Taking a 'Schwab' at teaching chemistry through guided-inquiry

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ABSTRACT

As part of ongoing educational reform initiatives in Singapore, 'science as inquiry' has been espoused as the central feature in the Singapore Ministry of Education's 2004 Science Curriculum Framework. In response to the framework, teachers are urged to adopt instructional practices that incorporate knowledge in science with the characteristics of scientific endeavours. What is scientific inquiry? What does inquiry-based science teaching look like? This paper illuminates the meaning of scientific inquiry and characterises inquiry-based teaching along a continuum of science instructional styles. A teaching model incorporating guided inquiry to that proposed in the Karplus and Thier SCIS Learning Cycle is proposed. The model features inductive learning as a means to facilitate the construction of concepts and utilises laboratory experiences to lead, rather than lag, the classroom phase of science teaching - a mode proposed by Joseph Schwab. This may offer a way for the teaching of science to be enacted so that instructional processes would be better aligned to the way scientific knowledge is constructed.

Keywords: Guided inquiry, inductive learning, laboratory experiences

1. INTRODUCTION

From the moment of birth, babies use their senses to make connections to the environment. Babies observe faces that come near, they grasp objects, they put things in their mouths, and they turn toward voices. Their natural curiosity is aroused in response to the things they perceive through their senses. Curiosity motivates them to establish meaning, to find out why and how things work the way they do. When young children learn to speak sufficiently, all too often, they wear us out with their “why,” “when,” “where,” and “how” questions. This is the essence of inquiry.

Every person develops meaning on a daily basis. Our observations and perceptions stimulate the construction of meaning. However, the manner in which meaning is constructed is not necessarily scientific in nature or based on empirical evidence. About six hundred years ago, man used his visual perception to conceive the earth as flat. This idea was reinforced by his daily observation of the sun’s movement across the sky. Subsequently, the belief that it was impossible to sail around the world was built on this limited understanding of the relationship of the earth to the sun. What manner of thinking would have motivated deeper questioning or investigation as to whether or not the earth was truly flat? I assert that scientific thinking affords us the necessary lens to critically question our observations, test ideas, and evaluate findings. In that way, the construction of knowledge will be based on empirical evidence and we would simultaneously gain an understanding about *how* we come to know what we know. This is what scientific inquiry is about.

> Curiosity is a fundamental human trait. By valuing this natural impulse to learn, the inquiry process can provide learners the necessary feedback and personal experiences they need to shape new and enduring views of the world. (Dyasi, 1999, p. 9)

Dyasi’s premise suggests that an inquiry-based teaching approach may be a means to engage children in learning and achieve more enduring conceptual understanding.

What does inquiry-based teaching look like in the classroom? What kinds of activities can students expect to find in an inquiry-based lesson? What do teachers need to know about inquiry and what skills do they need to develop before they can teach science using inquiry?

I begin this paper by tracing the origins of inquiry and its significance to science education in the United States. I will discuss what educators and researchers generally understand about inquiry and inquiry-based science teaching. From my review of the literature, I will highlight selected research findings on the student outcomes of inquiry-based science teaching. The National Science Education Standards (NSES or the “Standards”) will serve as a foundation for my understanding of inquiry in terms of the definition of inquiry, the essential features of inquiry, and the possible variations in inquiry-based science instruction. Finally, I will draw a model incorporating guided inquiry to that proposed in the Karplus and Thier SCIS Learning Cycle to offer an example of what inquiry-based science teaching could look like..

2. Review of the literature

2.1 Historical perspectives of inquiry

The notion of inquiry as an educational tool can be traced to John Dewey. In his 1909 address to the American Association for the Advancement of Science, Dewey expressed that science teaching had been over-emphasizing the accumulation of information and under-emphasizing science as a method of thinking and an attitude of the mind.

> Science teaching has suffered because science has been so frequently presented just as so much ready-made knowledge, so much subject-matter of fact and law, rather than as the effective method of inquiry into any subject-matter. (Dewey, 1910, p. 124)

According to Dewey (1933), inquiry refers to “an active, persistent, and careful consideration of any belief or supposed form of knowledge in the light of the grounds that support it and the further conclusions to which it tends” (p. 9). He argued that evidence, inference, and generalization are essential foundations for the construction of any form of knowledge. Dewey (1910) powerfully stated that

> the future of our civilization depends upon the widening spread and deepening hold of the scientific habit of mind; and that the problem of problems in our education is therefore to discover how to mature and make effective this scientific habit. (p. 127)

Hence, almost a century ago, Dewey articulated that developing thinking and reasoning, formulating habits of mind, and understanding the process of science were essential objectives for teaching science as inquiry. Since then, the role of the scientific method in science education has been a subject of continuous discussion.

In 1957, the launch of Sputnik by the Soviet Union was a historical turning point in American education. Sputnik symbolized a threat to American security and superiority in science, mathematics, and technology. Consequently, educational reform in the United States was accelerated in favour of higher academic standards, especially in science and mathematics. According to Bybee (1997), the existing curriculum was replaced by one that emphasized conceptually fundamental ideas in the two disciplines, the modes of scientific inquiry, and mathematical problem solving. The intention for the change was to have students not only learn terms, information, and applications, but also the structures and procedures of science and mathematics.

Also in the late fifties, Joseph Schwab -- a prominent advocate for the learning of science through the process of inquiry -- argued that science should be viewed as a set of principles for inquiry rather than a body of stable truths (Schwab, 1962). He felt that science in schools was taught in a way that was inconsistent with modern science in practice. According to Schwab, conceptual structures in science “could be revised when necessary in directions dictated by complexes of theory, diverse bodies of data, and numerous criteria of progress in science” (p. 11). So instead of having students encounter science as a set of unchallenged conclusions, science units should

> consist of the statement on a scientific problem, a view of the data needed for its solution, an account of the interpretation of these data, and a statement of the conclusions forged by the interpretation. (p. 52)

Schwab also suggested that laboratory experiences be used to "*lead* [italics added] rather than lag the classroom phase of science teaching" (Schwab, 1962, p. 52). This would involve students working on experiments *prior to* any formal explanation of science concepts or principles and students responding to the display of the phenomenon under study by posing questions, gathering evidence, and formulating explanations based on the evidence they collect.

Schwab described three different levels for laboratory science investigations. For the first level, students would learn what they did not already know by thinking about the questions posed in laboratory texts and carrying out the methods prescribed in the texts to investigate those questions. At the next level, the questions would be specified, but students would now devise the methods for investigation. The most sophisticated level would involve students raising their own questions and generating the methods for investigation. Thus, the three levels may be differentiated by the degrees of openness of the laboratory task and guidance given to students by the teacher. Consequently, the extent of inquiry in these kinds of tasks would also vary.

Schwab's distinction for the three possible approaches to laboratory science investigation may be viewed as a precursor to the different styles of inquiry-based science teaching. I will discuss these variations in a later section. But first, I will share what the National Research Council understands about scientific inquiry and the essential features of inquiry.

2.2 Scientific inquiry

In 1995, as part of a national effort in the United States to realize a vision for a scientifically literate population in the 21st century, the National Research Council (NRC) released the National Science Education Standards (NSES or the "Standards"). According to the NRC (1996), science is both a body of knowledge and a process through which scientific knowledge is created. The process portion of this definition refers specifically to scientific inquiry and is a major component of the Standards. The NRC (1996) eloquently articulated that

> scientific inquiry refers to the diverse ways in which scientists study the natural world and propose explanations based on evidence derived from their work. (p. 23)

The Standards serve to guide educators on ways to sustain students' curiosity in science and develop in them the abilities associated with scientific inquiry. The term inquiry is used in the NSES in two different ways. Inquiry refers to:

- the abilities needed to design and conduct scientific investigations; and
- the teaching and learning strategies that enable science concepts to be mastered through investigations.

Hence, inquiry involves questioning, exploring, planning investigations, gathering and interpreting data, predicting, testing predictions, drawing conclusions, and communicating results. These are the activities that mirror the work of scientists and characterize the process of science (NRC, 2000b).

2.3 ESSENTIAL FEATURES OF INQUIRY

The National Research Council (2000b) identified five essential features of classroom inquiry. These features presumably serve as tools to expose students to many important aspects of science and develop in students a deeper understanding of science concepts and processes. The features are outlined below in Table 1.

Table 1. *Essential features of classroom inquiry (NRC, 2000b, p.25)*

1.	Learners are engaged by scientifically oriented questions.
2.	Learners give priority to evidence, which allows them to develop and evaluate explanations that address scientifically oriented questions.
3.	Learners formulate explanations from evidence to address scientifically oriented questions.
4.	Learners evaluate their explanations in the light of alternative explanations, particularly those reflecting scientific understanding.
5.	Learners communicate and justify their proposed explanations.

Inquiry-based teaching may be described as “full” or “partial” depending on the extent to which all the essential features are present (NRC, 2000b). For example, if a teacher explains the workings for a phenomenon instead of having students explore, question, or generate their own explanations from evidence, then one or more essential features of inquiry will be missing and the inquiry instruction may be referred to as being partial.

2.4 VARIATIONS OF THE ESSENTIAL FEATURES OF INQUIRY IN THE CLASSROOM

In section 2.1, I discussed Schwab’s three possible approaches for laboratory science teaching. The approaches differed based on the degrees of openness of the task and the guidance given to students by the teacher. By similar reasoning, the five features of inquiry can vary depending on the amount of structure that teachers decide to build into inquiry-based lessons (NRC, 2000b). For example, one way students may be engaged in scientifically oriented questions is by posing the initial question on their own. They could also choose questions from a selection provided by the teacher, and then pose new questions from that point and further. In formulating explanations from evidence, students might summarize the evidence they collected, or they might use a set of evidence provided by the teacher. Table 2 describes in detail the possible variations in the five essential features of inquiry based on the relative proportions of teacher-direction and student self-direction (NRC, 2000b, p. 29).

Table 2. *Variations in the essential features of classroom inquiry (NRC, 2000b, p.29).*

Essential feature of inquiry	**More ← Amount of Learner Self-Direction → Less** **Less ← Amount of Direction from Teacher or Material → More**			
1. Learner engages in scientifically oriented questions	Learner poses a question	Learner selects among questions, poses new questions	Learner sharpens or clarifies question provided by teacher, materials, or other sources	Learner engages in question provided by teacher, materials, or other sources
2. Learner gives priority to evidence in responding to questions	Learner determines what constitutes evidence and collects it	Learner directed to collect certain data	Learner given data and asked to analyze	Learner given data and told how to analyze
3. Learner formulates explanations from evidence	Learner formulates explanation after summarizing evidence	Learner guided in process of formulating explanations from evidence	Learner given possible ways to use evidence to formulate explanation	Learner provided with evidence
4. Learner connects explanations to scientific knowledge	Learner independently examines other resources and forms the links to explanations	Learner directed toward areas and sources of scientific knowledge	Learner given possible connections	
5. Learner communicates and justifies explanations	Learner forms reasonable and logical argument to communicate explanations	Learner coached in development of communication	Learner provided broad guidelines to use to sharpen communication	Learner given steps and procedures for communication

There are many terms in the research literature associated with inquiry. Some common associations include: “hands-on” experiences, discovery, reflective thinking, and problem solving. Although related to these approaches, inquiry is not synonymous with any one of them (Crawford, 2000; Domin, 1999; Haury, 1993; Rankin, 1999). This range of misconceptions of inquiry makes it challenging for teachers to enact inquiry-based teaching in their classrooms (Crawford, 2000; Wallace & Kang, 2004).

Domin (1999) classified science instruction into four distinct styles: expository, discovery, problem-based, and inquiry. He differentiated among these styles using three descriptors: 1) outcome; 2) approach; and 3) procedure. The *outcome* of a task could be pre-determined -- known to the teacher but unknown to the student -- or undetermined -- unknown to the teacher and student. The *approach* to learning the phenomenon could be deductive, in which students apply a general principle to understand a phenomenon or inductive, in which students derive a general principle. Finally, the *procedure* for an investigation could either be given to students or student-generated. Table 3 summarizes Domin’s classification for the four styles of science instruction according to the three descriptors.

Table 3. *Descriptors of science instructional styles (Domin, 1999, p. 543)*

Style of instruction	Descriptor		
	outcome	**approach**	**procedure**
Expository[a]	pre-determined	deductive	given
Discovery[b]	pre-determined	inductive	given
Problem-based[c]	pre-determined	deductive	student-generated
Inquiry	undetermined	inductive	student-generated

[a] **Expository** instruction is similar to traditional or 'cook-book' style instruction where students follow given procedures to arrive at an expected outcome.

[b] In **discovery** instruction, students follow a procedure on what to do and record. Students are guided towards discovering certain outcomes.

[c] **Problem-based** instruction requires students to create procedures by applying a concept that they have learned or been exposed to solve a problem.

According to Domin (1999), inquiry instruction would involve students working on open-ended tasks (where the outcomes are unknown to them and the teacher), deriving general principles, and devising their own procedures with less teacher-direction than in traditional laboratory activities. This conception of inquiry is consistent with the canonical ideas about inquiry and has been specifically termed as *open-ended scientific inquiry* or *open inquiry* (Furtak, 2006; NRC, 2000b).

At this point, I wish to reiterate (with reference to Table 2) that variations are possible for the instructional approach called "inquiry." Furtak (2006) proposed thinking about inquiry as a continuum of various science instructional styles. An expository instructional approach may be positioned at one end of this continuum where teacher-direction is highest. Conversely, open-ended scientific inquiry will be positioned at the other end where learner self-direction is highest ('full' inquiry).

The three descriptors in Table 3 were not assigned any order of importance or priority to inquiry. For the purpose of positioning discovery instruction and problem-based instruction along the continuum, I will arbitrarily assign the *approach* descriptor a higher priority to inquiry relative to the *procedure* descriptor. Therefore, discovery instruction will be regarded as a more learner self-directed instructional style than problem-based instruction. Thus, the four science instructional styles can be arranged according to the continuum shown in Figure 1.

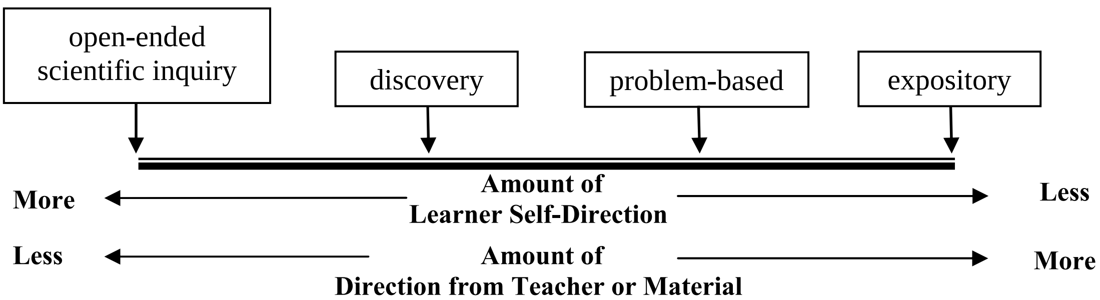

Figure 1. *A continuum for science instructional styles*

A teacher may decide to use an inquiry-based instructional approach, but start by giving more guidance to students in terms of posing the question, providing the procedure, or stating the outcome for an investigation. The general term *guided inquiry* has been used to describe this type of instructional approach (NRC, 2000b). Guided inquiry instruction may be positioned anywhere between the two extreme ends of the above continuum (Furtak, 2006).

3. MAKING A CASE FOR INQUIRY

> Tell me and I forget, show me and I remember, involve me and I understand. (Confucius, 450 B.C.)

The last part of this old saying highlights the importance of student involvement in learning in order for them to gain understanding. Inquiry-based science instruction utilizes the processes of science -- observing, interpreting, gathering evidence, predicting, and communicating -- so that students learn science through their involvement. In doing so, that is, through experimenting and not simply by theory, students stand to attain an understanding of the empirical basis of scientific evidence, and thereby develop deeper conceptual knowledge (Sund & Trowbridge, 1967).

Inquiry-based teaching has been hailed as an authentic approach for science education in part because it involves learning from direct experience (Dow, 1999). Numerous studies have revealed that inquiry-based teaching produces positive outcomes on student conceptual learning and cognitive achievement (Bernstein, 2003; Chang & Mao, 1999; Mao, Chang, & Barufaldi, 1998). Science activity-based programs that feature experimentation, direct experience, and observation result in gains over traditional instructional methods in student outcomes such as process skills, science content knowledge, and procedural knowledge (Bredderman, 1983; Glasson, 1989). An inquiry curriculum has also been reported to foster problem solving and independent learning (Shymansky, Hedges, & Woodworth, 1990).

4. ALIGNMENT BETWEEN INQUIRY AND HOW PEOPLE LEARN

A report in 1999, edited by Bransford, Brown and Cocking and entitled *How People Learn*, presented a broad consensus about how learning takes place (NRC, 2000a). The report drew from research on all content areas and synthesized research from fields like cognition, child development, and brain functioning. The research findings were connected to inquiry in important ways (NRC, 2000b). Figure 2 illustrates the connections between the features in inquiry and the ways that learning takes place.

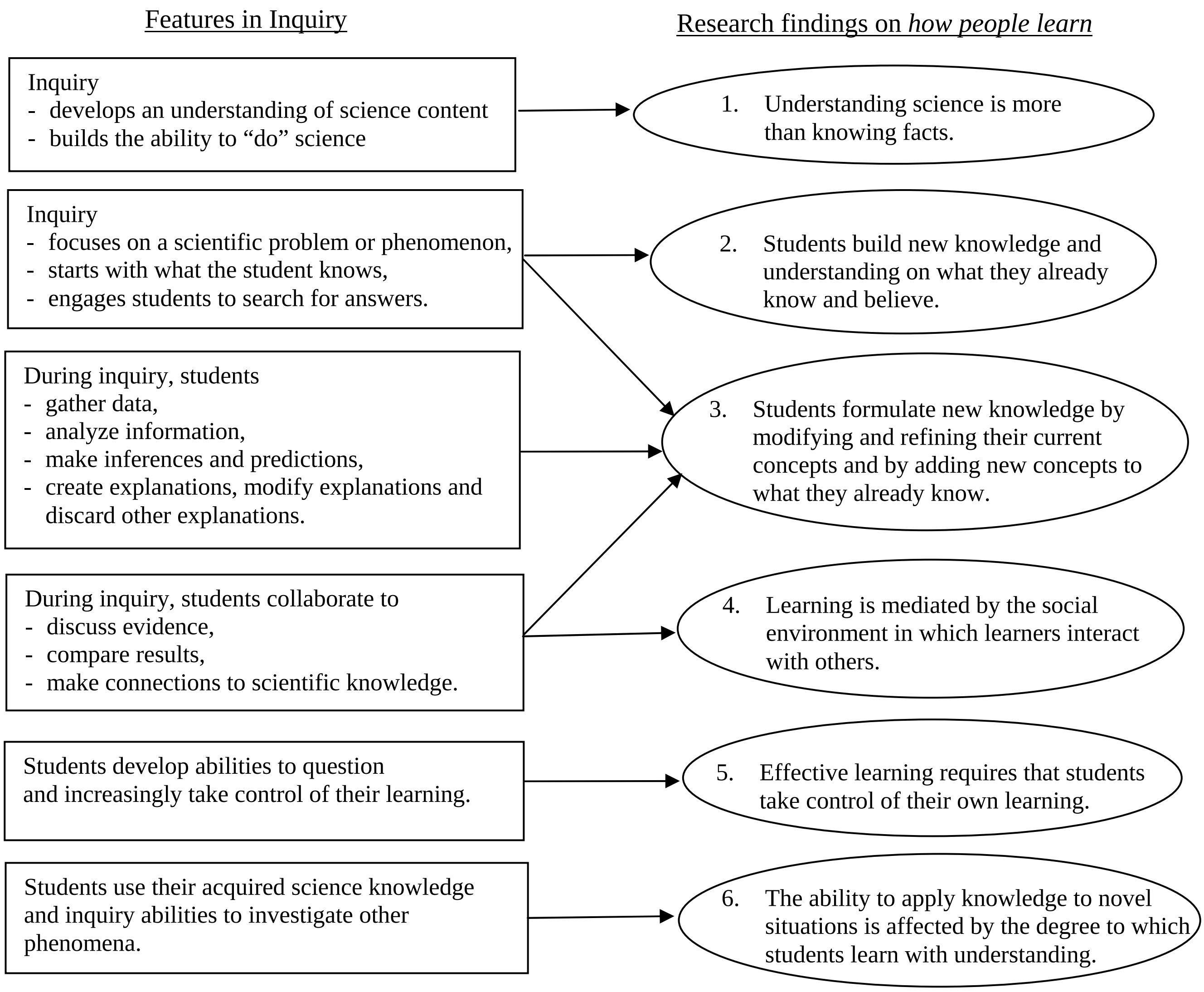

Figure 2. *Connections between the features in inquiry and the ways that learning takes place (Information adapted from: NRC, 2000b, pp. 116-121).*

In sum, inquiry as a teaching approach is aligned with how people learn. Inquiry has the potential to foster deep learning of science concepts and encourage students to think in ways that will lead them to inquire more deeply into those concepts. These capacities are recognized in science experts and are "required of almost everyone in order to successfully negotiate the complexities of contemporary life" (NRC, 2000a, p. 4).

5. CHALLENGES IN IMPLEMENTING INQUIRY

In the preceding section, I cited research findings that support the inclusion of inquiry-models in the teaching of science. However, the planning and enactment of inquiry-based instruction in the classroom have been described as challenging or difficult (Furtak, 2006; Hassard, 2001; Roehrig, 2004; Wallace & Kang, 2004). The implementation of inquiry-based lessons can be impeded or constrained by many factors. These include the availability and quality of induction programs for beginning teachers (Luft & Patterson 2002; Luft, Roehrig & Paterson, 2003), teachers' beliefs about students and students learning, teachers' understanding of the nature of science, teachers' cultural perceptions about school science education (Wallace & Kang, 2004), teachers' deficiency of pedagogical skills (Luft, 2001) and lack of time for planning (Hassard, 2001). What kinds of intervention or teacher professional development programs could possibly address these issues? What other barriers do teachers need to overcome in order to implement reform-based teaching approaches like inquiry-based science teaching? Do teachers need to first review their beliefs about the nature of science? Do teachers need to understand how scientific knowledge is generated?

According to Young (1996), the historical view of the purpose of education has largely influenced the way that science is traditionally taught. During the colonial era, Thomas Jefferson asserted that education should serve the basic functions of selecting and sorting students for more specific or advanced courses and providing people with information so that they could earn a living. Young (1996) asserts that "the conventional way of teaching science does not work for most students [today]" (p. 123). Students' loss of interest in science, students' aversion to higher science courses, and the lack of scientific literacy amongst adults are the result of this conventional approach to teaching science (Young, 1996). Scientific literacy is essential for citizens to be able to distinguish fact from myth, make decisions based on evidence, think creatively, and solve problems. These qualities are crucial for effective functioning in today's world and Young contends that the empowerment for effective functioning can be realized through inquiry-based science education.

In spite of the difficulties and potential obstacles confronting the implementation of inquiry-based science teaching, research and the current demands of society strongly urge educators to consider inquiry as a viable approach to improving student outcomes and equipping citizens for effective functioning. It is worthwhile to explore what can be done to facilitate teachers in utilizing inquiry and giving inquiry greater prominence in their repertoire of teaching strategies.

6. IMPLICATIONS FOR INQUIRY-BASED TEACHING IN THE SINGAPORE SCIENCE CLASSROOM

Some challenges in implementing inquiry-based teaching were discussed in section 5. Teachers, who view inquiry as having positive influences on many critical dimensions of student learning, may even relegate their personal goals for instruction to a secondary priority in the light of systemic, cultural, and public expectations of what they should be preparing students for and how students should be learning (Wallace & Kang, 2004). For example, parents may have a skewed interpretation of their children learning well on the basis of children completing lots of homework, memorizing content, reciting facts, and scoring high in standardized tests. According to a study by Wallace and Kang (2004), some teachers find their own balance between their personal teaching goals (which include inquiry) and externally imposed demands by using inquiry-based instruction as application and problem-solving *after* concept introduction, rather than a means for students to learn concepts inductively.

In Singapore, the national curriculum predetermines almost entirely what students learn over the course of their primary to secondary education. Similar to the description by Edwards and Mercer, cited in Furtak (2006), the nature of science education in Singapore may be viewed as "essentially a process of socialization into a pre-existing epistemological world” (p. 455). In my opinion, it is important but rare for students to be afforded the time and educational opportunities to discover knowledge or learn by induction. Science teachers in Singapore encounter constraints and competing demands similar to those I described earlier. With ‘science as inquiry’ centred in the Singapore science curriculum framework, in what way could inquiry-based instruction be perceived and put into operation such that it is useful and practical to both teachers and students?

7. AN INQUIRY-BASED MODEL FOR SCIENCE INSTRUCTION

I wish to introduce a possible model of teaching for Singapore science teachers to consider adopting. The model is based on the SCIS[1] Learning Cycle that was developed by Robert Karplus and Herbert Thier. The SCIS learning cycle comprises three phases: 1) *exploration*; 2) *concept invention*; and 3) *concept application*.

In the exploration phase, students are provided hands-on tasks in which they make observations, collect and analyze data, investigate relationships, and gather evidence to construct ‘discoveries’. Next comes the concept invention phase, in which students invent or construct concepts. In this second phase, teachers play a crucial role in helping students to organize information, relate information to their prior experiences, and fill in conceptual gaps that may have surfaced during exploration. Finally, in the concept application phase, students apply the concepts learned to solve problems in new situations. The problems could be similar to those found at the end of a chapter in text books or those that teachers normally assign for homework. I have modified the SCIS learning cycle to include *guided inquiry* in the first two phases.

The modified SCIS learning cycle is illustrated in Figure 3. I will elaborate on the insertion of guided inquiry in the next paragraph.

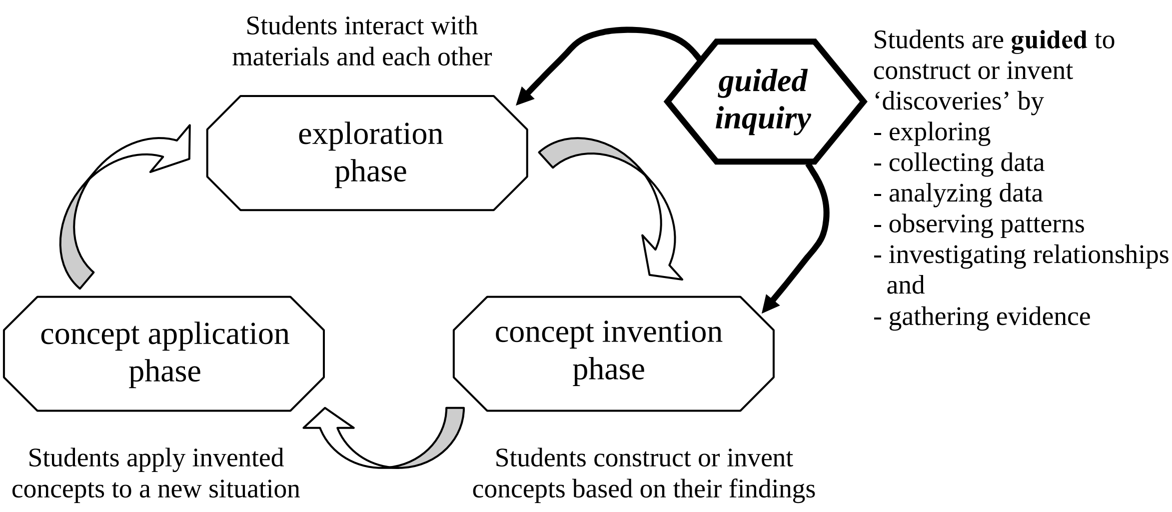

Figure 3. *The modified SCIS Learning Cycle with* ***guided inquiry*** *included as the teaching approach in the exploration and concept invention phases.*

[1] SCIS: Science Curriculum Improvement Study, an elementary science program in the United States. The description of the Karpuls and Thier SCIS Learning Cycle by Carin, Bass and Contant (2005) was used as a reference.

According to Carin et al. (2005), in order for students to assimilate presented information as usable and meaningful knowledge, it is essential for teachers to facilitate learning by first providing hands-on experiences. I view these activities which precede the formal transmission of content as useful because they afford students new concrete experiences that can act as scaffolds for the topic of study. Referring to Figure 3, I propose using guided inquiry in both the exploration and concept invention phases to further facilitate students' learning. According to Farrell, Moog, and Spencer (1999), guided inquiry tasks are "designed to lead students to hypothesis formation and testing" (p. 570). Therefore, with the incorporation of guided inquiry to the cycle, students learn through hands-on tasks accompanied by questions specifically designed to lead or guide them to explore, collect and analyze data, observe patterns, investigate relationships, and gather evidence to construct explanations and invent concepts. Students use the observations, data, and other findings to invent a part or all of a concept or relationship on their own. Hence, rather than having students encounter concepts entirely through the text or lectures, they are guided in learning a concept or principle by induction. The leading questions play an important role in the model by directing students to take note of specific information and organize data, and compel them to think critically and analytically. Students utilise the evidence they gathered to invent their understanding and valid conclusions. The invented concepts may vary between students. This occurrence provides an opportunity for students to challenge or support each other's ideas based on the evidence that each one has gathered. In addition, this also paints a picture that in science investigations, there may not be just one answer but instead a variety of answers which may be connected and support each other.

I wish to provide an example of what a lesson could look like using a teaching approach based on the modified SCIS learning cycle. I make reference to a Year 4 or high school tenth grade equivalent chemistry topic on electrolysis. A traditional or expository style of instruction would likely involve lecturing for efficient content transmission. Students would listen or read about the process of electrolysis and the expected products for the electrolysis of specific electrolytes. The order of ease of discharge of ions would be presented, together with situations for selective discharge of some ions. More often than not, attention would be drawn to memorising the order to discharge for efficient transfer so that the student would subsequently be able to address theoretical problems. Laboratory experiences that follow or lag content introduction would likely serve to illustrate or verify what students had been told in class. The learning approach in the above situation is characterised as deductive (refer to Table 3).

In what way could a laboratory lesson precede the teaching of content, and incorporate inductive thinking to have students construct concepts by guided inquiry? I make reference to the worksheet given in the Annex. Students would need some prior knowledge that:

- An electrolyte may be a molten ionic compound or an aqueous solution of an ionic compound, both having mobile ions.
- Electrolysis would involve the migration of cations (positive ions) to the cathode (negative electrode) and anions (negative ions) to the anode (positive electrode) under the influence of a direct current supply.
- The ions would undergo reduction or oxidation at the respective electrode.

Instruction, according to the modified SCIS learning cycle, starts with exploration. Students use a set of learning stations or experimental set-ups of electrolytic cells to electrolyse some electrolytes, namely: aqueous sodium nitrate, aqueous copper(II) sulfate, aqueous potassium iodide, and aqueous copper(II) chloride. With only an introductory knowledge about electrolysis, students make observations to identify the products of electrolysis to then deduce the ions that have been discharged. By considering the ions present in the aqueous electrolyte and making reference to the observations gathered, students then infer the order of discharge for the ions in that example. Through a set of leading questions and more information, students would be guided to observe patterns or connections to intuitively derive the relationships for the ease of discharge of ions and subsequently, the selective discharge of ions in the context of the concentration effect.

In sum, through a combination of hands-on experiences and questions that are crafted to lead students to make inferences and conclusions based on the data they gathered, students are guided to derive concepts about electrolysis through an inductive approach. The prior concrete experiences acquired over the exploration and concept invention phases would then serve as scaffolds for students to refine their understanding or learn new terms when formal content is introduced. Finally, in the application phase, students apply their new knowledge in exercises and problems (see last page on Annex). These tasks give them the opportunity to build confidence in using the new knowledge and transfer the knowledge to unfamiliar situations.

I view the proposed teaching model with guided inquiry included during exploration and concept invention as a way for teachers to operationalise Schwab's conception of having practical work "lead rather lag the classroom phase of science teaching" (Schwab, 1962, p. 52). I assert that guided inquiry provides students with relevant prior experiences that they can use as scaffolds for subsequent knowledge construction. Students are guided to think with reference to the evidence gathered and learn by induction. I also assert that this model of instruction affords students the opportunity to develop higher-order thinking skills as they construct their own understanding. I see this as a workable model of inquiry-based science instruction that fits well with the current realities facing teachers and students in the classroom.

8. CONCLUSION

According to Harlen and Jelly (1997), "decisions about teaching start from a view of learning, that is, the understanding of what it is to learn and how learning is brought about" (p. 67). If a teacher views science as a multitude of facts and abstract laws, then teaching would likely be reduced to the transmission of a body of knowledge. Consequently, students take away an image of science as absolute, fixed, or 'proven to be true' and deep conceptual understanding on the part of students would not be certain. As discussed in section 3, this view of science is incongruent with a modern view of science as ideas that are open to challenge in the light of new evidence. In addition, science education must prepare our young for effective functioning in this age of information and technology (Dewey, 1910; Schwab, 1962; Young, 1996; Harlen & Jelly, 1997). I personally view that education is not only how much a person learns, but also about *how* learning takes place -- the process. Having the view of science as current understandings that are open to change would translate to a goal for students to understand how scientific knowledge is created, that is, the process of science. Inquiry-based science instruction is essential to realising this goal.

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Annex

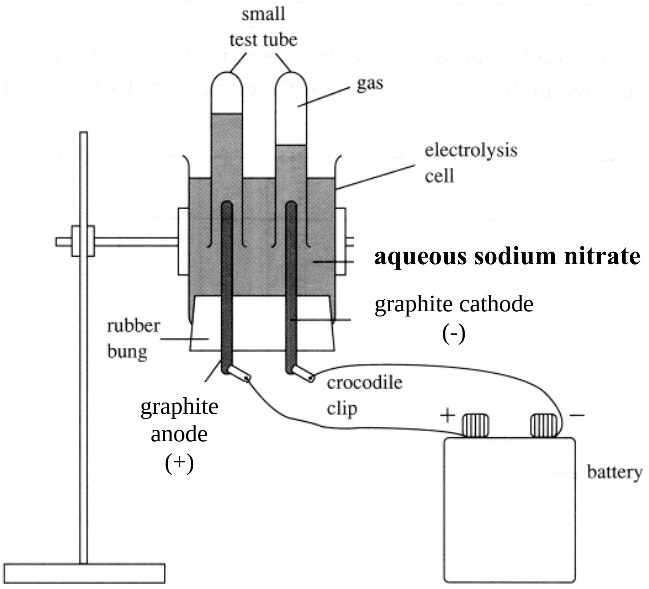
Raffles Institution
Raffles Programme - Year Four Chemistry

Name: ___________________________ (   ) Class: ______ Date: ________

Learning Stations: Electrolysis of aqueous solutions

Aim: To determine the order of ease of discharge via electrolysis for the following ions
~ cations copper(II) ions, Cu^{2+}; hydrogen ions, H^+; and sodium ions, Na^+
~ anions hydroxide ions, OH^-; nitrate ions, NO_3^-; and sulfate ions, SO_4^{2-}

Station A: Electrolysis of aqueous sodium nitrate ($NaNO_3$)



State the ions present in the following:

sodium nitrate : Na^+, NO_3^-

water : H^+, OH^-

Set up the apparatus shown in the diagram on the left to electrolyse **aqueous sodium nitrate**.

Complete the blanks below.

Anode (+)

a) State the ions which would migrate here: **NO_3^- and OH^- ions**

b) Make observations to deduce the product formed at the **anode** due to electrolysis.

Observations:
Colourless and odourless gas evolved, relights a glowing splint.

The product was **oxygen.**

c) Conclusion: Ease of discharge of **anions**

OH^-	ions were more readily discharged (oxidised) relative to	NO_3^-

d) What evidence supports your conclusion in **c)**?
Oxygen was produced due to the discharge or oxidation of OH^- ions.

Cathode (-)

a) State the ions which would migrate here: **Na^+ and H^+ ions**

b) Make observations to deduce the product formed at the **cathode** due to electrolysis.

Observations:
Colourless and odourless gas evolved extinguished a lighted splint with a 'pop' sound.

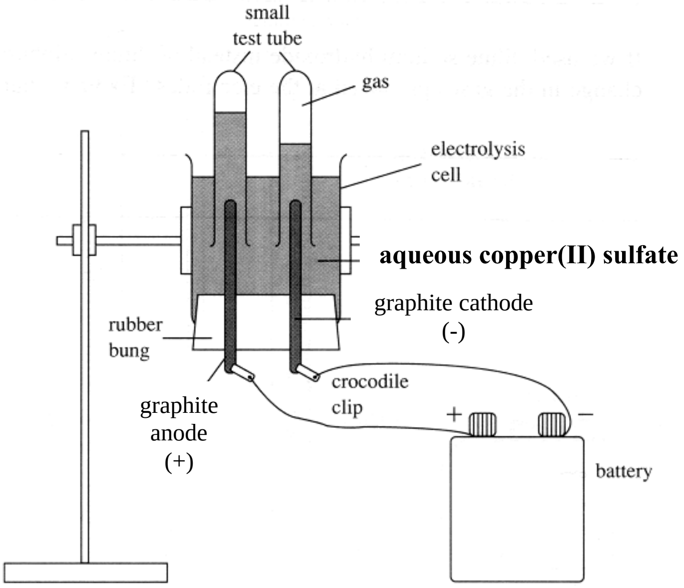
The product was **hydrogen.**

c) Conclusion: Ease of discharge of **cations**

H^+	ions were more readily discharged (reduced) relative to	Na^+

d) What evidence supports your conclusion in **c)**?
Hydrogen was produced due to the discharge or reduction of H^+ ions.

Station B: Electrolysis of aqueous copper(II) sulfate ($CuSO_4$)



State the ions present in the following:

copper(II) sulfate : **Cu^{2+}, SO_4^{2-}**

water : **H^+, OH^-**

Set up the apparatus shown in the diagram on the left to electrolyse **aqueous copper(II) sulfate**.

Complete the blanks below.

Anode (+)	**Cathode (-)**
a) State the ions which would migrate here: **SO_4^{2-} and OH^- ions**	**a)** State the ions which would migrate here: **Cu^{2+} and H^+ ions**
b) Make observations to deduce the product formed at the **anode** due to electrolysis. Observations: **Colourless and odourless gas evolved, relights a glowing splint.** The product was **oxygen.**	**b)** Make observations to deduce the product formed at the **cathode** due to electrolysis. Observations: **A reddish brown/pink solid was deposited at the cathode.** The product was **copper.**
c) Conclusion: Ease of discharge of **anions** **OH^-** ions were more readily discharged (oxidised) relative to **SO_4^{2-}**	**c)** Conclusion: Ease of discharge of **cations** **Cu^{2+}** ions were more readily discharged (reduced) relative to **H^+**
d) What evidence supports your conclusion in **c)**? **Oxygen was produced due to the discharge or oxidation of OH^- ions.**	**d)** What evidence supports your conclusion in **c)**? **Metallic copper was produced due to the discharge or reduction of Cu^{2+} ions.**

Conclusions

Based on your results from stations A and B, deduce the order of ease of discharge for the

~ anions OH^- ; NO_3^- ; and SO_4^{2-}

Order	
NO_3^-, SO_4^{2-}	least readily discharged
OH^-	most readily discharged

~ cations: Cu^{2+} ; H^+ ; and Na^+

Order	
Na^+	least readily discharged
H^+	
Cu^{2+}	most readily discharged

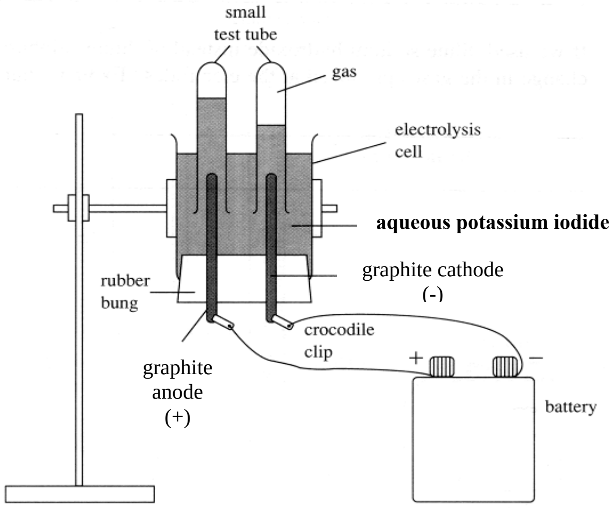
Teacher may wish to highlight that based on stations 1 and 2, the relative ease of oxidation between NO_3^- and SO_4^{2-} ions cannot be inferred.

Background: Chemists have performed numerous experiments to gather data on the ease of discharge of ions during the electrolysis of electrolytes. The trend for some common cations and anions is shown below.

Cations		Anions	
K^+	least readily discharged		
Ca^{2+}		F^-	least readily discharged
Na^+		SO_4^{2-}	
Mg^{2+}		NO_3^-	
Al^{3+}		Cl^-	
Zn^{2+}		Br^-	
Fe^{2+}		I^-	
Pb^{2+}		OH^-	most readily discharged
H^+			
Cu^{2+}			
Ag^+	most readily discharged		

Next, conduct the following two further experiments at stations **C** and **D**.

Station C: Electrolysis of aqueous potassium iod



State the ions present in the following:

potassium iodide : **K^+, I^-**

water : **H^+, OH^-**

Set up the apparatus shown in the diagram to electrolyse **aqueous potassium iodide**.

First, complete **a)** and **b)**, then carry out the electrolysis. Finally, complete **c)** and **d)**.

Anode (+)

a) State the ions which would migrate here: **I^-, OH^-**

b) Based on the above concept of order of ease of discharge, predict

- the ion which would be discharged: **OH^-**
- and hence, the product that would form at the **anode** : **oxygen**

c)Observations:
Solution around anode turns from colourless to brown. Starch indicator solution turned blue-black when added.

The product was **iodine.**

d) Based on **c)**, state which ion was preferentially discharged: **I^-**

Cathode (-)

a) State the ions which would migrate here: **H^+, K^+**

b) Based on the above concept of order of ease of discharge, predict

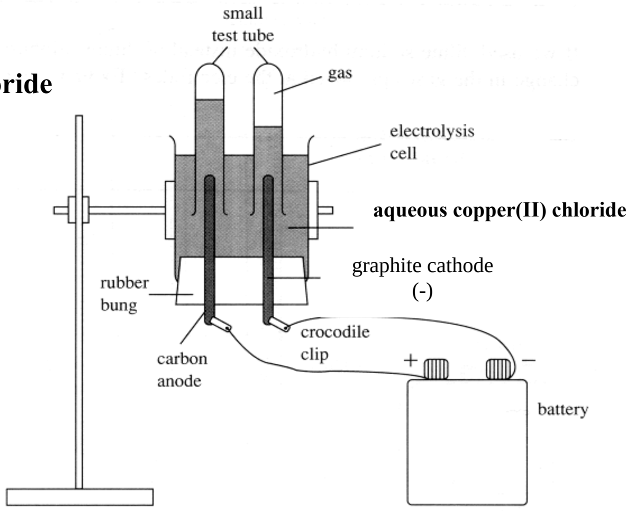
- the ion which would be discharged: **H^+**
- and hence, the product that would form at the **cathode** : **hydrogen**

c) Observations:
Colourless and odourless gas evolved extinguished a lighted splint with a 'pop' sound.

The product was **hydrogen**

d) Based on **c)**, state which ion was preferentially discharged **H^+**

Station D: Electrolysis of aqueous copper(II) chloride



State the ions present in the following:

copper(II) chloride : **Cu^{2+}, Cl^-**

water : **H^+, OH^-**

Set up the apparatus shown in the diagram to electrolyse **aqueous copper(II) chloride**.

First, complete **a)** and **b)**, then carry out the electrolysis. Finally, complete **c)** and **d)**.

Anode (+)

a) State the ions which would migrate here: **Cl^-, OH^-**

b) Based on the above concept of order of ease of discharge, predict

- the ion which would be discharged: **OH^-**
- and hence, the product that would form at the **anode** : **oxygen**

c) Observations:
A pungent gas was produced that bleaches litmus (turns litmus white).

The product was **chlorine.**

d) Based on **c)**, deduce the ion that was preferentially discharged : **Cl^-**

Cathode (-)

a) State the ions which would migrate here: **Cu^{2+}, H^+**

b) Based on the above concept of order of ease of discharge, predict

- the ion which would be discharged: **Cu^{2+}**
- and hence, the product that would form at the **cathode :** **copper**

c) Observations
A reddish brown/pink solid was deposited.

The product was **copper.**

d) Based on **c)**, deduce the ion that was preferentially discharged : **Cu^{2+}**

Conclusions - With reference to what was predicted part **b)** of stations 3 and 4, comment on the respective observations and deductions made in **c)** and **d)**.
Iodine was produced, meaning iodide ions were oxidised, despite hydroxide ions being more readily oxidised than iodide ions. Similarly, chlorine was produced, meaning chloride ions were oxidised, instead of hydroxide ions.

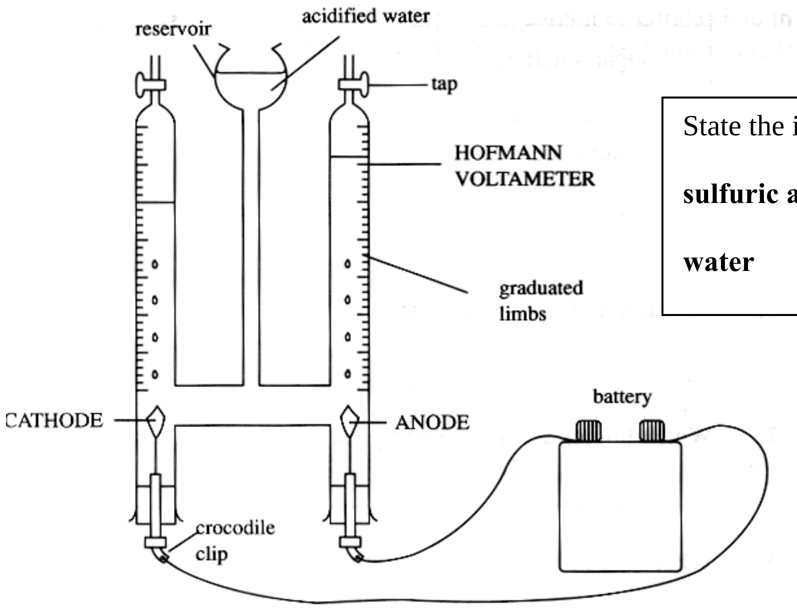
Copper was produced, meaning copper(II) ions were reduced as expected. Similarly, relative to potassium ions, hydrogen ions were more readily reduced to form hydrogen.

Explain the observations gathered for stations 3 and 4. (Hint: Only one in every 10 million water molecules dissociates into ions.)
In the respective aqueous electrolytes, the concentrations of Cu^{2+} and Cl^-, and the concentrations of K^+ and I^-, were very much higher than the concentrations of H^+ and OH^-.

The effect of concentration was predominant for Cl^- due to the close positions of Cl^- and OH^- in the order of ease of discharge. Hence, chloride ions were discharged.

This was not the case for K^+ with the greater difference in ease of discharge between the K^+ and H^+. Hence, H^+ ions (and not K^+ ions) were discharged, despite the higher concentration of K^+.

Station E: Demonstration on electrolysis of acidified water (dilute sulfuric acid)



State the ions present in the following:

sulfuric acid : H^+, SO_4^{2-}

water : H^+, OH^-

Anode (+)	**Cathode (-)**
a) State the ions which would migrate here: SO_4^{2-}, OH^-	**a)** State the ions which would migrate here: H^+
b) Make observations to deduce the product formed at the **anode** due to electrolysis. Observations: Colourless and odourless gas evolved, relights a glowing splint. The product was oxygen.	**b)** Make observations to deduce the product formed at the **cathode** due to electrolysis. Observations: Colourless and odourless gas evolved extinguished a lighted splint with a 'pop' sound. The product was hydrogen.
c) Equation for the reaction at the anode: $4OH^- \rightarrow 2H_2O + O_2 + 4e^-$	**c)** Equation for the reaction at the cathode: $2H^+ + 2e^- \rightarrow H_2$
d) Complete the statement: OH^- ions are **selectively discharged** because OH^- loses electrons or undergoes oxidation more readily than SO_4^{2-}.	**d)** Complete the statement: H^+ ions are **selectively discharged** because there are no other ions to compete for reduction.

In view of the ions that are discharged, complete the statement below.

As the electrolysis proceeds, the aqueous electrolyte becomes more concentrated in sulfuric acid.

Post-laboratory Questions

Consider the following electrolyses and answer the questions.

1. Electrolysis of aqueous sodium chloride

(a) The electrolysis of aqueous sodium chloride tends to produce chlorine gas at the anode. Under what circumstance may oxygen gas be produced?

Oxygen may be produced when the concentration of sodium chloride is sufficiently low (i.e. when the concentration effect is no longer predominant). Then, hydroxide ions would be oxidised relative to chloride ions, resulting in the production of oxygen,

2. Electrolysis of aqueous potassium iodide

A few drops of phenolphthalein was added to a sample of aqueous potassium iodide and the mixture was then electrolysed.

(a) What would be observed at the cathode?

The phenolphthalein will turn pink.

(b) Explain your observation in (a) above.

The hydrogen ions discharged at the cathode leave behind excess hydroxide ions which gives alkalinity. Thus, the indicator turns pink.

3. Electrolysis of acidified water

(a) Why was it necessary to acidify the water before electrolysis?

Pure water comprises almost entirely of water molecules and is a poor conductor of electricity. Adding an acid would increase the free ions for electrolysis to take place.

(b) Explain whether or not an a.c. (alternating current) supply can be used instead of a d.c. (direct current) to effect electrolysis?

An alternating current cannot be used for electrolysis.

The continual changing of polarity or charge on the electrode (i.e. the switching of anode and cathode) will prevent the discharge of ions.

(c) In practice, the volume of oxygen gas collected is less than half of the hydrogen gas collected. Why is this so?

Oxygen is more soluble than hydrogen in water. Some of the oxygen formed can dissolve in the electrolyte, leaving less than expected gaseous oxygen collected.

(d) State the particles that carry the electric current through the

i. wire of the external circuit : **electrons**

ii. electrolyte of acidified water : **freely moving H^+ and OH^- ions**