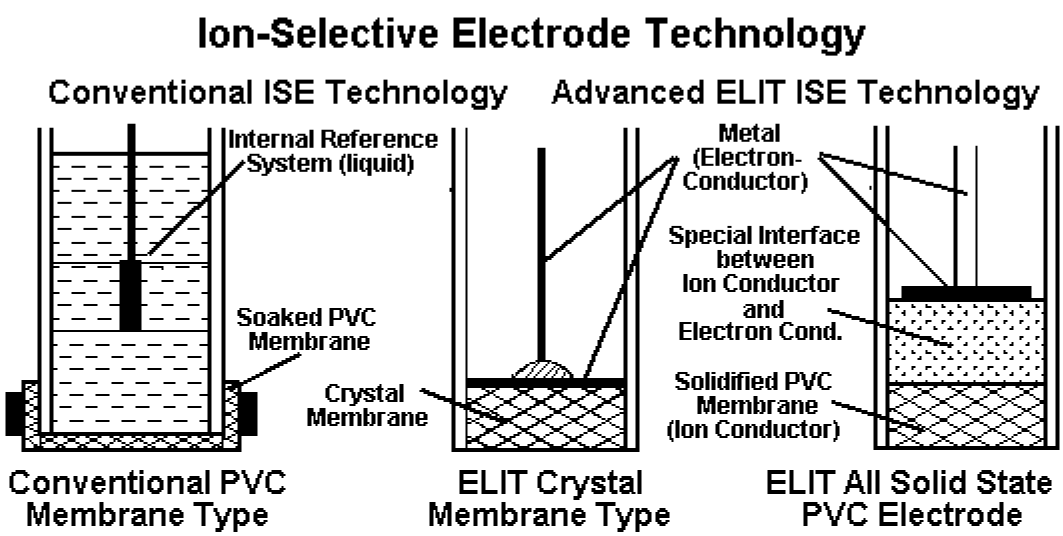


Figure 2. Three Types of Ion-Selective Electrodes [1]
(ELIT refers to a specific brand name of electrode.)

It turns out that other ions besides H^+ will effect the ISEs slightly because they can be carried across the membrane in small amounts. To account for these effects, you can simply add a term to the equation for each ion of concern as follows:

$$E = E^0 + \frac{2.303RT}{nF} Log\left[a_i I K_{ij} a_j^{\frac{Z_i}{Z_j}} \right] \qquad [4]$$

where:

K_{ij} = the selectivity coefficient for ion J on the ISE for species i.
A_j = activity of ion j.
Zi = charge on the ion you want to measure.
Zj = charge on the interferent.

Rationale

One of the goals of the Washington State University and National Science Foundation Institute for Science and Mathematics Education through Engineering Experiences is to have participants prepare a teaching module that is appropriate for their classroom. These activities will help to illustrate the connection between science and engineering. Students will be shown engineering principles that are applied in a diagnostic laboratory. This module is based on research being done in the Chemical Engineering Department at Washington State University under the direction of Professor Bernard Van Wie. The focus of this work is on developing inexpensive bio-sensing instruments (ion-selective electrodes) for testing such substances as pH, ammonium, and potassium ions.

ISEs have many advantages over more traditional solution testing systems. They are relatively inexpensive and simple to use, and have an extremely wide range of applications, as well as a wide concentration range (e.g.; 10^{-7} to 10^{-1} molar range). Once constructed, ISEs are quite simple to use and can hold up under rough handling (a.k.a. middle school students).

One item that might be of interest to students is that the U.S. Naval Research Laboratory has conducted research using these electrodes to monitor water sources for the presence of Copper (II) which is toxic to crustaceans. Copper (II) is known to contaminate harbors as it leaches from the paint of ship hulls where it is used to reduce the growth of barnacles that would otherwise coat the hulls and slow down the ships, thus increasing fuel consumption.

Science

Science can be defined as “accumulated and established knowledge, which has been systematized and formulated with reference to the discovery of general truths or the operation of general laws; knowledge classified and made available in work, life, or the search for truth; comprehensive, profound, or philosophical knowledge.” [5] Science is generally driven by the quest to find out **why** something happens. A method of learning about the natural world, science focuses on formulating and testing naturalistic explanations for natural occurrences.

Engineering

“Engineering is the application of science to the needs of humanity. This is accomplished through knowledge, mathematics, and practical experience applied to the design of useful objects or processes. Professional practitioners of engineering are called engineers.

Engineering is concerned with the design of a solution to a practical problem. A scientist may ask ‘why?’ and proceed to research the answer to the question. By contrast, engineers want to know **how** to solve a problem, and **how** to implement that solution. In other words, scientists investigate phenomena, whereas engineers create solutions to problems or improve upon existing solutions. However, in the course of their work, scientists may have to complete engineering tasks (such as: designing experimental apparatus, or building prototypes), while engineers often have to do research.
In general, it can be stated that a scientist builds in order to learn, but an engineer learns in order to build.” [6]

Goals

General Goals

The over-arching goal of this module is to introduce students to the field of engineering. Within this goal are three sub-goals.

The first sub-goal of this module is to enhance student interest in learning as they view science and mathematics through the context of monitoring things like: contamination of the environment; determining concentrations in body fluids (saliva, sweat, urine); determining concentrations in various beverages they drink (soft drinks, sports drinks, fruit juices); or checking the pH of common solutions (cleaners, motor oil, solvents).

A second sub-goal is to provide students with experience in conducting research using ion-selective electrodes, digital multimeters, voltage, and data gathering.

Third, this module provides opportunity for data analysis and handling, as well as an introduction to aspects of technology with which the students may not be familiar.

This module, either as a whole or in sections, could also be used in an extended research situation, such as a school science club, science fair project, or an independent study credit.

Learning Objectives

This module could be used to help meet Washington State GLEs (Grade Level Expectations). The specific GLEs that could be addressed are 1.1 (Properties of Substances), and 2.1 (Investigating Systems).

By the end of this module, the **middle school** student will be able to:

1. Briefly describe how an ion selective electrode operates.
2. Collect data using an ion selective electrode.
3. Construct a trend line and extrapolate data on a computer spread sheet.
4. Write a journal entry explaining the implications of this activity to their lives.

By the end of this module, the **high school** student will be able to:

1. Describe in detail how an ion selective electrode operates.
2. Define an ion and list characteristics of an ion.
3. Collect data using an ion selective electrode.
4. Construct a trend line and extrapolate data on a computer spreadsheet.
5. Analyze the data and make inferences as to the practical uses of this technology in our everyday lives.
6. Using the Nernst Equation, determine the linear equation and relationship between milli-volts and the log of concentration.

Equipment

To successfully complete this module, three specific pieces of equipment will be needed.

1. An ion-selective electrode for the chemical cation/anion desired.
2. A reference electrode (which can be used in conjunction with any of the ISEs).
3. A circuit board specifically designed for use with ISEs.

Please contact the authors on how to build or obtain this equipment.

Additional equipment and supplies that will be needed are:

1. Electrical digital mulitmeter.
2. pH buffer solutions.
3. Power source that will provide 3 volts (2 AA barriers, 2 AAA batteries, or electronic power source).

Lab #1

Purpose

This lesson will introduce students to the use of ion-selective electrodes and how those electrodes can be of practical use.

Safety

1. Students will be required to wear safety goggles, latex gloves and lab aprons at all times.
2. pH buffer solutions and/or other chemical solutions will be used during the lab and need to be handled carefully.
3. All solutions must be disposed of in appropriate containers supplied by instructor.
4. Absolutely NO food or beverage in the lab at any time.
5. Lab protocol, etiquette, and courtesy will be observed whenever in lab.

Prerequisite Skills/Knowledge

- beginning knowledge of how an ISE works, including the concept of ionization.
- familiarity with the use of a digital multimeter.
- basic knowledge of pH.
- data collection skills.

Instructional Strategies

Students will work in groups of three. One student will put the electrodes into the various solutions and rinse the electrodes between tests. Another student will be responsible to exchange the containers of pH and make sure that all the electrical contacts stay connected. The third student will be the recorder. Rotation of responsibilities is a good idea.

This particular lab will be convergent in style. There is a specific product which needs to be arrived at, with specific results. The objectives of subsequent labs will take this data and use it more divergently.

Materials/Equipment

1. Ion selective electrodes (for this activity we will be using pH ion electrodes, one per group).
2. Reference electrodes (one per group).
3. Electrical digital multimeter able to read milli-volts (one per group).
4. Power source that will provide 3 volts (2 AA barriers, 2 AAA batteries, or electronic power source).
5. Battery holders (one per group).
6. Circuit board specific to ion selective electrode testing (one per group).
7. pH buffer solutions of pH 4, 7 and 10.
8. Small Petri dishes for holding pH buffers (three per group).
9. Squeeze bottle filled with de-ionized water for rinsing electrodes between tests (one per group).
10. 250 ml beaker to catch water when rinsing electrodes.

Procedures

1. Connect the digital multimeter to the circuit board as per Figure 3. (An additional technique to ensure proper installation of wiring would be to color code the red connections with red marker and the black connections with black marker. Warning: connecting wires to the wrong sides (i.e.; reversing polarity) will damage the circuits.)
2. Connect the power supply to the circuit board as per Figure 3.
3. Connect the pH electrode and the reference electrode as per Figure 3.
4. Place wired circuit board into clamp/ring stand assembly.

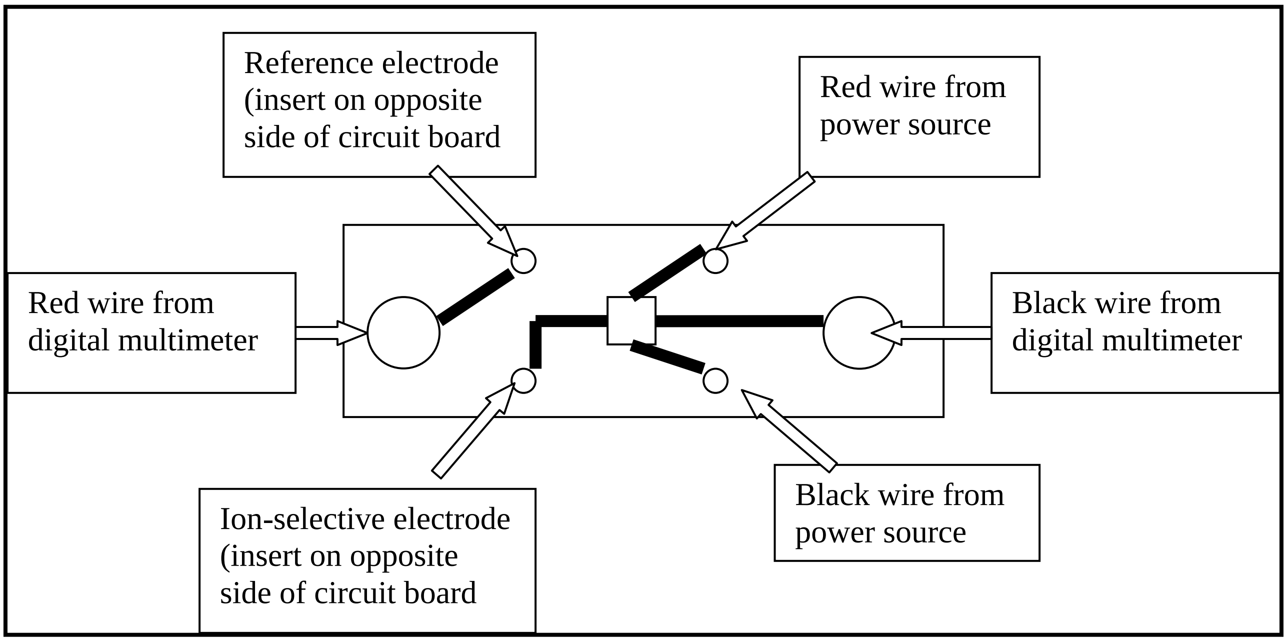


Figure 3. Proper wiring setup for circuit board

5. Measure out approximately 7 ml of pH buffer 10 and place in Petri dish.
6. Repeat procedure for the pH 7 and pH 4 buffer solutions.
7. Turn digital mulitmeter dial to mV or 2 V, depending upon the multimeter being used.
8. Place a 250 ml beaker or other similar item upside down on base of ring stand to provide a platform to elevate the Petri dishes.
9. Place the pH 10 Petri dish on the ring stand platform and lower the electrodes into the solution. Make sure electrodes are not in contact with bottom of Petri dish.
10. Allow at least 30 seconds for electrode readings to stabilize. Record data on table (see Appendix A).
11. Repeat procedure with pH 7 and pH 4 solutions, rinsing electrodes with de-ionized water between each test. Record results.
12. Allow for at least three tests of each pH level maintaining the order of pH 10, pH 7, and then pH 4. Record results.
13. Clean up as per instructor’s directions.

Analysis
See discussion questions.

Conclusions
See discussion questions.

Discussion Questions
1. About how many mV were there between each log of pH?
2. If that is true, about how many mV of difference would you expect between a pH of 6 and a pH of 8?
3. What is the importance of rinsing with de-ionized water between tests?

Extension questions for high school level
1. How was the range of milli-volts (45-60 mV) between logs (levels of pH) arrived at?
2. What significance does each of the values in the Nernst Equation hold?
3. What is the difference, chemically, of an acid and a base?
4. Why would both a strong acid and a strong base “burn” a hole in something?

Evaluation
1. Students will be asked to describe how an ion-selective electrode works.
2. Students will be asked to demonstrate their ability to accurately obtain data using the ISE and the digital multimeter.
3. Using the data gathered in this lab, students will be asked to predict what the pH of a cola might be.

Lab #2

Purpose
To enter data gathered from Lab #1 into a spreadsheet format and create a line of best fit for the data. Introduction to both Excel and Chart Wizard is a part of this lab.

Safety
1. Computer lab protocol, etiquette, and courtesy will be observed whenever in the computer lab.
2. No food or beverages in the computer lab.

Prerequisite Skills
- key-boarding skills on a computer.
- basic graphing skills
- basic understanding of logs and exponents

Instructional Strategies
Hopefully, your school has a computer lab and enough computers so that every student can have their own. If not, then simply partner the students. Instructor will model steps on projection screen or personal computer.

Materials/Equipment
1. Data tables from Lab #1.
2. Computers with Microsoft Excel or comparable spreadsheet program.

Procedures (including data gathering)
1. Teach students how to open Excel on their computer.
2. Enter data table from Lab #1 into Excel.
3. Highlight data in table and go into Chart Wizard.
4. Continue instruction in construction of line graph and line of best fit.
5. Have students extrapolate line out to pH values of 0 and 14.

Analysis
See Appendix B and C for example data and graphing analysis.

Conclusions
1. What is the slope of your line of best fit?
2. What is your R^2 value?

Discussion Questions
1. Of what use is the data table all by itself?
2. What does your R^2 value tell you about the data?
3. What concerns might you have with extrapolated data?
4. What might happen to your line of best fit and R^2 value if more data were collected to generate the graph?
5. How could you test either your extrapolation and/or interpolation of data?

Evaluation

Give students data sampling or allow them to collect their own data. Require students to produce finished product of a line graph which includes a line of best fit. Graph must include graph basics: title, x and y axis which include labels and intervals, and data to be graphed.

Lab #3

Purpose
To use extrapolation/interpolation to measure the pH of common solutions such as:
1. beverages (soft drinks, sport drinks, fruit juices, coffee).
2. bodily fluids (saliva, sweat, urine).
3. common solutions (cleansers, solvents).

Safety

1. Students will be required to wear safety goggles, latex gloves and lab aprons at all times.
2. pH buffer solutions and/or other chemical solutions will be used during the lab and need to be handled carefully.
3. All solutions must be disposed of in appropriate containers supplied by instructor.
4. Absolutely NO food or beverage in the lab at any time.
5. Lab protocol, etiquette and courtesy will be observed whenever in lab.

Prerequisite Skills
- ability to use the ion-selective electrode testing equipment.
- ability to record data accurately.
- ability to use Excel and Chart Wizard
- basic knowledge of and ability to extrapolate and interpolate

Instructional Strategies
Prior to this lab, conduct a discussion about some of the solutions with which students come in contact on a fairly common basis. Ask students to bring in their favorite beverages…legal, of course.
Allow students to test these solutions and record the results.

Materials/Equipment

1. Ion selective electrodes (for this activity we will be using pH ion electrodes, one per group).
2. ISEs to test for potassium, chlorine, ammonium, and fluoride.
3. Reference electrodes (one per group).
4. Electrical digital multimeter able to read milli-volts (one per group).
5. Power source that will provide 3 volts. (2 AA barriers, 2 AAA batteries, or electronic power source.
6. Battery holders (one per group).
7. Circuit board specific to ion selective electrode testing (one per group).
8. Small Petri dishes for holding solutions to be tested (five or six per group).
9. Squeeze bottle filled with de-ionized water for rinsing electrodes between tests.\ (one per group).
10. 250 ml beaker to catch water when rinsing electrodes.
11. Solutions for testing (see examples under "Purpose")

Procedures (including data gathering)

1. Connect the digital multimeter to the circuit board as per Figure 4. (An additional technique to ensure proper installation of wiring would be to color code the red connections with red marker and the black connections with black marker. Warning: connecting wires to the wrong sides (i.e.; reversing polarity) will damage the circuits.)
2. Connect the power supply to the circuit board as per Figure 4.
3. Connect the pH electrode and the reference electrode as per Figure 4.
4. Place wired circuit board into clamp/ring stand assembly.

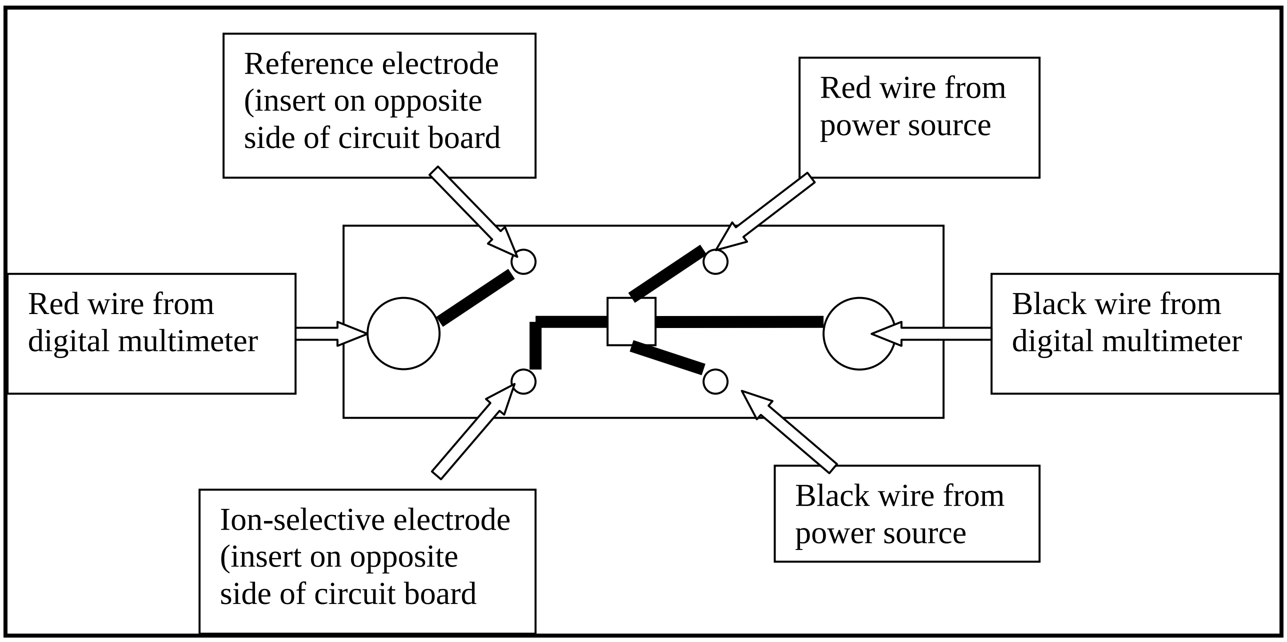


Figure 4. Proper wiring setup for circuit board

5. Fill Petri dishes with substances to be tested (i.e.; Coke, Windex, saliva, etc.).
6. Turn digital mulitmeter dial to mV or 2 V.
7. Place a 250 ml beaker or other similar item upside down on base of ring stand to provide a platform to elevate the Petri dishes.
8. Place the sample in the Petri dish on the ring stand platform and lower the electrodes into the solution. Make sure electrodes are not in contact with bottom of Petri dish.
9. Allow at least 30 seconds for electrode readings to stabilize. Record data on table (see Appendix A).
10. Repeat procedure with different sample solutions, rinsing electrodes with de-ionized water between each test. Record results.
11. Allow for at least three tests of each substance. Record results.
12. Clean up as per instructor’s directions.

Analysis

1. Calculate the pH of the samples using interpolation and/or extrapolation from the line of best graph.
2. Calculate the pH of the samples using the y intercept equation.
3. See Appendices B and C for example data and graphing.

Conclusions

1. Determine which substances are acids and which are bases.
2. Determine the concentration of Hydrogen ions in each substance.

Discussion Questions

1. What concerns might you have with extrapolated data?
2. How did these substances become acids and bases?
3. Are there any errors in your measurements or techniques?
4. If so, what would you do to reduce or eliminate these errors?
5. Could the pH of your samples change? If so, how?

Evaluation

1. Students will be asked to describe how an ion-selective electrode works.
2. Students will be asked to demonstrate their ability to accurately obtain data using the ISE and the digital multimeter.
3. Using the data gathered in this lab, students will be asked to predict what the pH of various substances might be.
4. Students will be asked to write a summary of what they have learned relative to pH, ion-selective electrodes and generating tables and graphs from data.

Appendix A

Table for Recording Ion-Selective Electrode Activity

pH buffer or substance to be tested (i.e.; soda pop, coffee, etc.)	milli-volts

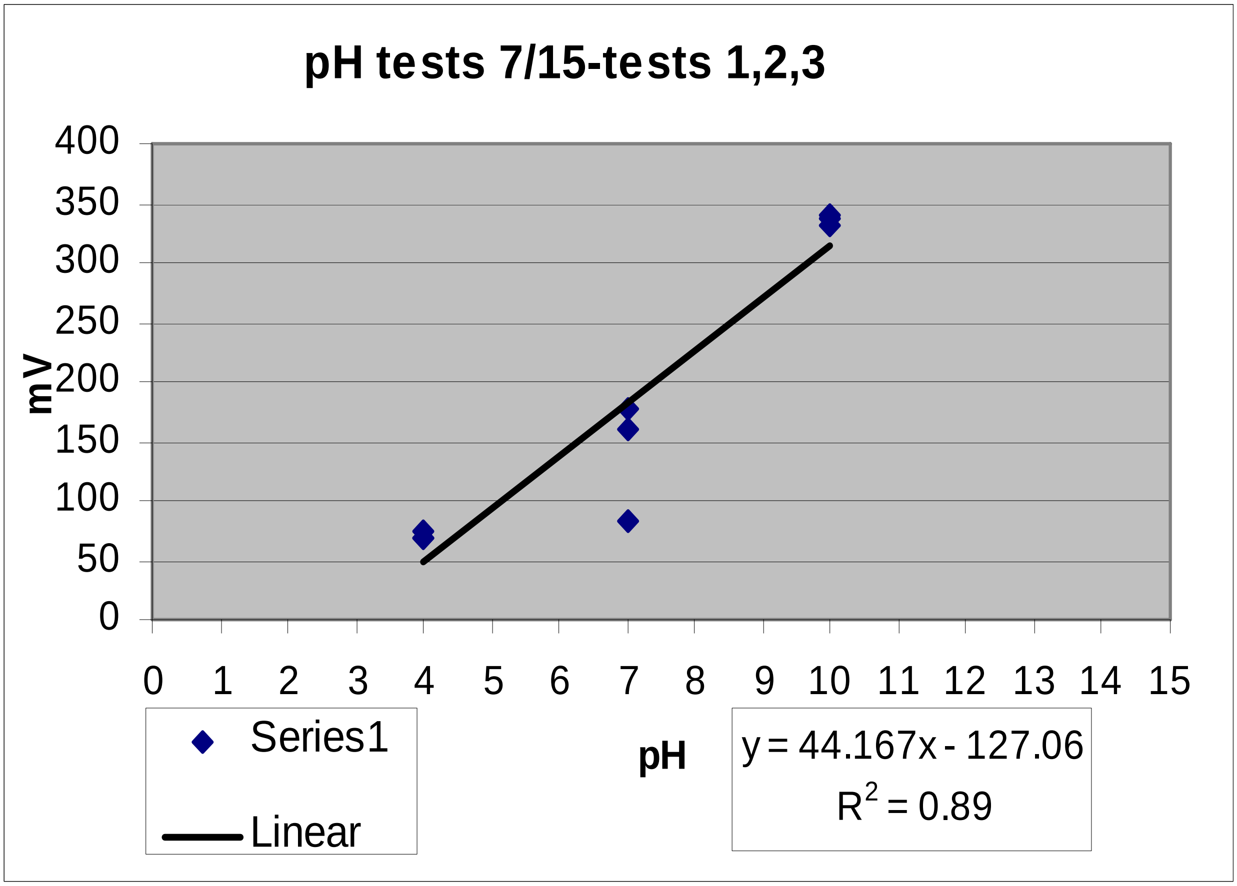
Appendix B

Data from pH Buffer Samples

Test #	pH	mV
1	10	337
1	7	83
1	4	74
2	10	339
2	7	176
2	4	69
3	10	331
3	7	161
3	4	69

Appendix C

Concentration Curve with Line of Best Fit and R^2 Value from Data in Appendix B



References

[1] C. Rundle; BSc. A Beginners Guide to Ion-Selective Electrode Measurements. (Nico2000 Ltd, London, U.K.). Chapter 2.

[2] http://www.gesource.ac.uk/ph-scale.html

[3] http://www.ns.ec.gc.ca\

[4] G.J. Moody and J.D.R Thomas, Selective Ion Sensitive Electrodes, Publishing Company, Watford Herts, England, 1971, p. 2.

[5] http://www.brainydictionary.com/words/sc/science216265.html

[6] http://encyclopedia.laborlawtalk.com/Engineering