# USING THE AVOW DIAGRAM ANALOGY FOR TEACHING DC CIRCUITS FROM A CONCEPTUAL CHANGE PERSPECTIVE

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# Using the AVOW Diagram Analogy for Teaching DC Circuits from a Conceptual Change Perspective

by

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# ABSTRACT

When teaching students about DC circuits, overcoming prior conceptions about electricity can be very challenging. In this study, a class of grade 12 students was taught a unit on DC circuits using AVOW diagrams. AVOW diagrams are an analogy that maps the current, resistance, voltage, and power onto a rectangular shape in such a way that the dimensions of the shape are related in the same way as the circuit parameters.

Classroom observation of the students and teacher were made when AVOW diagrams were integrated with the regular teaching sequence of the unit. At the end of the unit, a diagnostic test of student conceptions of DC circuits was administered and a sample of students were interviewed about how they used AVOW diagrams to learn and reason about DC circuits. This study concludes by evaluating how effective and appropriate the AVOW diagrams were in the teaching of this unit.

## ACKNOWLEDGEMENTS

For my wife Jenny, my daughter Iris, and my son Isaac. Our family would never have existed but for the start of this thesis and if it were not for my family, this thesis would have never ended.

I can't even begin to apologize to my thesis advisor, Dr. Karen Goodenough for what I have put her through but I can offer my sincere and unending thanks.

As for Mike, thanks for everything and good luck with the new newby.

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# Chapter 1: Introduction

Teaching electricity to high school physics students can be a challenging experience. Students do not easily let go of their previously generated conceptions about electricity (Dilber & Duzgun, 2008; McDermott & Shaffer, 1992) and when they do adopt scientific conceptions of electricity, they often revert back to their earlier conceptions (Licht, 1991). To add to this difficulty, students will also incorrectly recall phenomenon that they have observed in order to support their incorrect ideas (Duit & Rhoneck, 1998).

Student conceptions of electricity are well documented in research literature. Student conceptions progress from very naïve conceptions to very sophisticated and scientific ones as students age and develop (Osborne, 1983; Shipstone, 1984). Each additional stage of development is marked by a new awareness of some aspect of electricity; an effort to rationalize this newly observed aspect of electricity, and an attempt to integrate this new awareness with the student's prevailing conception of electricity. For example, the simplest conception of electricity is the unipolar model where electricity flows through one wire from a source such as a battery to a device such as a light bulb. This model is sufficient until it is noticed that there must be two wires for electricity to flow. The clashing currents model accounts for the need for two wires by supposing that there are two types of current that flow from the source and when they meet at the device, they release energy. Upon learning that there is only one type of current and that it flows in only one direction, an attenuation model is adopted to explain why batteries run out of energy. Each device in the circuit consumes electricity leaving less electricity for the next device and the battery loses electricity until it is dead. Finally, when it is learned that current is not consumed, the scientific conception of circuits can be developed.

While not all students will develop what is considered to be scientific conceptions of electricity, high school physics students are expected to have sophisticated conceptions of electricity and they are challenged to use their conceptions to predict and explain aspects of electrical phenomenon that non-physics students may never encounter. As a high school physics teacher, one challenge that I have faced is helping my students develop more sophisticated conceptions of electricity. This research study describes my investigation of a tool intended to help physics students develop the conceptions that they need to hold in order to be successful in their studies.

Electricity is commonly explained through the use of analogs. For example, the presence of equal numbers of opposite charges resulting in neutrality is compared to the behaviour of integers. Atoms contain equal numbers of positive protons as negative electrons and for electrically charged objects such as ions or a balloon that has been rubbed with a bit of fur, the total charge is equal to the sum of the number of electrons and the number of protons. The attraction of opposite charges is compared to opposite magnetic poles where a positive electric charge attracts a negative one and repels another positive one in the same way that a north magnetic pole will attract a south magnetic pole and repel another north pole. The flow of electric current is compared to the flow of water where the water molecules are like the electrons, the amount of water flowing is like the current and the pressure of the flow is like the voltage or potential difference of the electricity. There are, however, difficulties with the analogies that are usually evoked in the study of electricity. Different analogies elicit different predictions about what will happen in a circuit and it is necessary to switch between analogies to predict and explain various electrical phenomena. This can lead to confusion and frustration for students as they work to develop the sophistication required to move from one analogy to another. This research study investigates AVOW diagrams, an analogy that encapsulates all of the behavior of DC circuits in a logically consistent and easy to understand way.

AVOW diagrams were developed by Cheng and Shipstone (2003a). Rather than representing electricity as flowing water or crowds moving through corridors, diagrams that portray the basic elements of a circuit: current (amperes), voltage (volts), resistance (ohms), and power (watts) are used to promote conceptual change in high school physics students. Current is the flow of electrons through the circuit and is conserved throughout the circuit. That is, the same number of electrons that enter any part of the circuit is equal to the number of electrons that leave that part of the circuit. It is the electrons that carry the energy used by the circuit elements. The amount of energy that each electron carries is described by the terms voltage or potential difference. These terms are used interchangeably and they are measured by comparing the difference in energy that an electron has before entering and after leaving any section of a circuit. An electron's energy will decrease very little when it travels through a section of wire and it will decrease much more when travelling through a device such a light bulb or a resistor. The sum of all of these voltage drops or potential differences is exactly equal to the voltage supplied by the battery. Each voltage drop occurs because each part of the circuit resists the flow of electricity and this resistance converts the energy carried by the electron into a useful form such as light from a light bulb or motion from an electric motor. Finally, power measures the rate at which the energy is used.

AVOW diagrams are meant to both completely represent the fundamental dimensions of an electrical circuit as well as the relationships among them. Additionally, the diagrams are intended to uncover student misconceptions about electricity and suggest ways to correct these misconceptions.

While Cheng and Shipstone (2003b) provide preliminary evidence to suggest that this is a viable and promising approach to teaching electricity in the context of A-Level students (students who are following the Advanced Level General Certificate of Education as preparation for entrance to university) in the United Kingdom, it remains to be seen if their approach can be generalized to other classroom situations. The purpose of this study is to investigate the possibility and utility of their approach in a similar classroom.

**1.1 Context**

At the time this research project took place, I was teaching physics and other science courses in a high school in central Alberta, Canada. There was another physics teacher in the school who had acted as my mentor when I began my teaching career and together we were responsible for teaching all of the physics students. Our students had always seemed to be successful in the unit on DC circuits, but my investigation into teaching analogies suggested that while physics students generally could successfully apply formulas and calculations to circuits, they did not have a good qualitative understanding of the behavior of DC circuits (Cohen, Eylon, & Ganiel, 1983).

When I read Cheng and Shipstone's (2003a) paper on AVOW diagrams, I decided that I would like to introduce these diagrams to a class and investigate how they were perceived and adopted by the students and the teacher. In order to make this research meaningful, it was necessary to evaluate the efficacy of the approach, identify its strengths and weaknesses, and then decide if it could and should be used again.

In order to be able to make an informed decision about AVOW diagrams, I needed to determine:

- How can the AVOW diagram approach be used to teach about DC circuits in the context of a typical classroom?
- How do students use AVOW diagrams to reason about DC circuits?
- How do AVOW diagrams facilitate progression from simple to scientific conceptions of electricity?

### 1.2 Methodology

I decided to use case study as my research methodology for this research study. Yin (2009) describes questions that ask "how" and "why" as ones that lead to experiments, histories, and case studies. Since I did not want to disrupt the regular classroom environment of the students involved in the study, a case study involving direct observation seemed to be, at the same time, the least intrusive and the most informative approach. For this study I recruited the other physics teacher, Mr. Burns (all names reported in this study are pseudonyms), to use AVOW diagrams with one of his classes and to allow me to observe and interview his students.

Stake (2005) categorizes case studies as intrinsic, instrumental, or collective. Instrumental case studies attempt to generalize from one particular case and collective case studies try to generalize from a number of cases. Intrinsic case studies, however, focus on simply understanding a particular case that is of interest to the researcher.

The decision to study Mr. Burns and his class instead of one of my own classes was informed by a number of factors. Primarily, I felt that by observing my own students, I would not be able to view the use of AVOW diagrams as objectively as I would like. The second reason was that by collaborating with Mr. Burns, I would be able to take advantage of his many years of successful teaching to identify potential problems posed by the use of the diagrams. I would also have a colleague with whom I could discuss my observations and my interpretations of the observations and other data collected. My final reason for using Mr. Burns' class was that I was not scheduled to teach another unit of electricity for another year after my preliminary research had been completed.

The data sets used in this study were summaries of Mr. Burns' and my meetings where we studied AVOW diagrams and planned how they would be incorporated into his unit on circuits, observations of the classroom sessions where Mr. Burns used the AVOW diagrams and a diagnostic test was administered at the end of the unit to determine which conceptions the students used to reason about circuits, and finally, students were interviewed about some of the questions on the test. In the interview, the students were prompted to use AVOW diagrams and their use of the diagrams was discussed with the students in the interview.

### 1.3 Structure of the Thesis

Chapter 2 summarizes literature that deals with misconceptions, conceptual models of electricity, student difficulties with electricity, and research on conceptual change. The use of analogies in fostering conceptual change is described and then the AVOW diagram analogy for teaching DC circuits is presented.

Chapter 3 describes the methodology of this research study. It begins with a description of case study research and then gives a description of the context of the research study including a description of the school and sample class. I then describe the way that the AVOW diagrams were incorporated into the unit. A diagnostic test of student conceptions of electricity is used to uncover student understanding, and this test, DIRECT 1.0, is detailed in this chapter. The chapter ends with a description of the interview process used in this research project.

Chapter 4 provides the data used to answer the research questions. It begins with observations about the planning and presentation of this unit. These observations are followed by an analysis of the results of the DIRECT 1.0 test. Results from interviews with students about their answers to the questions on this test are then presented. Finally, there is a discussion of the overall conclusions about the use of AVOW diagrams in teaching DC circuits.

Chapter 5 summarizes the research and answers the research questions. In this chapter I discuss notable strengths and limitations of this approach and provides suggestions for future research.

# Chapter 2: Literature Review

It has been observed that students do not often hold expert conceptions of DC circuits (Taber, de Trafford, & Quail, 2006; Tsai, 2003) and students' conceptions about electricity do not easily change with instruction (McDermott & Shaffer, 1992). It has also been observed that as quickly as three to five months after seeming to develop accurate conceptions, students can revert to earlier conceptions (Licht, 1991), and even incorrectly recall previous observations in order to support their older conceptions (Duit & Rhoneck 1998). In their investigation of students in an electrical engineering technology program, Métioui, Brassard, Levasseur, and Lavoie (1996) reported that after five semesters of formal instruction, students still retained inadequate conceptions of current and voltage. Electricity is seen as a fundamental topic in most levels of science instruction and yet many of the fundamental concepts are poorly or incorrectly understood and used by both students and teachers (Pardhan & Bano, 2001; Stocklmayer & Treagust, 1996). Despite over twenty years of research, education about electricity remains very problematic (Mulhall, McKittrick & Gunstone, 2001). Applying the principles of conceptual change theory to the teaching and learning of electricity may help to ameliorate these difficulties.

Conceptual change is a popular area of research and several approaches to encouraging conceptual change have been developed, tested, and modified. Research in this area is grounded in a constructivist perspective. A constructivist approach assumes that learners use knowledge that they already have to construct new knowledge. Learners construct knowledge based on what they have been exposed to so that they can make sense of their experiences (Tobin, 1990). "When teaching concepts, as a form of communication, the teacher must form an adequate model of the student's way of viewing an idea and s/he then must assist the student in restructuring those views to be more adequate from the student's and from the teacher's perspective" (Confrey, 1990, p. 109). Knowledge is actively constructed by the learner rather than being passively received by the learner (von Glasersfeld, 1990).

The subject of conceptual change research spans all ages of students from young elementary students to university students and is largely based on a conceptual change model developed by Posner, Strike, Hewson, and Gertzog (1982). According to this conceptual change model, it is expected that students are not blank slates but rather that they have prior ideas about phenomena. If their understanding is at odds with the accepted scientific understanding, their conception may be changed in the following manner. Students are presented with a phenomenon that cannot be explained by their current conceptions and that is in conflict with what their conceptions would lead them to believe. This cognitive conflict is then resolved by presenting a conception that is superior to the students' current conceptions. For example, students, who believe the unipolar model of electricity, do not see the need for two wires to connect a bulb to a battery. Challenging students to light a bulb by making just one connection with a single wire can generate cognitive conflict. While it is possible to light a bulb with just one wire, the bulb itself must also be in contact with the battery to complete the circuit. This can bring about conceptual change because the students must recognize that their conception does not account for their inability to light the bulb. The new conception, where each element of a circuit must be connected at two points is more useful than their old conception in that it explains why the bulb can not be lit with just one connection. As long as the new conception is also intelligible and plausible, the new conception could replace the prior one.

Analogies can be used to present new conceptions in a manner that makes the new conceptions understandable, believable, and demonstrates their utility. An analogy compares two different ideas by identifying attributes that they have in common. The following simple analogy describes the process of teaching a mathematics lesson. Teaching a lesson in mathematics is like painting a fence. The surface of the fence needs to be prepared in the same way in that students need to be informed about what they will learn and why they might need to learn it. The paint on a fence needs to be applied in an even manner without missing any spots in the same way that math facts need to be presented in a logical order, without omitting any important ideas. The paint must not be applied too thickly or it will not adhere. A math lesson should also proceed at a pace that is not too ambitious. Paint on a fence needs time to cure just as students need time to process new information. Finally, the finished coat of paint needs to be inspected and any flaws corrected in the same way that students need to have their knowledge tested and corrected as required.

Duit, Roth, Komorek, and Wilbers (2001) outlined the role that analogies can play in the process of conceptual change. Students develop conceptual frameworks as they incorporate new knowledge into their existing knowledge. Knowledge structures from previously understood domains can be transferred to new domains by mapping attributes from the familiar domain to the novel one. For example, students who are familiar with the way that planets orbit the sun can adopt and adapt that conception to understand and explain the way electrons move around the nucleus in Rutherford's model of the atom.

Since the flow of electricity through a circuit cannot be directly observed, teachers often use analogies when they instruct their students. Such analogies commonly compare electricity to flowing water or crowds of people (Gentner & Gentner, 1983). Osborne (1983) described an analogy that compared electric current to the flow of blood carrying heat to a body's extremities. The generation and use of analogies to relate unfamiliar concepts to familiar ones is common to many learning situations, particularly in the area of learning science (Duit, Roth, Kormorek, & Wilbers, 2001). However, teaching with analogies can cause difficulties in cases where the analogy breaks down and the base domain no longer maps onto the target domain or in situations where students are not sufficiently familiar with the base domain (Glynn, 2007). Gentner and Gentner (1983) described and provided a study where students are encouraged to use a model of flowing water and water reservoirs to explain current and batteries. At the end of the study, the authors found that students came to incorrect conclusions about electricity because they were not familiar with the way that water and water reservoirs arranged in parallel or series affect water pressure and flow.

This research study examined the use an analogy to encourage students to change their conceptions about electricity to scientifically accepted conceptions of electricity. A summary of research that informed this study can be broken down into seven broad categories. It is important to clarify how the terms conception, misconception and alternate conception are used and understood in research literature. Section 2.1 discusses the definitions and uses of the terms misconception and alternative conception. Students use a variety of conceptions in many areas of science but the area of interest in this project was specifically how students conceive of electricity. Section 2.2 will deal with students' conceptions, misconceptions, and alternate conceptions of electricity. Learning about electricity can be problematic and the challenges faced by students when learning about circuits will be described in section 2.3. This research study attempted to use a conceptual change approach to teach students about electricity. Section 2.4 outlines work on conceptual change theory. One way to attempt to encourage conceptual change is through the use of analogies. Section 2.5 will describe how analogies can be used to foster conceptual change. The specific analogy used in this research project is called an AVOW diagram (Cheng & Shipstone, 2003a). These diagrams and their use as an analog for DC circuits comprises section 2.6. A summary of the research on the use of AVOW diagrams is presented in section 2.7.

## 2.1 Definition of Misconception

There are a number of terms used in research literature to describe the ideas and conceptions that students have that are not the same as accepted scientific conceptions. Wandersee, Mintzes, and Novak (1994) listed naïve beliefs, erroneous ideas, preconceptions, spontaneous reasoning, and personal models of reality as examples of some of these terms. In a discussion about the best term for this idea, Wandersee, Mintzes, and Novak (1994) favoured the use of *alternative conception* to the more popular term *misconception*. Alternative conception is preferred because it recognizes the work that the learner has already done to generate a particular conception. The term conveys the idea that the conception is rational and contextually valid. It also implies that the alternative conception can be built upon to generate a scientifically accepted conception. An example of this sort of conception could be that all objects in motion will eventually stop. This is at odds with the scientific conception that objects in motion will remain in motion unless acted upon by an outside force. The alternative conception is rational and contextually valid because all everyday objects that are in motion will eventually be observed to stop. This is because friction is always present as an outside force that acts to stop the motion.

Misconception, on the other hand, implies that there are errors in the conception and that the errors need to be corrected or that the conception must be discarded before a scientifically accepted conception can be developed. Wandersee, Mintzes, and Novak (1994) suggested that the use of the term misconception might be at odds with constructivist views of knowledge. These authors make a further distinction between the terms *misconception* and *alternative conception*. Student knowledge can be termed a misconception, (or naïve conception, erroneous ideas, preconceptions, limited or inappropriate propositional hierarchy, and differential uptake of science) if and only if the knowledge is being compared to a standard knowledge base. When students' understandings do not match the accepted scientific understanding, the student is considered to be in error and thus his/her conception is a *misconception*. In other words, conceptions are misconceptions only when students' responses do not align with what is considered to be scientifically acceptable.

Students are exposed to the world both inside and outside of the classroom and much of the way that they make sense of the world is not tested in school. Students may never be asked about how they think of how a rainbow is formed but they likely have some sort of idea. When this sort of student knowledge is studied on its own terms, it should be called alternative conceptions, or alternative frameworks, children's science, commonsense theories, personal constructs, and multiple private versions of science. When examining how students understand and explain their experiences without comparison to accepted scientific understanding, *alternative conception* is a more appropriate term than *misconception*. Students have *misconceptions* when their conceptions do not match the conceptions that their teachers would prefer that they have. Since the goal of this teaching unit is to have the students achieve the conception of electricity defined by the curriculum, the term *misconception* will be used. However, since an alternative conception only becomes a misconception when compared to an accepted and desired conception, it is important to understand students' alternative conceptions.

Wandersee et al. (1994) summarized key aspects of alternative conception research by presenting eight knowledge claims that can be gleaned from alternative conception literature:

> (1) Learners come to formal science instruction with a diverse set of alternative conceptions concerning natural objects and events.
> (2) The alternative conceptions that learners bring to formal science instruction cut across age, ability, gender, and cultural boundaries.
> (3) Alternative conceptions are tenacious and resistant to extinction by conventional teaching strategies.

> (4) Alternative conceptions often parallel explanations of natural phenomenon offered by previous generations of scientists and philosophers.
> (5) Alternative conceptions have their origins in a diverse set of personal experiences including direct observation and perception, peer culture and language, as well as in teachers' explanations and instructional materials.
> (6) Teachers often subscribe to the same alternative conceptions as their students.
> (7) Learners' prior knowledge interacts with knowledge presented in formal instruction, resulting in a diverse set of unintended learning outcomes.
> (8) Instructional approaches that facilitate conceptual change can be effective classroom tools. (p. 195)

**2.2 Alternative Conceptions of Electricity**

The ways that students conceive of electricity have been thoroughly investigated and well-documented in research literature. Students' conceptions of electricity are based on the way that they model the behaviour of electric current. Common conceptions about the way that current flows through circuits are found across cultures and ages and these conceptions can be grouped into broad categories. Osborne (1983) grouped the conceptual models in the following manner: unipolar, clashing currents, current attenuation or consumption, current sharing, and scientifically accepted. These models will be explained in the following section. As children grow, they are exposed to increasingly sophisticated aspects of electricity. As students, they are taught about electrical phenomena that highlight aspects of electricity that challenge their earlier conceptions.

### 2.2.1 Categories of Conceptions of Electricity

A scientifically accepted conception of electricity can be described by examining the sequential models used by students and identifying the observations and refinements that are made to bring that model closer to the accepted one. The simplest model is a unipolar model. In this model, electricity flows along a wire from a power supply to the device using the electricity. For example, a bulb is connected to a battery as illustrated in figure 2.1. Electricity flows from the battery to the bulb. There is no provision for the flow of electrons from the bulb back to the battery.

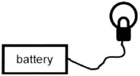



Figure 2.1. Unipolar model. Electricity flows from the battery to the bulb.

Since most lights and lamps that students see are connected to a wall outlet with just one cord, and since the two wires that are inside the cord are rarely shown to students, the unipolar model explains the observations made at this level.

The next model is the clashing currents model. It recognizes that there is a need for two current paths between a power supply and the device using the power. Electricity is thought of as having negative and positive elements that meet at the electrical device and when they meet as shown in figure 2.2, they release energy. This model explains why a light bulb will not light if it is connected to just one end of a battery but must be connected to both ends. It also explains that electrical devices must have two terminals.

There must be a path for the two different currents to follow so that they may meet inside of the electrical device.

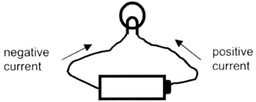



Figure 2.2. Clashing current model. Positive and negative current meets in the bulb and releases energy.

When the idea that there is only one kind of current is presented, students need to change their conception to accommodate this new idea. The third model described by Osborne (1983) is an attenuation model with current flowing in only one direction. The current flows from the battery to the electrical device and back to the battery. But if current returns to the battery, then there is no reason for a battery to become drained. Something must be leaving the battery that is consumed by the bulb. This results in the idea that the electrical device consumes a portion of the current and that the amount of current flowing into a device is not the same as the amount of current that flows out of the device. This model is further characterized by the way that multiple devices in the circuit consume current. Devices such as motors or elements such as resistors that are closer to the source of current will consume more current than devices or elements further from the source as shown in figure 2.3.

One consequence of this presumed attenuation is that this model allows for a way to determine the direction of flow of current. According to this conception, bulbs should

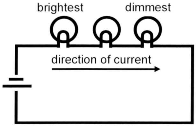



Figure 2.3. Attenuation model. Current is diminished as it passes through each bulb. Less current returns to the battery than leaves.

become progressively dimmer the further along the current path that they are. However, this progressive dimming is never observed. Attempting to reconcile this observation leads to the idea that the elements or devices in a circuit act together to affect the amount of current flowing through the device. This is the current sharing model. This conception can be supported by using a battery to light a number of bulbs connected in series and then reversing the polarity of the battery and observing that the brightness of the bulbs do not change upon this reversal. Current is seen to be equal through each of the elements in the circuit but this model differs from the scientific one in that it is still believed that current is consumed.

Finally, the scientific model includes the idea that current is conserved throughout the circuit. The amount of current that flows through the circuit depends on the power supply and all of the elements and devices in the circuit. This model is shown in figure 2.4.

The models of electricity described above are limited to describing the way that students conceive of current flowing through DC circuits. However, student conceptions of electricity extend beyond the domain of circuits and deal with the ideas of energy, power, voltage, resistance and current and these ideas provide the framework for their models of electricity.

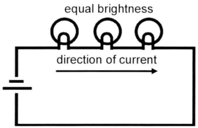



Figure 2.4. Scientific model. Current is conserved as it passes through each bulb and as it passes through the entire circuit.

Borges and Gilbert (1999) suggested that successful models of electricity must address the following:

(1) differentiation of basic terms used to speak about electricity, like current, electricity and energy;

(2) recognition of bipolarity of batteries and other circuit elements;

(3) recognition of the necessity of a closed circuit if a current is to circulate;

(4) issue of the conservation or non-conservation of current;

(5) effects of electrical resistance on current;

(6) models for current circulation;

(7) nature of electric current. (p. 100)

Other than the scientifically accepted model of current flow, none of the various models described in this section address these issues completely and correctly. For example, the unipolar model does not recognize the bipolarity of circuit elements and the attenuation and sharing models do not require that current be conserved.

Furthermore, these non-scientific models do not clearly and correctly define current, voltage, electricity, and energy. Gentner and Gentner (1983) reported that in interviews, many people make use of a generalized force-attribute when reasoning about circuits. This attribute is used to represent both current, voltage, and power without discrimination. A key aspect of this attribute is that it decreases as it flows around the circuit. Duit and Rhoneck (1998) noted that in everyday language, the word *current* is often used where the word *energy* would be scientifically more correct. Heller and Finley (1992) interviewed practicing science teachers about electricity and found that they treated current as energy when explaining and predicting the behaviour of circuits. This is in conflict with the scientific understanding where energy is consumed by elements in the circuit but current is not. This lack of clear differentiation appears across the continuum and is not characteristic of any particular model.

One important aspect of the nature of electric current not specifically addressed by these models is the cause-and-effect relationship between voltage and current. It is very common that the battery is seen by students to be a source of constant current. Students believe that a battery will provide the same amount of current to a circuit with one bulb as it would to a circuit with two (Heller & Finley, 1992; Licht, 1991). In reality, the amount of current depends on the voltage of the battery and the resistance of the circuit. Adding a bulb in series will increase the resistance and thus lower the current. Adding a bulb in parallel will decrease the resistance and increase the current. The belief that batteries supply a constant current may be held by students using any of the models of current flow described in the previous section.

Cohen, Eylon, and Ganiel (1983) found that students often use current as the basis for their reasoning about circuits rather than voltage. In a sense, students see voltage as a result of current instead of as the cause of the current. One example of this is when a second bulb is added to a circuit in parallel. Since the battery supplies constant current, the current must be split between each bulb. Therefore, each of the two bulbs receives half of the original current and thus will be dimmer than the bulb in the original circuit. In reality, this does not happen and each bulb in parallel actually displays the same brightness as the original bulb. This conception can be strongly resistant to change. Cohen et al. (1983) discussed a student who says "I know this from experiment that when two bulbs are connected in parallel to a battery, their light is weaker than when only one is connected to the same battery." (p. 409).

In order to understand DC circuits, students must make use of a model that correctly reflects the nature of electricity. As students progress in their education and encounter electricity in progressively more sophisticated settings, their models must change in order to accommodate newly observed phenomena. A primary student sees that a lamp is plugged into a wall outlet with one cord and if the cord is not plugged in, then the lamp will not light. The unipolar model of electricity is sufficient to account for this observation. Later, two wires instead of one cord must be introduced when the elementary student is given a small bulb and a battery and is asked to make the bulb glow. When more bulbs and switches are added to the mix, the student needs to be able to predict and explain how different arrangements bring about different results. Adding voltmeters and ammeters further increases the demands on the student's model of electricity. Unfortunately, there are many obstacles to be overcome in order to achieve a complete and correct scientific conception of electricity.

### 2.3 Challenges in Learning About Electricity

Students face a number of challenges when they learn about electricity. These difficulties can be grouped into themes that will be addressed in the next sections of this chapter. Section 2.3.1 will examine the way that students reason about electricity, while section 2.3.2 will presents the ways that students interpret the information that they are given about electricity. Section 2.3.3 addresses the level of sophistication that students bring to their study of electricity and the final section 2.3.4 examines the ways that teachers conceptualize and teach electricity.

#### 2.3.1 Student Reasoning

When thinking about electric circuits, it is important to use information about the entire circuit in order to successfully reach correct conclusions. Students do not always reason in this holistic manner but instead will often make use of sequential or local reasoning. This means that students will focus on small parts of the circuit and ignore the circuit as a whole. An example of local reasoning is that students will identify that adding a resistor in series before one bulb will decrease the brightness of that one bulb but they will not identify that it will decrease the brightness of any other bulb that is in series as well. Sequential reasoning is demonstrated when a student believes that a resistor placed before a bulb will cause the bulb to dim but that one placed after a bulb will have no effect.

Sequential reasoning is a logical consequence of following the attenuation model. As identified by Shipstone (1984), students believe there are only "downstream" effects. For example, a resistor placed before a bulb in a circuit will cause the bulb to be dimmer than if it had been placed in the circuit after the bulb. Shipstone suggested that this misconception might be mitigated through the use of a teaching analogy. He does not, however, propose an appropriate one.

This way of thinking about circuits is most clearly revealed when students claim that switches must be placed before light bulbs in order to control the bulb. While students quickly overcome that misconception, they have more difficulty with the idea of adding a resistor before or after a light bulb. Sequential reasoning causes students to predict that the brightness of the bulb shown in Figure 2.5 will change if the resistance of resistor 1 is changed but changing resistor 2 will have no effect on the brightness of the bulb. This is because resistor 2 is found further along the current path than the bulb.

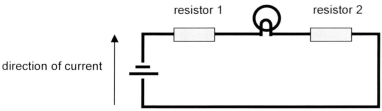



Figure 2.5. Two resistors and a bulb in series.

Shipstone (1988) described this reasoning to be used by 40 percent of students after finishing an advanced course in DC circuits (average age of 15), as well as in a group of prospective physics teachers who had graduated from engineering and physics programs.

Duit and Rhoneck (1998) addressed the issue of local reasoning. When students reason this way, they do not usually consider the circuit as a whole rather, they focus on one circuit element at a time. When a current path splits into two paths, students assume that equal amounts of current travel down each path regardless of the resistance along either path. A student using local reasoning would contend that, for the circuit shown in Figure 2.6, the current in branch 1 would be the same as the current in branch 2 even though the resistances of each branch are not the same.

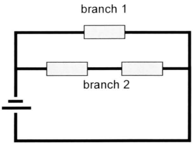



Figure 2.6. A combination circuit.

Students defend this contention by explaining that since electrons at the junction point are unable to know that one of the branches has less resistance than the other branch, then the resistances can not have an effect on the way that the current splits. The scientifically accepted conception, however, reasons in the following manner. The potential differences across branch 1 and branch 2 are the same since any electron that flows through branch 1 must return to the battery having lost the same amount of energy in the circuit that had been added to it by the battery. The same is true of any electron that passes through branch 2. The amount of current that passes through each branch depends only on the resistance of the branch and the potential difference across the branch. If the resistances are the same for each branch, then the current through each branch will be the same. If the resistance of the first branch is half as much as the second branch, then there will be twice as much current in the first branch as in the second. The difference between these two views is that the scientifically accepted conception requires that the entire current path be considered when analyzing a circuit and local reasoning does not.

Sengupta and Wilensky (2009) suggested that novices and experts think about electricity at different levels. For example, novices consider current to be a substance that flows and experts consider current to be the flow of a substance. The difference is that novices think of current as thing and experts think of it as a process. When a novice learns that a resistor reduces current, it is completely sensible to believe that there is less current in the part of a circuit after the resistor than in the part before. To the novice, the current consumption model makes sense. For the expert who sees current as the flow of electrons through the circuit, a resistor reduces the flow of electrons through the entire circuit and there is no attenuation or consumption of current.

**2.3.2 Student Interpretation and Understanding**

Students and experts use analogies to understand electricity. There are many analogies that are useful for understanding electricity and some work better for particular situations than others. The successful use of analogies also depends on a correct understanding of the base concept and the mapping of the base concept to the target one. For example, when discussing the behaviour of the molecules in a gas, a billiard ball (base) can be used as an analogy for the molecule (target). It must be understood that billiard balls do not stick together, they are indivisible, and that they return to their original shape after each collision. In the same way, an ideal gas does not condense or chemically react, it does not decompose into its constituent atoms, and it is not possible to differentiate between molecules that have collided and molecules that have not. They are not deformed in any way.

Osborne (1983) used blood flow as an analog for current in a circuit to explain electricity to an eleven-year-old student. In his analogy, blood (current) carried heat (energy) to a cold finger (glowing bulb) from the heart (battery). Blood must return to the heart and the amount of blood in the body must remain constant. This analogy worked well until the student used the analogy to support his clashing-current model of electricity. In this model, there are two types of current that meet in the bulb and release energy. The student knew of two kinds of blood, of oxygen-rich red blood and oxygen-poor blue blood, and viewed them as two different kinds of current, just like his imagined positive and negative electrical current. This example illustrates how an analogy can be used to support scientifically unacceptable conceptions of electricity if the teacher and student do not share the same understanding of the analogy.

Gentner and Gentner (1983) asked students about various circuit configurations as well as the analogies that they use to think about electric circuits. They focused on two analogies: the flowing water analogy and the analogy where electrons are modeled on crowds of people moving through hallways and doors. They found that different analogies produced different answers about the behaviour of electric circuits. They gave an example of one subject who used the flowing water analogy to infer that the current through two resistors in parallel would be less than the current through just one resistor. He reasoned that since the current flowing through the circuit split, encountered the resistors, and then joined again, as shown in figure 2.7, that the current essentially encounters two resistors. Since the current had to flow through two resistors, the resistance must be greater than the resistance of one resistor and therefore would be less current. The misconception is not uncovered because the model does not prompt the student to think about the current splitting in half with one half of the current encountering one resistor and the other half encountering a different resistor.

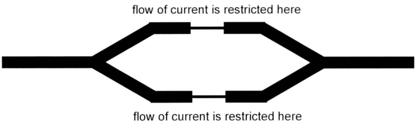



Figure 2.7. A representation of parallel resistors using a flowing water analogy.

The subject was then prompted to think about the problem from a moving crowd perspective. He envisioned the resistors as two independent gates in a corridor that would allow people to pass. He realized that this implied that more people could pass through the two gates than could pass through just one. This is shown in figure 2.8.

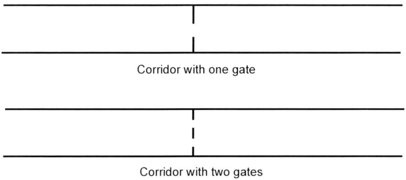



Figure 2.8. Moving crowds representation of resistors in parallel. Since there are two different gates in the second corridor that people can pass through, twice as many people can pass and the current is therefore greater.

This suggests that students are able to use more than analogy to think about circuits and that their choice of which analogy to use affects the accuracy of their reasoning.

Dupin and Joshua (1989) investigated the use of two different analogies in the context of the French education system. In the first analogy, a train moves along a closed track. The train has no engine and the front of the train is linked to the back of the train so that the train is the same length as the track as shown in figure 2.9.

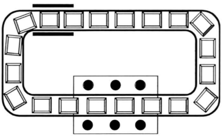



Figure 2.9. Train analogy.

There are workers in a station that push the train with a constant force and there are obstacles along the track that slow the train. In this analogy, the movement of the train cars is the current, the pushing of the men in the station is the battery, and the obstacles represent resistance. This analogy demonstrates that current is conserved and that resistance at any point in the circuit affects the whole circuit. It also demonstrates that more resistors will cause a decrease in the flow of current. This analogy, however, does not illustrate or explain parallel resistors or voltage between different points in the circuit.

To address parallel resistors, Dupin and Joshua (1989) compared electric current to heat flow and a refrigerator to a battery. Essentially, the refrigerator maintains a constant temperature difference between the room and inside of the refrigerator. The temperature difference is analogous to the potential difference maintained by a battery. Resistors are conceptualized as holes in the side of the refrigerator through which heat can flow. Two holes, like two resistors in parallel, allow more heat to flow out of the refrigerator than one hole. According to Dupin and Joshua, the French curriculum requires that the behaviour of both series and parallel resistors be addressed. Neither the train analogy nor the refrigerator analogy deals with both series and parallel resistors. One remedy would be to use both analogies but the authors suspect that using two analogies would be problematic for teachers and students.

The need for two different analogies to explain series and parallel resistors can be awkward for students. Experts are easily able to use a number of ways to look at a particular situation and are able to select and use the best analogy for the situation. Students, on the other hand, are not as adept at shifting between analogies as required by the context (Gentner & Gentner, 1983).

Another way that experts' problem-solving abilities diverge from students' abilities is that experts are able to correctly identify which factors are most relevant to a specific case (Larkin, McDermott, Simon, & Simon, 1980). Gutwill, Frederiksen, and Ranney (1996) conducted a study in which students were explicitly taught to use a variety of perspectives to think about circuits. Students were encouraged to look at the structure of the circuit, the flow of current or energy through the circuit, and the behaviour of the individual electrons in the circuit. They found that students that used a variety of perspectives in a conceptual test on circuits outperformed students who did not shift between perspectives.

Maloney, O'Kuma, Hieggelke, and Van Heuvelen (2001) constructed a survey of students' knowledge of electricity and magnetism. Aimed at university students, the results of this survey are in accordance with previous findings in the area of student conceptions of electricity and magnetism. While this survey does not specifically address electric circuits, the results support other research in this area. Of particular importance is the caution that everyday language and physics language often use very different meanings for the same words and that it is difficult to control how students use these words. Furthermore, different teachers can use slightly different meanings for the same words or different words for the same concept (voltage and potential difference, for example).

Shipstone (1984) gave examples of how language can affect students' ideas about circuits. For example, one student explains that bulbs in series will be equally bright because they equally share the power from the power supply. It is unclear from this statement if the student is reasoning correctly by relating brightness to power, or if the student is confusing power with current and using a model of electricity where all elements of a circuit equally share the current supplied by the battery. Another example shows students referring to voltage as a property that flows in a circuit rather than as a comparison between two parts of a circuit. Gentner and Gentner (1983) referred to a general strength attribute that students often use in place of current, voltage, and energy that seems to combine elements of these concepts. They describe the attribute in the following way:

> People in interviews do appear to have a kind of composite strength attribute that is interchangeably referred to as current, voltage, velocity of the electrons, power, pressure, or force of the electrons. This strength attribute fails to obey steady-state: It decreases as the stuff flows around the circuit, with the sharpest diminution occurring at the resistor. (p. 124)

**2.3.3 Student Expertise**

Some of the difficulties that students have with DC circuits might be attributed to a lack of sophistication and experience with respect to electricity. For example, students have less difficulty reasoning quantitatively and algorithmically about circuits than they do reasoning qualitatively. Students also have barriers when it comes to sorting relevant from irrelevant information. In a classroom setting this means that students might focus on one aspect of a circuit (such as current conservation) when the key to solving the problem might be a different aspect of the circuit (the voltage across parallel branches are equal). In the laboratory, naïve students might fixate on the small variations due to the limitations of the equipment or they can make incorrect observations that support their ideas about the way that circuits behave. Furthermore, it has been shown that misconceptions are remarkably persistent despite extensive instruction (Mulhall, McKittrick & Gunstone, 2001).

Cohen, Eylon, and Ganiel (1983) discussed two aspects of student difficulty with DC circuits. The first is that while (after instruction) students become adept at solving problems relating to current, voltage, and resistance quantitatively in DC circuits using equations, they are often unable to do so qualitatively. Students use complicated and poorly understood algorithms for solving circuits, but do not demonstrate a deep understanding of what is actually going on within the circuit. Furthermore, they show that students primarily reason about circuits from a current rather than potential difference perspective. Cohen, Eylon, and Ganiel, (1983) suggested that students' reliance on a current perspective facilitates many misconceptions and misunderstandings about circuits. To address these difficulties, they suggest that it would be worthwhile to investigate "methods designed to develop the understanding of functional relationships between the variable that characterize electric circuits" (Cohen, Eylon, & Ganiel, 1983, p. 412).

Taber, de Trafford, and Quail (2006) explained several factors that can confound student learning about circuits, some of which have not often been addressed in the literature. For example, teachers and other experts have learned to see physical circuits as schematic diagrams and schematic diagrams as actual circuits. Teachers see that an ammeter and a voltmeter, though they have very similar appearances, perform different functions. Teachers know that the colour of a wire has little bearing on its function in a circuit but students might not. Finally, teachers might say that current readings of 1.9 A and 2.0 A are the same even though they are clearly different to a student.

While students do not always abstract information the same way that teachers do, they also do not literally and actually *see* things the same way that teachers do. Duit and Rhoneck (1998) provided an example, reported by Schlichting (1991), where a strand of high resistance wire glows when connected to a battery. Students were asked to predict what part of the wire (left, right, middle, or all) would start to glow first. Despite the fact that all parts of the wire began to glow at the same time, students reported observations that matched their predictions. This illustrates the strength of students' prior conceptions and their influence on what they learn about circuits.

Misconceptions persist even after significant instruction. As another example, Dupin and Joshua (1987) surveyed the conceptions of French students and found that 60 percent of fourth year university science students consider batteries to be sources of constant current.

### 2.3.4 Teacher Influences on Student Conceptions of Electricity

It should be self-evident that the way that teachers talk about electricity and the conceptions that teachers hold about electricity will affect their students' conceptions. Shipstone (1984) proposed that teachers might inadvertently reinforce misconceptions by the way that they speak about electricity. For example, a teacher might say "The current flows out of the positive terminal of the battery here, passes through the lamp L1, then splits up at the junction with some going to lamp L2, and the rest to the variable resistor R..." (p. 197) and by not emphasizing that the current is moving through all parts of the circuit at the same time rather than in the step-wise fashion described by the teacher, reinforce a student's sequential reasoning processes.

Gunstone, Mulhall, and McKittrick (2009) interviewed Australian physics teachers and textbook authors. They found that while some of the teachers appreciated the significant difficulties that arise when teaching about electricity, others admitted that while students have difficulty learning the concepts, they are not very difficult to teach. The authors commented "We confess to having considerable difficulty with the notion that teaching can be easy when it is recognized that learning is difficult." (p. 523). Additionally, the interviews showed that several of the teachers' "understandings of voltage and related concepts were clearly inadequate." (Gunstone, et al., 2009, p. 524).

In interviews with middle school science teachers, Pardhan and Bano (2001) discussed series and parallel circuits. Some of the teachers used current consumption models (both attenuation and sharing interpretations) when reasoning about series circuits. When discussing parallel circuits, almost all of the teachers maintained that adding more bulbs in parallel to a circuit would not change the amount of current flowing through the circuit. Webb (1992) conducted a study where pre-service and in-service primary teachers were presented with four basic models of electricity. The models included were unipolar (where current only flows to, but not from, a bulb), clashing current (where there is a positive and a negative current that meet in the bulb), current consumption (where the current leaving the bulb is less than the current entering), and the scientifically accepted current conservation model. The teachers were asked to select which model best represented how they viewed electricity. Less than one third of the teachers selected the scientifically accepted conception of the flow of current through a circuit. However, after experimenting with bulbs, batteries and ammeters and following a teaching sequence described by Cosgrove and Osborne (1985), the percentage of teachers choosing the scientifically accepted conception increased to greater than eighty percent. This suggests that while teachers may not have accepted conceptions of electricity, their conceptions can change. The challenge is to find ways to help foster this conceptual change in students.

**2.4 Research on Conceptual Change**

Educational research regarding conceptual change in the past has largely focused on science concepts and in particular, the domain of physics (Duit, 2006; Grayson, 2004). Research beginning in the 1970s consisted of investigating students' pre-instructional conceptions. This area has been thoroughly studied and research has shifted to looking at the mechanisms of conceptual change, as well as interventions that might encourage conceptual change. This section will review work on conceptual change and the subsequent section will discuss the use of analogies to encourage conceptual change.

**2.4.1 Conceptual Change Framework**

"Accommodation of a scientific conception: Toward a theory of conceptual change" by Posner, Strike, Hewson, and Gertzog (1982) formalized the process of confronting students with data that was at odds with their prior conceptions. It was believed that conceptual change would occur if students experienced dissatisfaction with their current conception and were presented with an alternative conception that was intelligible, plausible, and fruitful. For a new conception to be intelligible, the student must be able to understand the new conception. Plausible conceptions must be believable and the new conceptions must be fruitful if they are to allow students to develop new knowledge above and beyond what they were able to attain with their prior conceptions. It was expected that the intelligibility criterion must be met prior to plausibility and plausibility prior to fruitfulness. Posner, et al. (1982) expected that the old conception and the new conception would not coexist and that the change would be a sharp one. This approach to conceptual change provided the basis for many studies on conceptual change. Researchers expanded on this approach and applied it to many different situations and contexts.

For example, Wandersee, Mintzes, and Novak (1994) analyzed several of these conceptual change studies and suggested that teaching approaches based on conceptual change theory are more efficient than other teaching approaches. Duit and Treagust (2003) echoed this conclusion.

Despite this apparent success, there appear to be limitations on the classical conceptual change approach. Conceptual change approaches have so far been largely restricted to specific areas of science content such as electricity and forces. The areas of investigation are small when compared to possible areas of investigation that might include science-technology-society concerns such as global warming, biodiversity, noise pollution, and radiation risk (Fensham 2001).

**2.4.2 Expanded Views of Conceptual Change**

Even within this narrow context of specific science domains, research perspectives have also expanded with time. Conceptual change was once looked at from just a rational and clinical perspective. From this perspective, factors such as students' learning intentions, motivations, and learning situations were ignored. Later research, however, examined these factors as well. Descriptions of learning environments that promote conceptual change, as well as suggestions and guidelines for designing these environments are becoming more noticeable. An example of this is provided by Vosniadou, Ioannides, Dimitrakopoulous, and Papademetriou (2001) where the authors recommended limiting the breadth of curriculum, considering the order of instruction of particular concepts, considering students' prior knowledge, facilitating metaconceptual awareness, addressing students' prior conceptions, motivating for conceptual change, producing cognitive conflict, and providing models and external representations.

The nature of conceptual change has also been refined. It is no longer suggested that students should discard their old conceptions and it has even been suggested that perhaps they should not discard them (Smith, diSessa, & Roschelle, 1993; Tyson, Venville, Harrison & Treagust, 1997). Tao and Gunstone (1999) showed that students who hold alternative conceptions might change those conceptions when faced with conceptual conflict in one context but that they may revert to their original conception in another context. The conceptual change model recognizes the importance of students' prior conceptions and concedes their possible utility for interpreting the real world. An example of this would be when a physics teacher introduces students to Newton's First Law of Motion. Students usually remain unconvinced that an object in motion will remain in motion if there is no (net) force acting on it. This is because in all of their experience, everything that is in motion eventually comes to a stop. Their conception of motion has much more utility in the real world of bicycles and skateboards than Newton's idealized universe-without-friction where objects keep moving even though there is no force acting on them. Thus, different and even conflicting conceptions can be held at the same time as long as the student is conscious of the context in which they are applicable.

Furthermore, conceptual change is now believed to be a gradual rather than sudden process (Tao & Gunstone, 1999; Vosniadou et al., 2001; Vosniadou, 2003). A new conception gains status as it proves itself again and again to be superior to a prior conception. This idea has important ramifications for the use of conceptual change approaches to teaching. For example, it is not sufficient to show students just once that their conceptions are not adequate, but rather student misconceptions must be challenged again and again and shown to be in error.

Another focus of conceptual change research is the examination of students' meta-conceptual awareness (Qian, 2000; Tyson et al., 1997; Vosniadou et al., 2001). It appears that what students think about knowledge and learning influences the success or failure of different teaching approaches. It is believed that conceptual change is enhanced when students are made consciously aware of the way that they are thinking and reasoning about a concept, why they are thinking and reasoning that way, and what the limitations of their thinking and reasoning might be.

Students' motivations in the classroom also need to be considered in the context of conceptual change (Pintrich, Marx, & Boyle, 1993). For example, whether a student's motivation for learning is intrinsic or extrinsic affects the process of conceptual change by influencing the attention that students give to new information and the metacognitive strategies that they employ to attempt to understand that new information.

### 2.4.3 Conceptual Change Challenges in the Classroom

It has been suggested that anomalous data is not the only strategy that is useful for instigating conceptual change. Conflict between a student's conceptions and scientifically accepted conceptions might be invoked through the use of analogies, metaphors, and discussion (Limon, 2001; Mason, 2001)

Duit and Treagust (2003) identified the incorporation of conceptual change research into teaching practice as an area in need of future work. Conceptual change research from a cognitive psychological perspective, as opposed to a teaching and learning perspective is, by necessity, characterized by experimental controls that are not replicable in the classroom. Fundamentally, conceptual change research should provide an excellent starting point for improving science teaching and learning and it is necessary to present conceptual change theory and strategies in such a way that they can and will be used by teachers in their everyday practice. However, the authors also caution that there is an increasing discrepancy between what researchers consider to be teaching for conceptual change and the teaching practice of many teachers (Duit and Treagust,

Limon (2001) discussed some of the practical difficulties involved with incorporating cognitive conflict strategy into a classroom environment. These include anomalous data being merely assimilated into current conceptions without inducing cognitive change, discrepancy between what teachers and students perceive as being meaningful, students with insufficient prior knowledge, insufficient student reasoning skills, and student beliefs about knowledge and learning that are not conducive to conceptual change. Limon suggests that the cognitive conflict pathway to conceptual change appears better suited to the controlled setting of one interviewer/teacher and a very small number of subjects/students.

Complete replacement of old conceptions with new and correct scientific ones has turned out to be an unrealistic goal of conceptual change research (Cobern, 1994) and this has led to the consensus that old conceptions can be valuable in certain contexts and that students need guidance to build new conceptions for contexts that are not well served by the old conceptions (Smith, diSessa, & Rochelle, 1993). An important role of the teacher from this perspective is helping students decide when to use a particular conception. Wiser and Amin (2001) gave an example where the teacher develops and differentiates the concepts of everyday temperature and scientific temperature, and everyday heat and scientific heat. Student experiences are first understood using the everyday meanings of heat and temperature and their observations are then redefined in the scientific terms. This process validates students' prior knowledge and conceptions, but it also illustrates how they are different from scientific ones. Cognitive conflict is created gently and a clear and reasonable resolution of the conflict is provided for the students by illustrating how the scientific conceptions predict and explain better than the everyday conceptions.

**2.5 Analogies**

Duit, Roth, Komorek, and Wilbers (2001) described the use of analogies in science teaching and the way that the emphasis in research on analogies has changed over time. Focus has shifted from the analysis and characterization of analogies towards their potential for bringing about conceptual change.

There is a wide variation in the literature with respect to the use of the word *analogy*. Duit (1991) differentiated between an analogy and a metaphor by saying that an analogy is explicit in its comparisons and a metaphor is implicit in its comparisons between two domains. Essentially, however, metaphors and analogies both refer to the concept of mapping one domain onto another.

Gentner (1982) defined models used in science as analogies within the context of science and science teaching in the following way:

> The models used in science belong to a large class of analogies that can be characterized as structure-mappings between complex systems. Typically,

> the target system to be understood is new or abstract, and the base system in terms of which the target system is described is familiar and perhaps visualisable. In these analogies, the objects of the known domain are mapped onto the objects of the domain of inquiry, allowing the predicates of the first domain to be applied in the other domain. Further, among the base predicates, it is primarily the relations among the nodes of the base domain that are applied to the target domain. Thus, a structure-mapping analogy asserts that identical operations and relationships hold among non-identical objects. (p. 108)

Duit (1991) pointed out that the word *analogy* is often used to refer to the base domain as well as the comparison between the base and target domain and thus, the words *analogy* and *model* are often used interchangeably.

### 2.5.1 Characteristics of Analogies

Teachers often attempt to explain new concepts to students by relating a familiar context to a new and unfamiliar one. This is the essence of teaching and learning using analogies. In order to investigate the use of analogies in teaching and learning, it is necessary to discuss what is meant by analogy and what characteristics can be used to describe them. Gentner (1982) defined the following terms: base domain, target domain, expressive analogy, explanatory analogy, base specificity, richness, clarity, systematicity, scope, and validity. These terms encompass the essential elements of an analogy and provide a way to systematically describe the characteristics of a particular analogy. The following sections will elaborate on those definitions.

Every analogy is comprised of two parts; the base domain and the target domain. The base is used to relate information about the target. In general, the base is more familiar to the student than the target, is easier for the student to visualize, and is already understood by the student. The target is usually new to the student and more abstract than the base.

In an analogy, objects in the base domain will map onto objects in the target domain. For example, with the billiard ball model of the atom, a billiard ball is an object in the base domain and an atom is the object in the target domain (Rouvray, 1995). Additionally, object attributes map from the base to the target. A billiard ball is a sphere, it is indivisible, and the eight ball cannot be changed to the nine-ball. In this model of the atom, atoms are spheres, are indivisible, and cannot be transmuted into different atoms. One limit of analogies is that it is not possible for all object attributes to be mapped from the base to the target domain. For example, billiard balls are made of ivory and atoms are not, billiard balls can be seen with the naked eye and atoms cannot and billiard balls do not bind together but atoms do.

It is not just the attributes of objects in the base domain that map onto attributes of objects in the target. The relationships between the objects in the base domain might also map onto relationships between the objects in the target. For example, the steering wheel of a car controls the direction of the front tires, which then determines which way a car will turn. In an airplane, the rudder pedals control the configuration of the tail, which then determines the direction that the airplane will turn. The relationships between steering wheel, tires, and direction are the same as the relationships between rudder pedals, tail, and direction of travel. However, as with object attributes, not all relationships will map well from base to target. Tires change the direction of motion of a car through the force of friction. The tail of a plane changes the direction of motion by changing airflow patterns to create a pressure differential between each side of the tail that creates a force pushing the tail to one side.

An analogy that maps attributes rather than relationships is generally more expressive than explanatory. Literary metaphors are examples of expressive analogies. Gentner (1982) gave T.S. Eliot's *The Hollow Men* as an example of a literary analogy. In this example, Eliot maps wind blowing through dry grass and rats' feet running over broken glass onto men's voices. The imagery is vivid but this analogy does not explain how men use air flowing past vocal cords to produce sound. It does, however, provide a very definite sense of the quality of the voices.

Scientific analogies, however, are usually more explanatory than expressive. Paris and Glynn (2004) compared a single cell to a factory. The nucleus of the cell is like the control centre of the factory; the mitochondria are like the power generator; and the ribosomes are like the production machines. In this analogy, it is not just the attributes that map from the base to the target, (for example, ribosomes produce proteins that are used by the cell or exported for use by other cells in the same way that production machines turn raw materials into finished products) but relationships between the objects also carry over. For example, the mitochondria provide energy for the ribosomes and the power generator provides energy to the production machines. The nucleus coordinates the activities of the mitochondria and ribosomes just as the control centre of a factory coordinates the needs of the production machines with the power generator's capacity.

Base specificity refers to how well a student understands the base domain. Familiarity with the base should not be confused with understanding of the base domain.

Gentner (1982) gave the example of an analogy where a "lonely sodium atom searches for a compatible chloride ion" (p. 113) and explains that while interpersonal attraction is familiar, some of the rules of this attraction are far more variable and capricious than the rules of electrostatic attraction. While Gentner (1982) maintained that the base domain must be at least as well specified as the target domain, Duit (1991) argued for a less hierarchical and more symmetrical relationship between target and base. Duit suggested that both the target and base domains can be developed simultaneously with either domain facilitating understanding of the other domain regardless of which is the base and which is the target.

Clarity refers to how precisely the base domain maps onto the target (Gentner, 1982). Ideally, there should be a one to one correspondence from base to target. An analogy's clarity decreases when two or more objects in the base map onto one object in the target or if one object in the base can map onto two or more objects in the target. Using the previous example of the car and the plane, changing the direction of the tires changes the direction that the car travels but in an airplane, a direction change can be caused by changing the position of the vertical control surface of the tail or by changing the positions of the horizontal control surfaces. Thus, the orientation of the car's tires could map onto the orientation of the vertical or horizontal control surfaces. Any analogy used in science teaching should have high clarity.

Richness describes how many objects, attributes, and relationships can be mapped from the base to the target (Gentner, 1982). In the billiard ball model of the atom, attributes of a billiard ball such as colour, size, temperature, texture, hardness, elasticity, mass, composition, and luster do not map onto the atom. Scientific analogies tend to be low in richness but they are not necessarily so. Richness and clarity should be considered to be independent of one another.

Newton's law of universal gravitation as shown in figure 2.10 is an expression of the relationship between several highly constrained object attributes and relationships.

$$F_g = \frac{Gm_1m_2}{r^2}$$

Figure 2.10. Newton's law of universal gravitation.

Changing the value of any variable, such as the mass of one object, results in the value of at least one other variable changing, usually the force of gravity, in order to maintain the equality. Coulomb's law describes the attractive or repulsive electrostatic force that exists between two charged particles. Coulomb's law is shown in figure 2.11.

$$F_e = \frac{kq_1q_2}{r^2}$$

Figure 2.11. Coulomb's law.

The parallels found between these two laws allow for one to be used as a very systematic analogy for the other. The force of gravity is mapped onto the electrostatic force, the universal gravitational constant mapped onto Coulomb's constant, the masses are mapped onto the charges, and the distance between the masses are mapped onto the distance between the charges. Students who understand the relationships between the variables in Newton's law of gravitation can apply that understanding to the relationships between the variables in Coulomb's law. Analogies for teaching science should have high clarity and systematicity but do not need to demonstrate a degree of richness beyond the scope required by the analogy's context.

The final two characteristics of analogies are scope and validity. Scope refers to the number of specific cases for which the analogy holds. To exemplify scope, Gentner (1982) highlighted the analogy that compares the solar system to an atom. It is a good analogy when restricted to the hydrogen atom (with one electron) but does not function as well for atoms with more than one electron. The effect of the gravity of one planet on another planet's orbit is almost insignificant but the effect of the electrostatic force of one electron on another is greater by several orders of magnitude. Gentner maintains that while scope, richness, and clarity are theoretically independent of one another, there is a practical upper limit of the sum of these characteristics. When generating an analogy, a gain in one characteristic usually requires a loss in one or both of the other.

Validity is a straightforward evaluation of an analogy. Does the base domain accurately map onto the target domain? Can predictions made using the base domain be verified in the target? If the answer to either of these questions is "no" then the analogy is not valid (Gentner, 1982).

**2.5.2 Factors to Consider When Using Analogies in Science Teaching**

Clement (1987) described a study of engineering students who were asked to solve some qualitative physics problems and to think out loud as they solved the problems. One quarter of the responses to the questions made use of at least one analogy. This suggests that analogies are a familiar and natural way of approaching problems in physics. However, the results of empirical studies on the effective use of analogies are ambiguous and that the successful use of analogies can depend on several factors that include how well the analogy represents the target domain, student familiarity and understanding of the base domain, spontaneous use of the analogy by the student, and the student perception of the advantages of using the analogy (Duit, 1991). These factors may act to either encourage or confound analogical learning.

Analogies often do not fully represent the target domain. As discussed earlier, Gentner and Gentner (1983) found that while the flowing water analogy worked well to explain series circuits, a moving crowd model was needed to explain parallel circuits. Multiple analogies may be required to fully develop the target domain, as well as to avoid misconceptions generated by the use of a single analogy (Duit, 1991).

It is also necessary that students be familiar with the base domain and that the students do not have misconceptions about the base domain. Glynn, Duit, and Thiele (1995) found that textbook authors and science teachers who used analogies often made use of a secondary analogy in addition to the primary one. Since no one analog maps exactly onto the target, the use of more than one analogy can prevent misconceptions that might occur when an analogy breaks down. The use of multiple analogies also encourages students to examine a concept from multiple perspectives.

Even when a student has successfully made use of an analogy, the student may need to be prompted to use that analogy. Treagust, Harrison, and Venville (1996) studied two groups of students. One was taught about the refraction of light with the use of an analogy and the other was taught without an analogy. Both groups were interviewed about their answers to an optics test and both groups provided similar explanations that indicated a poor conception of refraction. However, when the analogy was cued for students in the analogy group, their explanations improved in quality.

Another factor that must be considered is that the target domain must be sufficiently novel and challenging that there is a clear benefit for using analogical reasoning (Gick & Holyoak, 1983). Gabel and Sherwood (1980) supported this idea when they suggested that students with a lower formal reasoning ability benefit more from analogies than more capable students.

Finally, it is important to consider the hierarchical relationship between the analog domain and the target. Gentner (1982) described the use of analogies in such a way that mapping occurs only from base to target, whereas Duit, Roth, Kormorek, and Wilbers (2001) maintained that the mapping is more of a two-way exchange, especially when both the target and the base are not well understood. Duit, Roth, Kormorek, and Wilbers used the term piggybacking to describe this situation. An example of this is when Newton's Law of Universal Gravitation and Coulomb's Law (of electrostatic forces) are compared and contrasted when teaching physics (Treagust, Duit, Joslin, & Lindauer, 1992). Generally, gravity is taught prior to electrostatics and teachers often map masses and gravitational fields onto charges and electric fields. While the intent is to use gravity as the base domain, students often do not sufficiently understand gravity to make good use of this analogy. When this is the case, then the domains of gravity and electrostatics are both target and base. Knowledge about both domains is increased as examples from one domain are used to illustrate and explain examples from the other.

Kurtz, Miao, and Gentner (2001) investigated the back and forth comparison between domains and label the process mutual alignment. The authors suggest that this approach brings about a greater investigation of the similarities between two domains with a high degree of systematicity and thus, highlights more points of comparison for the students who are using the analogy. When more valid connections are made between the base and target, the analogy becomes more meaningful for the student. May, Hammer, and Roy (2006) gave an example of this by describing how a third-grade science student created an analogy that compared lava and rocks to water and ice. In the study, the student used his knowledge of the base domain to make inferences about the target domain, and then using those inferences to refine his understanding of the base domain.

**2.5.3 Techniques for Using Analogies**

Using analogies in teaching can take many forms. Treagust, Duit, Joslin, and Lindauer (1992) observed teachers using analogies in science teaching and found that some analogies were used simply to show a relationship between the target and the base domains. Other analogies were more deeply enriched in that the limitations of the analogy as well as misconceptions that might arise from the analogy were addressed. Two formal approaches to the use of analogies in teaching will be described below. The first is the TWA (teaching-with-analogies) model and the second is referred to as bridging analogies.

The TWA (teaching-with-analogies) model (Glynn, 1994) identifies the following operations that a teacher uses when teaching science with analogies. The operations (which need not occur sequentially) are as follows:

1. Introduce the target concept.
2. Recall the analog concept.
3. Identify similar features of concepts.
4. Map similar features.
5. Draw conclusions about concepts.
6. Indicate where analogy breaks down. (p. 13)

Glynn noted that misconceptions could occur when analogies break down and that teachers need to address these misconceptions by asking students questions about features that are not shared by the target and analog concepts. Glynn highlighted the constructivist orientation of this method by emphasizing that an analogy "connects prior knowledge with new knowledge when teaching a complex concept" (p. 53). Glynn, Duit, and Thiele (1995) compared novice and expert knowledge. Novice knowledge is often learned by rote whereas expert knowledge is organized into conceptual networks based on the relationships embodied by that knowledge. It is suggested that the teaching with analogies method is one way to help students develop their knowledge structures so that they evolve closer to an expert's conceptions.

Another approach to using analogies to teach science is referred to as bridging analogies (Clement, 1993). This approach assumes that students might be unwilling or unable to see the analogical relationship between the base and target domains. For example, students are often unwilling to concede that a table will push upwards on a book placed on its surface. This view is at odds with the scientific conception that the table must exert a force on the book. If the table did not exert a force equal in size to the force of gravity, the book would accelerate towards the floor. Students believe that static objects are not able to exert forces. When the analogy of a hand pushing against a spring is introduced, students agree that the spring pushes back against the hand but the table still does not push back against the book.

Clement (1993) proposed that an intermediate or bridging analogy that is midway between the example of the book on a table and the hand pushing against the spring might convince students that the original analogy is valid. The hand and spring analog is called the anchor and the book on the table is the target. A bridging case is introduced and in this example, it is a book resting on a springy, flexible board. This bridging case is chosen because it shares characteristics with both the anchor and target and as such, it should be easier to convince a student that the anchor is analogous to the bridging case, which in turn is analogous to the target. The bridging analogy approach differs from other analogical teaching approaches primarily in that it pays significant attention to ensuring that students agree with the plausibility and validity of the analogical relationship. Bryce and MacMillan (2005) conducted a study of how students used this particular bridging analogy and found that while it seemed that this method caused conceptual change more effectively that more conventional teaching methods, they did not consider the results of their study conclusive. On the other hand, Clement and Steinberg (2002) carefully described the bridging analogies used by a single teacher to help a single science student develop an excellent understanding of DC circuits.

**2.5.4 Potential Problems Arising From the Use of Analogies**

Duit, Roth, Kormorek, and Wilbers (2001) recognized the benefits of teaching by analogy but also offer several cautions. The first is that teachers and students may view both the base and the target domain differently. For example, if the flowing water analogy is used, it is important to remember that, in many cases, students do not always have a correct understanding of hydrodynamics. Furthermore, using the flowing water analogy to describe how current flows can fail if students have not sufficiently differentiated between current and voltage (Gentner & Gentner, 1983). Teachers that provide analogies are very familiar with the target and base, as well as the analogical relations that they attempt to create between them. For the teacher, the analogy is already constructed and so are all the meanings of the various relations. Students, on the other hand, have not yet constructed the analogy and are in danger of missing the point.

Furthermore, students and teachers are likely to have different conceptions of the base domain. When the solar system is used as an analogy for a hydrogen atom, it is assumed that students should be aware that:

1. The mass of the sun is much greater than the mass of the planets.
2. The planets travel around the sun.
3. There must be a centripetal force keeping the planets in their orbits.
4. Gravity provides this centripetal force.
5. The planets do not appreciably slow down.
6. There is no force needed to maintain the planets' speed.

These assumptions should not be taken for granted and yet they are some of the fundamental observational sentences that will be needed to build the solar system analogy of the hydrogen atom (Gentner & Gentner, 1983).

Since the target domain is often unfamiliar to the students, teachers generally assume that the students have no knowledge about it. This may be a false assumption. Teachers are cautioned to take the time to find out what their students already think about the base and the target. Teachers are also cautioned that students will use analogical reasoning processes that are not necessarily straightforward or correct. The extreme case of this can be seen when students are required to build their own analogies. Duit, Roth, Kormorek, and Wilbers (2001) wrote, "Our observations also suggest that it is unlikely that different groups of students generate the same understandings about complex phenomenon (i.e., formulate theoretical sentences) as they start from different contexts" (p. 300).

Building and using analogies requires constructing and testing many observational sentences in the base and target domains. These are not always the relations that the teacher has intended. It is suggested that the use of analogical reasoning be guided and monitored, keeping in mind the principle that students and teachers do not always see things the same way or even see the same things at all. "The construction of specific analogical relations has to be seen as an accomplishment rather than as an unproblematic matter of course" (Duit, Roth, Kormorek, and Wilbers, 2001, p. 300).

Glynn (2008) cautioned that analogies may impede rather than aid learning for a number of different reasons. Simple analogies that do not systematically map attributes from the base to the target are not as effective as more elaborate analogies. Analogies that are both verbal and visual are more effective than analogies that are less rich. "It is risky to use analogies without thinking about them. If used effectively, they can enhance learning by building conceptual bridges between old and new knowledge; if used ineffectively, they can hinder learning by causing misconceptions" (p. 118).

**2.6 AVOW Diagrams as an Analogical Method of Teaching DC Circuits**

There is are many analogies that are used to teach students about DC circuits but none of them are able to address all of the misconceptions that students have about electricity. Cheng and Shipstone (2003a) developed AVOW diagrams as a law-encoding diagram that captures all of the relevant relationships between current (amperes), potential difference (volts), resistance (ohms), and power (watts) in a DC circuit. The analogy compares the DC circuit (the target domain) to a rectangle (the base domain). Voltage and current are compared to the height and width of a rectangle, the power used by the circuit is compared to the area of a rectangle, and the resistance of a circuit is compared to the height-to-width ratio of the rectangle. The diagrams, by virtue of their geometrical arrangement, correctly illustrate the relationships among the parameters of a DC circuit. From a conceptual change point of view (Posner, Strike, Hewson, and Gertzog, 1982), students who are dissatisfied with their prior conceptions of electricity should find AVOW diagrams to be a more suitable and fruitful conception.

**2.6.1 Nature of AVOW Diagrams**

While AVOW diagrams are discussed in greater detail in Appendix A, the following qualitative description outlines their basic form and function. The simplest AVOW diagram consists of a rectangle that represents the load on a DC circuit. The load can be either a light bulb or a resistor but not other circuit elements such as capacitors or transistors. The width of the rectangle represents the current through the circuit and the height of the rectangle represents the potential difference across the circuit. The AVOW diagram for a simple circuit is given in Figure 2.12.

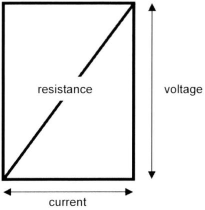



Figure 2.12. AVOW diagram representation of circuit parameters.

The power used by a circuit can be calculated by determining the product of the current and the voltage. With respect to the AVOW diagram, this means that the power used by the circuit is represented by the area of the rectangle.

Ohm's law states that the current flowing through a circuit is proportional to the voltage across the circuit and inversely proportional to the resistance of the circuit. Ohm's law is expressed mathematically as: $I=V/R$. This formula can be rearranged to: $R=V/I$ and this expression is used to determine the slope of the diagonal of the rectangle.

Generally, wires are assumed to have no resistance in most physics problems and thus, if represented in an AVOW diagram, would have no height and it would not be possible to include them in the diagram. As a result, the box shown can be assumed to represent one resistor or bulb in a DC circuit. The mapping relationship between the analog (AVOW diagram) and the target (DC circuit) is shown in figure 2.13.

| **AVOW Diagram** (Analog) | | **DC circuit** (Target) |
|---|---|---|
| Rectangle | compared with | Load in circuit |
| Width of rectangle | compared with | Current through circuit |
| Height of rectangle | compared with | Voltage across circuit |
| Area of rectangle | compared with | Power used by circuit |
| Slope of diagonal of rectangle | compared with | Resistance of circuit |

Figure 2.13. Mapping relationship between an AVOW diagram and a DC circuit.

AVOW diagrams appear to provide a simple and self-consistent analogy for DC circuits. The constraint that the diagram must be a rectangle ensures that current must be conserved and that the voltage drop across any path in the circuit must be the same as the voltage drop across any other path in the circuit. If current is not conserved, the AVOW diagram would be wider at some points than at others and if different current paths had different voltage drops, the diagram would not have a uniform height. Furthermore, the diagrams show that a change in one part of the circuit necessarily affects the rest of the circuit. Examples of how the diagrams reinforce a scientific conception of circuits are shown in Appendix A.

**2.6.2 Rationale for Using AVOW Diagrams**

McDermott and Schaffer (1992) described a number of difficulties that students have when studying DC circuits. These difficulties are observed both before and after instruction and do not seem to be addressed by current teaching methods. While not all of the identified difficulties can be remedied through the use of AVOW diagrams, the following difficulties might be overcome by using AVOW diagrams:

1. Failure to distinguish among related concepts such as current, voltage, and energy
2. Belief that the direction of current and order of elements matter
3. Belief that current is "used up" in a circuit
4. Belief that the battery is a constant current source
5. Failure to recognize that an ideal battery maintains a constant potential difference between its terminals
6. Failure to distinguish between branches connected in parallel across a battery and connected in parallel elsewhere
7. Tendency to focus on number of elements or branches (two bulbs half as bright as one bulb)
8. Failure to distinguish between the equivalent resistance of a network and the resistance of an individual element
9. Difficulty in identifying series and parallel connections
10. Inability to reason quantitatively about the behaviour of electric circuits
11. Tendency to reason sequentially and locally, rather than holistically
12. Lack of a conceptual model for predicting and explaining the behaviour of simple DC circuits

Appendix A illustrates how AVOW diagrams can address common student misconceptions about DC circuits.

**2.7 Research on AVOW Diagrams**

There has not been a lot of published research on the effectiveness of the use of AVOW diagrams in teaching. Cheng (2002) described the construction of AVOW diagrams and their use in solving both simple and complex problems in DC circuits. The author then conducted a study that compared two groups of nine university students. Each group included students who were considered to be novices with respect to DC circuits in that none of them were studying physical sciences or engineering, but each group did have solid mathematics backgrounds. One group received instruction about

DC circuits using AVOW diagrams and the other received instruction using equations. This study indicated that the AVOW students were better at recalling the basic facts about DC circuits and the relationships among the circuit parameters. The study showed that the AVOW students were more adept at solving complex and challenging problems than the equation group. This was shown by AVOW students drawing diagrams that correctly represented complex circuits and then deducing mostly correct answers from their drawings. Students in the equation group often failed to even begin a solution. Finally, AVOW students, in verbal interviews, appeared to have internalized the facts about the parameters of DC circuits and the relationships among them more consistently than the equations group.

Cheng and Shipstone (2003a, 2003b) conducted a second, more extensive study, with A-level students (students in the UK who are enrolled in a program of study in preparation for entrance to universities). In this study, a class of students was taught DC circuits using AVOW diagrams. The authors (p. 292) proposed that using AVOW diagrams would:

1. develop students' ability to break down a complex circuit into its component parts without losing sight of its behaviour as a complete circuit;
2. resolve any misunderstandings that the students might have had and help them develop clear working concepts of current and voltage in circuits, and;
3. enhance their problem solving skills.

Comparisons between the experimental group of 16 students and a group of 19 similar students indicated that AVOW diagrams were able to achieve these objectives. Furthermore, the AVOW students appeared to outperform the comparison groups when tested on DC circuits.

More interesting outcomes from this study were identified by the teacher who taught the AVOW diagrams to the class. He noted that students were more amenable to discussing circuits using diagrams than using equations. Students were willing to draw diagrams and articulate the behaviour of the diagrams. Additionally, the diagrams appeared to increase student confidence in themselves. Students were willing to begin solving problems by drawing diagrams and then correcting the diagrams as needed to more closely represent the problem. Students were also able to quickly identify when their analysis was incorrect based on the diagrams that they drew and then use that information to correct their diagrams.

Aside from these two studies conducted by the creator of AVOW diagrams, there have not been any studies published that examine the use and effectiveness of AVOW diagrams in teaching and learning DC circuits. It is important to determine how AVOW diagrams might be adapted by teachers to fit their individual teaching circumstances and if their use can be effective for teaching DC circuits.

**2.8 Summary**

The problems associated with teaching students about electricity have been the focus of numerous studies. The conceptions that students hold about electricity have been carefully described, analyzed, and documented. Despite this attention, the difficulties surrounding this topic remain. Conceptual change theory has been used to teach many areas of science and it has shown to be a useful framework for helping students with difficult ideas. The use of analogies in teaching science is another area that has been well represented in the literature and analogies have been shown to be very useful when teaching difficult concepts. When attempting to use a conceptual change framework in conjunction with analogies to teach DC circuits, one significant difficulty presents itself. Almost all analogs to DC circuits do not completely map all of the attributes and relationships that are inherent in a circuit. AVOW diagrams were developed to address this lack of a complete analog. While the diagrams and their use are fully described in the literature, there is a lack of published studies that investigate their utility in a typical high school physics class.

## Chapter 3: Methodology

Crotty (1998) listed four questions that should be asked when embarking on a research project. These questions are:

1. What *methods* do we propose to use?
2. What *methodology* governs our choice and use of methods?
3. What *theoretical perspective* lies behind the methodology in question?
4. What *epistemology* informs this theoretical perspective? (p. 2)

While the answers to questions one and two form the bulk of this chapter, it is appropriate to discuss questions three and four first.

Conceptual change theory has informed both the development of the teaching unit used in this study as well as the structure of the study itself. The first research question, "How can the AVOW diagram approach be used to teach about DC circuits in the context of a typical classroom?" addresses the practical considerations that result from attempting to use AVOW diagrams to foster conceptual change in a physics class. The second question, "How do students use AVOW diagrams to reason about DC circuits?" explores the conceptions that students develop about AVOW diagrams and how similar those conceptions are to a scientifically acceptable one. The third question, "How do AVOW diagrams facilitate progression from simple to scientific conceptions of electricity?" has been explored by examining the efficacy of this approach to help students identify if and how their prior conceptions of electricity fail to match a scientifically correct one and to help students to construct a more scientifically acceptable conception. The data collected in this study reflects student conceptions of electricity and any changes in these conceptions that may have occurred.

Crotty (1998) suggested that epistemology and ontology are closely related and that research literature often conflates them. Schraw and Olafson (2008) differentiated the concepts by constructing a two-dimensional scale intended to locate a teacher's ontological and epistemological beliefs along a continuum ranging between realist and relativist perspectives. Their scheme is useful for characterizing the epistemological framework of this study as they provide a list of statements to illustrate the meaning of each perspective that are specific to teachers. Table 3.1 shows these statements and the perspectives that they represent.

All of the epistemological statements are consistent with the beliefs that informed this study and this suggests that epistemological relativism and realism are not necessarily mutually exclusive. In the fine details, physics is a subject that requires a high degree of realism but the broad strokes reveal the relativistic aspects of the discipline. In this study, it was shown that students used a variety of ways of thinking about circuits to arrive at the same correct conclusions. Each student maintained a different and personal understanding of the circuit but all of them produced the same answers. This is consistent with the objectives of the teaching unit on DC circuits. The goal of the unit was for every student to be able to understand and solve DC circuits in accordance with the curriculum but it was expected that each individual's progress towards that goal would be as varied as the individuals themselves. Furthermore, this study recognized that while students are generally capable of following an algorithm to find a quantitative solution to a circuit, their qualitative understanding of the circuit could be demonstrated to be lacking. An essential element of this study has been the probing of different students' unique understanding of circuits.

Table 3.1

*Epistemological and ontological perspectives*

| Perspective | Statements |
|---|---|
| Epistemological realist | There are things that students simply need to know. |
| | I am teaching information that requires memorization and mastery. |
| | There are specific basic skills that need to be mastered. |
| Epistemological relativist | The things we teach need to change along with the world. |
| | The content of the curriculum should be responsive to the needs of the community. |
| | It is useful for students to engage in tasks for which there is no indisputably correct answer. |
| | Students design their own problems to solve. |
| Ontological realist | Student assignments should always be done individually. |
| | It is more practical to give the whole class the same assignment. |
| | The teacher must decide on what activities are to be done. |
| Ontological relativist | Students need to be involved in actively learning through discussions, projects, and presentations. |
| | Students work in small groups to complete an assignment as a team. |

Schraw and Olafson (2008) said, "an ontological realist assumes one underlying reality that is the same for everyone. Instructionally, this means that all children should receive the same type of instruction at the same time regardless of their individual circumstances and context" (p. 33) and that an ontological relativist assumes different realities for different people. As with the epistemological perspectives, a physics class is necessarily both ontologically realist and relativist. Students are enrolled in a class together and are evaluated at the same time with the same exams and are expected to produce the same answers. On the other hand, the diverse abilities, experiences, and understandings of a class are apparent with every exchange of information between teacher and student.

Since the physics classroom is a place that requires a dual position of realism and relativism, and epistemological and ontological beliefs that guided this investigation incorporated both perspectives. A circuit behaves as it does independently of the way a student thinks about it. However, the way a student thinks about a circuit is constructed in a different way for each students and understanding how a student arrives at an answer is as important as whether or not the answer accurately reflects an objective reality. The methods and methodology used for this study were selected to best account for these epistemological and ontological issues.

**3.1 Case study methodology**

Merriam (2002) posed two questions that must be asked of a particular piece of qualitative research. The first is whether or not the problem can be addressed by using qualitative inquiry and the second is whether or not the research addresses a previous gap in knowledge. As the lack of published research on the use of AVOW diagrams has already been established, it is only necessary to deal with the first question here. Qualitative research should be used to answer questions about meaning and understanding rather than surface opinions and cause-and-effect relationships. In this study, I explored and examined how students think about and use a novel representation of DC circuits. I also developed an understanding of how incorporating AVOW diagrams into a teaching unit affects the ways that teachers and students think and talk about circuits. A quantitative approach to this study would have had an experimental design with a test group and a control group writing pre-tests and post-tests and a comparison of the results of two different teaching approaches. The quantitative approach, however, would not have uncovered the reasons why teaching with AVOW diagrams caused students to score either better or worse that the comparison group. The approach used in this study asks students why they chose to use or not use AVOW diagrams and what difficulties they present. This information cannot be generated through quantitative means.

Yin (2009) characterized research questions as falling into two main categories defined by the questions that they asked. "What" questions were exploratory, seeking to develop hypotheses and propositions that could be studied subsequently. These questions could be answered by many different research methods such as exploratory surveys, experiments, or case studies. The answers to other "what" questions described the details of particular phenomena and how often they occur. These sorts of questions could be best-answered using surveys or archival data. According to Yin, "how" and "why" questions were explanatory in nature and, as such, lead to case studies. In contemporary situations where the researcher did not have control over behavioral events, unlike in a laboratory setting, case study allowed investigators to directly observe subjects, as well as interview subjects who are involved in the research project. In this research project, a teacher and his students were observed while he incorporated AVOW diagrams into his teaching of DC circuits and students were interviewed about their experiences in learning about DC circuits through the use of AVOW diagrams. Consequently, case study is an appropriate research methodology for this investigation.

Stake (2005) characterized case studies into three categories: intrinsic, instrumental, and collective. Intrinsic case studies are undertaken because the researcher is interested in understanding a particular case and may not be motivated to generalize from the case. A case study is instrumental if the intention is to generalize about or provide insight into an area that is exemplified by the particular case. Case studies need not be defined entirely as either intrinsic or instrumental. The boundary between them is not a sharp one and the purpose of a case study can overlap both definitions. Stake's final category is collective case study where many cases are examined with the intent to generalize and theorize. This investigation is best characterized as being intrinsic. I wanted to know how using AVOW diagrams would affect teaching physics in my school.

The sample selected for this study arose from my position as a physics teacher at Central High School (all names are pseudonyms) and the willingness of the other physics teacher at the school to volunteer for the study. I needed to study a class that was at my school as I was required to continue my regular teaching duties during my investigation and I was fortunate to be teaching at a school where there were three physics classes each year that would be suitable for study.

### 3.2 Data Collection Methods

I recruited the other physics teacher at the school, Mr. Burns, and his class as subjects for this research. The study began in March 2007 when Mr. Burns and I began to plan the use of AVOW diagrams in his class and continued until the end of April 2007 when the final interviews were completed.

The sessions where Mr. Burns and I explored AVOW diagrams and adapted them for his classroom were documented. This is where we explored the range of circuits that can be described by AVOW diagrams and how they can be used.

I then observed the class on four occasions for the duration of the 84-minute classes and by the end of the fourth observation period, Mr. Burns had concluded his instructional phase of the unit. For each classroom session, I made notes of the examples that Mr. Burns used and the discussions that arose from the notes. After each instructional period, Mr. Burns reviewed my notes for accuracy and completeness. Normal classroom assessment activities such as quizzes and homework were examined by both Mr. Burns and me to check students' use and understanding of AVOW diagrams. Mr. Burns and I discussed these assessments to ensure that we agreed on how we interpreted the students' use of the diagrams. After the four instructional periods that I had observed, Mr. Burns' students then participated in a laboratory activity, wrote quizzes, practiced solving DC circuits and wrote a diagnostic test of conceptions of DC circuits. The results of the test were analyzed and used to select interview questions for students who had volunteered to be interviewed. This unit consisted of seven 84-minute class periods and an end of unit examination. Students were then interviewed about their responses to specific test items and how they had used or could have used AVOW diagrams to answer the items. I recorded the interviews, transcribed them and kept the sketches of AVOW diagrams made by the students during the interview. The interview transcriptions and recordings were examined to find examples of how students used AVOW diagrams to answer test items and to find what may have confounded their use.

The results of this research are presented primarily as a report on the observations made by the teacher and me as AVOW diagrams were used in the unit on DC circuits. In section 4.2, I present summaries of how students worked through the test items that I presented to them. These summaries include their verbal responses and, where appropriate, reproductions of their sketches of AVOW diagrams. Common themes that arose from different students were identified and the implications of these recurring themes are explored. These specific methods of reporting and interpreting the data generated by this research study were selected for their suitability to answer the research questions.

As part of the research process, attention must be paid to the way that the case study addresses issues of internal and external validity. Internal validity refers to the congruency between the research findings and reality (Merriam, 2002). This research project maintains internal validity by using multiple sources of data collection and by collaborating with the classroom teacher. The multiple data sources allowed me to compare classroom observations of how students used AVOW diagrams with the way students described using AVOW diagrams in interviews. The diagnostic test of DC circuit conceptions provided an objective indication of the way that the students thought about DC circuits. The question shown in figure 3.1, for example, identifies if students are using a current consumption conception or a scientifically acceptable conception of DC circuits. Observations that I made were also compared with the observations and interpretations of the classroom teacher after each classroom session.

**17) Rank the currents at points 1, 2, 3, 4, 5, and 6 from highest to lowest.**

**(A) 5, 1, 3, 2, 4, 6**
**(B) 5, 3, 1, 4, 2, 6**
**(C) 5 = 6, 3 = 4, 1 = 2**
**(D) 5 = 6, 1 = 2 = 3 = 4**
**(E) 1 = 2 = 3 = 4 = 5 = 6**

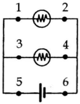



Figure 3.1. DIRECT 1.0 question 17.

External validity refers to how the results of the research can be generalized to other situations. The nature of qualitative research is such that small and non-random samples are selected so that they can be studied in-depth. However, these samples limit how well the findings can be generalized. The producer of qualitative research should provide sufficient description and information so that the reader of the research can determine for himself or herself how applicable the research is to his or her context.

Lincoln and Guba (1985) discuss the issue of the trustworthiness of an inquiry. Establishing credibility, transferability, dependability, and confirmability can ensure trustworthiness. Credibility reflects the extent to which the results of a piece of research can be counted on to accurately reflect the subject of the study. Transferability is the degree to which the findings of the research can be applied to other situations and contexts. Dependability describes the degree to which the results of a study would be consistent with another study undertaken in a similar context. Confirmability measures how well the findings of the research are supported by the data collected.

Lincoln and Guba suggest a number of activities to ensure credibility. One activity is prolonged engagement. The observer should be familiar enough with the context of the study so that he or she can appreciate and understand the context. Prolonged engagement also ensures that the observer is able to detect distortions such as prior expectations of the observer. My experience as a physics teacher in this school ensured that I was familiar with the context of the study.

Another activity that increases credibility is persistent observation. Lincoln and Guba (1985) write: "The purpose of persistent observation is to identify those characteristics and elements in the situation that are most relevant to the problem or issue being pursued and focusing on them in detail" (p. 304). This study examined the use of AVOW diagrams by the students and the teacher in a physics class. Components such as the lab activity that the students completed, the STS (science, technology, and society) outcomes covered in this unit, and the algebraic and formulaic calculations practiced by the students were not detailed as they were not relevant to the study. However, as many instances as possible of the use of AVOW diagrams were observed and studied.

Lincoln and Guba (1985) describe triangulation as a third activity that establishes credibility. Triangulation can be achieved by using multiple sources of data or multiple methods of collecting data. In this study, I established triangulation by observing the implementation of AVOW diagrams and interviewing several students about the use of the diagrams.

The issue of transferability deals with how the findings of the inquiry might be applied to other contexts. A description of the class that I studied is provided as well as the methods that were used in incorporating AVOW diagrams. The curriculum outcomes required by this unit on DC circuits is characterized in the description of the lessons provided in Chapter 4 and are also included in Appendix D.

In order to address dependability and confirmability, I had Mr. Burns check my interpretations of the interview transcripts, DIRECT 1.0 Test results, and classroom observations. Student interviews also included questions about what they thought about the way that AVOW diagrams were used in this unit. Comments and interpretations made by Mr. Burns and the students were consistent with the findings of this study.

### 3.3 Role of the Researcher

In this study, I was one of two physics teachers at the high school where the study took place. The study was designed and implemented by me, which included selecting the area of research, generating research questions, conducting a review of the literature, and determining the research methodology. The other physics teacher at the school taught the group of students that were studied. In this research project, I acted as a participant observer. During the planning stage, decisions about how to implement the use of AVOW diagrams were made collaboratively by both the classroom teacher and the researcher in a way that was not different from the way that any new instructional approach would be planned. I participated in and made observations of this planning process but as the project progressed to the stage where students were taught, the role of the researcher became more observer than participant. The researcher observed classroom instruction and at the conclusion of the unit, interviewed the subjects and administered and scored the DIRECT 1.0 test.

### 3.4 Use of DIRECT 1.0

The Determining and Interpreting Resistive Electric circuits Concepts Test Version 1.0 (DIRECT 1.0) is a 29-question multiple-choice test designed to uncover students' conceptions of electricity in DC circuits (Engelhardt & Beichner, 2004; Engelhardt, 1997). This test was used in this research study for three purposes. The first was to determine if the conceptions about DC circuits held by the study sample were different from the conceptions held by other high school students. The second purpose was to identify specific misconceptions held by the students in the study group. Finally, the individual test items were used to provide a starting point for interview questions about the conceptions of DC circuits held by the interviewed students and as questions that might be answered through the use of AVOW diagrams. The DIRECT 1.0 test is the product of a doctoral thesis study and Engelhardt (1997) provides detailed statistical and interview data to support the validity and reliability of the test.

### 3.5 Classroom Observations and Student Interviews

Four classroom periods were observed as Mr. Burns introduced AVOW diagrams to his class. Notes were made during the class and after each class. Mr. Burns checked the notes to ensure that my observations matched his impressions of the class.

After the administration of DIRECT 1.0, the test was scored and the students' responses were tabulated. Nine of the questions on the DIRECT 1.0 test had been identified as being particularly amenable to the use of AVOW diagrams. For each interview, I chose three of the nine questions that I had identified as being of interest. I wanted to interview enough students so that each of the questions of interest could be discussed with at least three students. I assumed that students who had correctly answered a question correctly understood the concept tested by the question. Students were not interviewed about questions that they had answered correctly.

A sign-up sheet for interviews was prepared with interview times that included times before the start of class, during the lunch break, and immediately following the last class of the day for the eight school days following the administration of the test. Eight students volunteered to be interviewed, but I needed two more students to ensure adequate representation of the questions of interest. I asked two additional students if they would be willing to be interviewed and they both agreed that they would.

Ethical issues with respect to the interview process, as well as the rest of the study, are discussed in section 3.10.

### 3.6 Interview Conditions and Structure

I conducted the interviews in Mr. Burns' classroom before class, at lunch, and after school. One interview took place in a chemistry laboratory at lunchtime. The interviews were audio taped and then later transcribed. All of the interviews were similarly structured.

Students were told that I was interested in questions on the test that might be solved using AVOW diagrams. Students were informed that the questions that had been selected for them were chosen because they were interesting and that they would only be asked about three questions. Students were not told that they were being asked about questions that they had answered incorrectly.

For each question, students were asked to draw AVOW diagrams for the circuit or circuits represented in the diagram. Once the drawing was complete, they were asked to use the diagram to answer the question. If the students were unable to draw an AVOW diagram or if the diagram was sufficiently incorrect to lead to a correct answer, the students were coached towards a correct diagram. In some interviews, it was apparent that the student was not going to be able to draw a correct diagram and it was necessary for me to draw one for the student myself.

In the course of answering these questions, some students were asked if they recalled their original responses and if they could explain their reasoning for their original answers. Once all three questions were addressed, students were asked if they had any comments about the AVOW diagrams and finally if they would suggest that we continue to use these diagrams while teaching DC circuits.

### 3.7 General Comments About Interviews

The interview results will be discussed in detail in Chapter 4 but there are several things that should be noted about the interview process. Several students needed to be reminded that in the context of the test, all the resistors and bulbs should be considered to be identical. Many students initially drew diagrams that showed unequal resistances. In some cases, they were able to correctly modify their diagrams to represent equal resistances but in some situations, they were unable to do so. Some students were completely unable to draw appropriate diagrams.

Students generally understood the meaning of the questions on the test. There were two questions where students had some difficulty interpreting the multiple choice answers and one student was unable to equate the term "energy delivered per second to the light bulb" with the concept of power.

### 3.8 Sample

The group of students that were examined in this study was chosen because it was the physics class that was about to begin their unit on circuits when the preliminary work for the project had been completed. This preliminary work included the literature review for Chapter 2 and approval from the Interdisciplinary Committee on Ethics in Human Research (ICEHR) at Memorial University of Newfoundland. The following sections will describe the school from which the sample was chosen as well as a brief characterization of the sample itself.

#### 3.8.1 School Profile

Central High School is located in Red Deer, Alberta. At the time of the study, the city of Red Deer had a population of about 86,000 people. The local population was growing quickly as a result of an economic boom related to the oilfield. Central High School had 1300 students from grade 9 to grade 12 and was one of three high schools in the city. The school opened in 1994 and has served as a model school for technology integration. The Math and Science department had its own computer lab, an open laboratory space for up to three classes, and several classrooms equipped with Smartboard (interactive whiteboards with digital projectors linked to computers) technology. The teaching staff of 63 was highly collaborative and supportive of new initiatives.

The student population in the 2006-2007 school year included 1.5% English as a second language students and 7.0% students with special needs (such as diagnosed learning disabilities or physical disabilities). The average education level of parents is 14.6 years, meaning that most parents had completed high school and many had completed post-secondary study. At Central, there were usually four sections of Physics 20 (grade 11) and three sections of Physics 30 (grade 12) taught each year. The average class size ranges from 25 to 35 students.

### 3.8.2 Classroom Context

This study was conducted with one Physics 30 class from the second semester of the 2006/2007 school year and it was the only section of Physics 30 in that semester. The program of studies for this course is provided in Appendix D. This course is divided into four units: Conservation laws (energy and momentum), Electric forces and fields, Magnetic forces and fields, and Nature of matter (including atomic, nuclear physics, and quantum physics). The outcome from the Physics 20-30 Program of Studies (1998) that is addressed with AVOW diagrams is: "Illustrate, using biophysical, industrial and other examples, technological applications of electromagnetic theories and effects; and describe, quantitatively, analyze and predict the functioning of simple resistive direct current circuits, using Ohm' s law and Kirchhoff' s rules (p. 8)."

Mr. Burns and I were the two physics teachers at the school but it was Mr. Burns who taught the class used for this study. I chose to use his class for two reasons. First, I believed that it would be prudent as a researcher to maintain some distance between myself and the classroom adoption of AVOW diagrams. I wanted to see how AVOW diagrams would be used by a teacher and not by a researcher and I felt that attempting to maintain my roles as a teacher and a researcher might lead to conflict. For example, if AVOW diagrams had proven to be confusing to students and inappropriate for this unit, a regular teacher would quickly discontinue their use. However, a researcher might be inclined to continue with their use for the sake of the study and in doing so neglect the needs of the students. By using a class that was not my own, the decision to continue using AVOW diagrams would be made by a teacher with the best interests of his students paramount. Second, it was important not to spend more than the normal time or effort on teaching the unit on DC circuits and by utilizing another teacher's class for the study, the introduced modifications required by the use of AVOW diagrams would be limited to the time allotted by the curriculum requirements.

Mr. Burns agreed to take part in this study due to his interest in new and innovative teaching methods. Mr. Burns and I had often discussed the teaching methods we used in our classrooms and we attempted to ensure that students in either of our classes had similar experiences. That meant that we used similar problem solving strategies, vocabulary, and expectations. We often also used common unit examinations and shared other assessment tools. We both had a strong interest in providing our students with the best possible learning environment.

Mr. Burns generally used a consistent teaching style with all of his classes. Information was often presented in the form of notes on the whiteboard or Smartboard and exercises consisted of teacher-generated handouts or questions from the student workbook. A typical class began with a call for questions from the previous day's homework, which he then addressed. While this was occurring, there would often be a short assignment on the board or notes to be copied. While students were working on these, there was time for Mr. Burns to provide individual attention to students who had expressed a need for help. Then Mr. Burns would proceed into the formal part of his lesson. He generally engaged all of his students by asking questions to check for understanding as well as to provide opportunities for clarification. The progress of each lesson was strongly influenced by the students' questions and answers. Lessons typically concluded with students working on questions from their workbooks or teacher-generated worksheets. Students were encouraged to collaborate with their peers while working on these questions and Mr. Burns was always available during class time and often outside of class time to help students whenever needed.

The study group consisted of a class of 28 students and the ages of the students ranged from 16 to 18. There were 17 males and 11 females in this class. All of the students in this class passed the course and Mr. Burns characterized them as representative of a typical grade 12 physics class. Students had all completed the prerequisite grade 11 physics course. Since it was possible to complete grade 11 physics in the first semester of grade 11, there were some grade 11 students taking this grade 12 class. The students' mathematics background ranged from completion of grade 10 mathematics to completion of grade 12 mathematics. Their abilities and motivation ranged from one or two exceptionally able students to one or two students who found the course quite difficult and struggled to maintain a passing grade with the bulk of the students being representative of the type of students that would be expected to be enrolled in an academic science course. The students were eager to do well in their studies and were willing to complete assigned work and to study outside of class in order to do so. At the end of the course, Mr. Burns indicated that this group of students had reached similar levels of achievement to his other classes.

### 3.9 Unit Implementation

Mr. Burns and I found it necessary to modify the teaching approach used by Cheng and Shipstone (2003b) so that it would fit better with our teaching environment. The following paragraphs describe the work of Cheng and Shipstone (2003b), as well as the modifications made in our approach for this study.

#### 3.9.1 Modifications of AVOW Approach

Since Cheng and Shipstone's teaching unit did not completely match the curriculum outcomes required by Alberta Education and the time allotted for the unit, Mr. Burns and I eliminated some of the topics covered by Shipstone and Cheng. Table 3.2 shows the content and duration of Cheng and Shipstone's unit. The sections omitted in this study were: calculation of electron drift velocity, diode characteristics, internal resistance of cells, potential dividers, and atomic energy levels and band theory. This

Table 3.2

*Cheng and Shipstone (2003b) unit teaching plan*

| Lesson | Lesson Content (Homework) | AVOW time (min) |
|---|---|---|
| 1 | Current as flow of charge. Relation to drift velocity, $I=n_eAv$. Calculation of electron drift velocity in a wire. Current density. Potential difference. [Calculations on $I=n_eAv$] | 0 |
| 2 | P.D. in circuits. Current continuity and current at junctions. Box diagrams and open book model of circuit. Exercise 1. Resistance. | 30 |
| 3 | Power relationships. Ohm's Law and AVOW diagrams. Characteristics of 12V lamp (class expt). [Exercises 2 and 3.] | 10 |
| 4 | Equivalence of circuits with different layouts. Resistance in series (theory). Resistances in parallel. Power distributions. | 15 |
| 5 | Resistances in parallel (theory). Use of AVOW diagrams to represent any resistor. Calculations of resistances of resistor combinations by AVOW diagram and formulae. Energy transfer in circuits. [Exercises 4 and 5.] | 20 |
| 6 | Scaling of AVOW diagrams in terms of current and voltage. Exercise 6. AVOW diagrams used to predict effects of adding more resistance. Exercise 7. | 45 |
| 7 | Exploring changes in circuits using AVOW diagrams. Exercise 8. Effect of voltmeter loading on circuit. Measurement of low and high resistances. | 30 |
| 8 | Diode characteristic (demonstration). Cells, internal resistance and representation by AVOW diagrams. | 15 |
| 9 | Series and parallel combinations of cells, with and without internal resistance. [Textbook exercises.] | 10 |
| 10 | Measurement of internal resistance (class expt.). | 0 |
| 11 | Cell combinations revisited. Power output. Kirchoff's Laws. | 5 |
| 12 | Calculations of Kirchoff's Laws. | 5 |
| 13 | The potential divider. Effect of drawing current form a potential divider. [Textbook exercises.] | 5 |
| 14 | Resistance and resistivity. Conductance and conductivity. Atomic energy level and introduction to band theory. | 0 |
| 15 | Simple band theory of conductors, semiconductors, and insulators. | 0 |

research study unit had seven lessons of eighty-four minutes each for a total of 588 minutes compared to fifteen lessons of fifty-five minutes for a total of 825 minutes. The lessons were taught daily while Cheng and Shipstone (2003b) presented lessons twice each week. In the study, their regular classroom teacher did not teach the group. Instead, Shipstone acted as the classroom teacher. As a result, he did not know the students or the extent of their previous experiences. He did not collect homework assignments between classes so the feedback that he was able to glean from the students about their learning was limited to the classroom environment. Cheng and Shipstone chose not to have the regular classroom teacher teach the unit in order to ensure that the instructor was sufficiently familiar with the AVOW diagram method. For this project, I decided that Mr. Burns' understanding of the use of AVOW diagrams was sufficient to allow him to teach this unit to his students and that doing so would allow me to focus on my observations of the study group.

Cheng and Shipstone administered a pre-test to their experimental group and post-tests to their experimental group and a control group of similar students. Since my study is focused on how this group of students in this context used AVOW diagrams, a control group was not recruited. Shipstone and Cheng did not use the DIRECT 1.0 test with their students so there were no results that could be compared to mine. It was decided to forgo a pre-test because there was not going to be a comparison group of pre-test data. Furthermore, it would not be possible to separate the effect of AVOW diagrams on pre-test and post-test responses from the effect of simply teaching the unit on DC circuits.

The most significant difference between the approach used for this project and Cheng and Shipstone's was not to use scaled AVOW diagrams. The diagrams used by Cheng and Shipstone had been constructed with rulers and it was intended that students would be able to directly measure the dimensions of the diagrams instead of performing calculations to determine circuit parameters. For example, a circuit that might have drawn five amperes of current would be drawn five centimeters wide and a circuit that drew only three amperes would be three centimeters wide. In order to make diagrams of reasonable size, their students sometimes needed to use scale factors in order to make drawings to represent values such as 100 volts. In my study, Mr. Burns and I agreed that his students would sketch diagrams with an approximate scale. A resistor with twice as much current as another would be about twice as wide but rulers would not be needed for their construction. Cheng and Shipstone's students were expected to be able to determine voltage or current from their diagrams by directly measuring from their diagrams and applying a scale factor. The students in my study would use formulas to calculate the currents and voltages represented by their diagrams.

### 3.9.2 Student Background

Students in Alberta study electricity in grade 9 and therefore have some experience with the concepts of current, voltage, power, and resistance as well as parallel and series circuits prior to Physics 30. Both Mr. Burns and I have observed that by the time that students get to grade 12, some of these concepts are forgotten or poorly understood. In his teaching, Mr. Burns takes this into account and is careful to review and reinforce the concepts that were developed in previous courses. Mr. Burns chooses to teach circuits from a voltage perspective. This means that all the behaviour of the circuit components is explained using potential difference instead of current. Voltage is described as being the cause of current and batteries are considered to be sources of constant voltage. The current in a circuit flows as a result of the voltage provided by the battery.

Prior to their unit on DC circuits in this course students complete a unit on the conservation of momentum and energy and a unit on electrostatics. Students thus are already familiar with the concept of potential difference from their study of charged parallel plates. They are familiar with voltage as a measure of the energy difference between two charged plates per unit charge and electrons are known to be charge carriers. This teaching sequence allows Mr. Burns to build on this knowledge for the unit on DC circuits.

### 3.10 Data Analysis

The data collected in this study fell into one of three main categories. The first category is observations of the planning process and classroom teaching of DC circuits using AVOW diagrams. These observations provided details about the discussions and decisions that were made during the planning process. Observations of the classroom teaching provides information about the way that AVOW diagrams were presented to students. When developing conceptions of DC circuits, there are a number of approaches that can be selected by the teacher and the observations made by the researcher describe not only the general approach used by the teacher in this study but also the way that AVOW diagrams were incorporated into this approach. Observations from the planning and teaching stages were examined to determine if AVOW diagrams had been a suitable method for teaching about DC circuits. I looked for evidence to indicate if AVOW diagrams were able to represent the circuits studied in the unit, if the diagrams could be understood by the students, if the diagrams facilitated fruitful discussion with the students about DC circuits, and if there were any unforeseen pitfalls arising from the use of the AVOW diagrams.

The results of the DIRECT 1.0 test comprise the next set of data. This diagnostic test is designed to identify student conceptions of DC circuits. DIRECT 1.0 is a multiple-choice test for which each response is intended to reflect a particular common misconception about DC circuits. A particular student's response to a question indicates what conception the student used when answering the question. One question posed in this research project is, "How can the AVOW diagram approach be used to teach about DC circuits in the context of a typical classroom?" If at the end of this teaching unit, students displayed conceptions of DC circuits that were significantly different from what might be expected, this difference should be investigated further. The test was scored and the responses to each question were tabulated. I identified test questions that could be answered by using AVOW diagrams and checked how well the students in the study group answered those particular questions. The DIRECT 1.0 test was also used as a starting point for the interviews that comprise the final data set.

The interviews were analyzed to determine patterns in the use of AVOW diagrams by the students. Clement (2000) characterized the purpose of educational research as generative, where the study focuses on building theoretical model, and convergent, where the study aims to support or refute an existing theoretical model. My suited to an interpretive rather than coded analysis of interview data as I was not sure what sort of responses I might get from the interviews and it would not be possible to establish a coding scheme prior to analyzing the interviews.

In the interviews, I paid attention to whether or not students spontaneously used AVOW diagrams for the questions and if the students were able to correctly construct an AVOW diagram to model the questions from the test. Once the AVOW diagram had been correctly constructed, I determined if the student was able to use the diagram to determine the correct answer to the question. Overall, the data were examined from the perspective of whether or not the AVOW diagrams could be used successfully and if it would be prudent to use them in future classes.

### 3.11 Ethical Issues

There were several aspects of this project that could have conceivably caused harm to the participants. The first stemmed from the inclusion of the AVOW diagram analogy in the teaching sequence. While it was possible that this method of teaching about DC circuits could have impeded the students' learning about DC circuits, teachers often try new methods of teaching and since the analogy had already been used in a similar context with no ill effects noted, it was unlikely to significantly hinder a student in this context. Furthermore, in the process of teaching DC circuits, the teachers have at their disposal several different analogies that may be used to correct student misconceptions and teachers often introduce and evaluate new analogies as part of their regular teaching practice. The inclusion of the AVOW diagram analogy was not outside the range of normal teaching practice.

The presence of an observer in the classroom was a second possible source of harm for students. However, this disruption was minimized by the fact that the observer was a teacher at the students' school. Since teachers are encouraged to observe their colleagues, this observation did not fall outside the range of normal teaching practice.

There was also some risk inherent in the interview process. Since the participants may have disclosed unexpected information in the interview, the interviewer needed to be prepared to deal with this unexpected information. The Alberta Teachers' Association Code of Conduct, the Alberta School Act, and local board and school policies inform and govern teachers' responses to these types of disclosure. There was no unexpected information disclosed during the interview process.

Participants were not compelled to participate in an interview. Transcriptions were done by the researcher and kept confidential. Portions of the interview used in the final research project protected the anonymity of the participant by the use of pseudonyms and avoiding or eliminating any identifying information.

Finally, since the teacher of this class, and not the researcher, assigned all grades, there were no repercussions for not participating in the research. Completion of the test and interviews were completely voluntary. Assurances were given to students that their academic achievement would not be impacted by participation or non-participation in this study.

The benefit of this research stemmed from possibly developing a better analogy for teaching and learning about DC circuits. Student participants stood to gain a better understanding of DC circuits and teachers might gain one more analogy with which to better teach their students.

The Interdisciplinary Committee on Ethics in Human Research (ICEHR) at Memorial University of Newfoundland requires that a number of issues be addressed when conducting research with human subjects. Subjects must be competent to give consent. Students in this group ranged in age from 16 to 18 years and were capable of understanding the potential harms and benefits of participating in this research. While the age of majority in Alberta is 18 years, it is a general school policy that 18 year old students still require parent or guardian consent in order to participate in school activities. Consent from either a parent or a guardian was required in order to participate in this research. Students were not included in this research unless both parents and students gave consent.

As a teacher in the participants' school, the researcher was in a position of authority over the participants and thus it might have been possible that the students' participation was compelled. However, since the researcher was not the classroom teacher of these students, there could be little chance of repercussions for not participating. The DIRECT 1.0 test administered as part of this study is similar to other assessments made in the course of teaching DC circuits. The test took approximately 30 minutes and the results of the test were not included in the students' grades. Students were free to forgo the test without any repercussions. With respect to informed consent, students were fully briefed about the research prior to requesting consent. Class time was used prior to requesting consent at which time the research project was explained to students. They were informed about the observation and interview processes. Since the idea of informed consent was novel to the students, it was introduced to the students and discussion was encouraged. Students were aware that their consent applies to the collection and use of data from observations, the DIRECT 1.0 test, and voluntary interviews. Students were informed that they were free to withdraw from the study at any point and that they were also free to withdraw any related data.

An information letter was provided to both students and for their parents/guardians. A signed copy of a consent form was returned to the researcher. Since the participants in this study were students at the researcher's school, it was not possible for the participants to be anonymous to the researcher. However, names or identifying characteristics were not used in the presentation of this research and thus the participants are anonymous to everyone but the researcher.

Student names were attached to the DIRECT 1.0 test so that interview questions could be tailored to individual students but student names were not shown to anyone other than Mr. Burns. Names were removed from all materials and all materials were assigned a pseudonym. Data remained confidential, as the identity of the students is only known to the researcher. There were no research assistants, secretaries, data entry personnel, interpreters, volunteers, or other people involved in this research with access to identifiable information about the participants.

The researcher was bound by the provisions of the Alberta School Act and the Alberta Teachers' Association Code of Conduct and as such, was required to report any information that indicates that the student is in need of protection or is in jeopardy.

**3.12 Limitations of the Study**

This was a case study that focused on a single teacher and a single group of students and I attempted to provide enough detail about the context of the study so that other teachers could use the results of the study to make informed decisions about incorporating AVOW diagrams into their own teaching practice.

Upon reflection at the end of the study, one change that I would make relates to my method of collecting observation data. At the start of this study, I was inexperienced in the skills required of a good observer. While I was able to make sufficient notes to be able to reconstruct the events that I had observed, I would have been better served by videotaping the classes that I observed. Such a recording would have allowed for a richer description of the events that occurred in the classroom. However, the need for better observations must be counterbalanced by the potential for a video camera to disrupt normal classroom activities. Furthermore, there are privacy issues that arise from the use of video recordings that might not make taping feasible.

**3.13 Summary**

Case study research requires rich and detailed description of the methods used in the investigation as well as the results of those methods. This chapter provided information on the research methods used in this study. The selection and characteristics of the class studied was described and details about the implementation of the teaching unit were provided. The objectives that were addressed by the teaching unit were outlined and the way that these objectives might be met through the use of AVOW diagrams was described. The data analysis methods were described and discussed. The final section detailed the ethical issues that were considered and described the steps taken to ensure that this study was conducted ethically.

# Chapter 4: Analysis of Data

I discussed the methodology for this research project in the previous chapter and I also described the research setting and sample. The results of this project will now be discussed, including information about the planning and implementation of the unit on DC circuits and the modifications that were made in order to include AVOW diagrams. Results from the DIRECT 1.0 test of student misconceptions are presented and responses from interviews about those questions will also be discussed. Finally, my observations and evaluations about the use of AVOW diagrams are presented. The specific answers to the research questions will be provided in chapter 5.

Neither Mr. Burns nor I had ever used AVOW diagrams to teach DC circuits prior to this study. The following sections describe the process that we followed in order to decide how best to use the AVOW diagrams, as well as observations from the presentation of the diagrams to the students.

## 4.1 Implementation of the Teaching Unit

In planning our use of AVOW diagrams, Mr. Burns and I needed to become proficient ourselves in the use of the diagrams as well as being able to anticipate how students would make use of them. We began by using the AVOW approach ourselves to solve typical DC circuits that the students would be expected to encounter. We solved a circuit with just one resistor and though this example was almost trivial, it allowed us to clarify how the elements of a circuit are mapped onto an AVOW diagram. We then proceeded to examine series circuits, parallel circuits, and combination circuits. We were quickly excited by the prospect of comparing the parameters of a circuit without having to resort to calculations. Figure 4.1 provides an example of a comparison of a circuit with one resistor to circuits with two resistors in parallel and in series. See Appendix A for a detailed explanation of the application of AVOW diagrams.

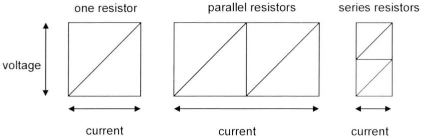



Figure 4.1. AVOW diagrams for resistors in series and parallel.

This example clearly shows the differences between these three circuits without any quantitative measures. Our next step was to attempt to use AVOW diagrams to solve the type of circuit shown in Figure 4.2.

Without using AVOW diagrams, solving this circuit would normally be achieved by finding the equivalent resistance of $R_2$ and $R_3$ and then finding the total resistance of the circuit. Once the total resistance had been determined, the total current could be found using V=IR. Then the potential difference across $R_1$ could be found by using the total current of the circuit and $R_1$. The potential difference across $R_2$ and $R_3$ are the same and could be found by subtracting the potential difference of $R_1$ from the potential difference of the entire circuit. Finally, the current through $R_2$ and $R_3$ can be calculated again using V=IR.

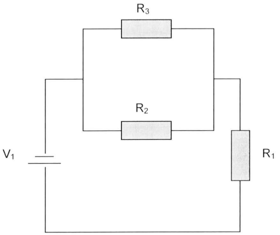



Figure 4.2. A circuit diagram of a combination circuit.

An AVOW diagram for this circuit that assumes equal resistance for each resistor is shown in figure 4.3.

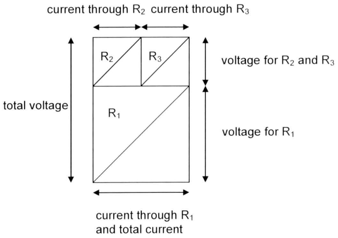



Figure 4.3. AVOW diagram for combination circuit.

Once the AVOW diagram is constructed, the order of the steps required to find the solution still remains essentially the same but the relationships that students often forget are explicitly shown by the diagram. These often forgotten relationships include the potential difference across $R_2$ and $R_3$ being equal and that the current through $R_2$ and $R_3$ added together equal the current through the entire circuit and are also equal to the current through $R_1$. It is also clear from the diagram that the potential difference across $R_1$ and $R_2$ is equal to the total potential difference across the circuit. From our experience, we had found that students often find that they do not know how to begin solving a circuit and we hoped that the constructed diagram would be suggestive of a starting point. We also felt that as students completed the diagrams, relationships that are often overlooked by students would be highlighted.

The next step was to investigate what happens if all of the resistors had different resistances. For example, what would happen if $R_1$ had a lower resistance? The total height of the AVOW diagram would have to remain constant but the slope of the diagonal would decrease as shown in Figure 4.4.

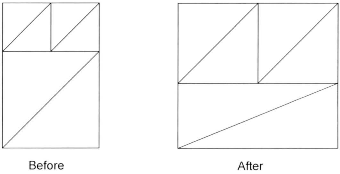



Figure 4.4. AVOW diagrams for a circuit before and after the resistance changes.

The first thing that we noticed was that the diagram illustrates how the potential difference across $R_1$ and $R_2$ increases and across $R_1$ decreases as a result of the change to the circuit. In our experience, students rarely took this change into account. It was at this point that Mr. Burns and I decided that these diagrams could become a powerful discussion tool for our classes.

Finally, Mr. Burns and I tried to develop an approach that used AVOW diagrams to explain the reasons why ammeters are always connected in series and must have a low resistance while voltmeters are connected in parallel and must have a very high resistance.

We began by proposing that the measuring of current in a circuit would be directly analogous to taking a measurement from the AVOW diagram. To measure the current represented by the diagram, a ruler could be placed across the bottom of the diagram since the current is represented by the width. A resistor placed in this way on the diagram represents a series connection. This corresponds to the proper connection of an ammeter. Since the act of measuring should not change the properties of the circuit, an ammeter must have a very low resistance. Adding an element in series in an AVOW diagram that does not significantly change the circuit requires that the resistance of the element be negligible. That is, the slope of the diagonal for the rectangle should be close to zero. When this is the case, there is very little added height to the diagram. Mr. Burns and I believed that it would be easy to demonstrate this to students by using AVOW diagrams. Extending the analogy to an actual circuit would provide students with a way to think about how meters need to be connected. We were then able to very quickly develop a similar argument to explain the placement of a voltmeter and the necessity for the width of such a rectangle to be close to zero. To measure the potential difference, the ruler must be placed along the vertical edge of the diagram. This is a parallel connection and in order to maintain the original state of the circuit, the resistance of the voltmeter must be very high.

The last decision that we had to make was whether or not we were going to use the AVOW diagrams qualitatively, as we had been doing in our discussion, or if we would follow Shipstone and Cheng's (2003b) procedure and have the students construct scale drawings. After a few quick attempts to construct scale drawings of our own, we decided that it would be better for the students to use formulas to determine the values of the circuit parameters rather than using scale drawings. The practical reason for this was that the final examination for the course is administered by Alberta Learning and would be marked by a panel of teachers who would likely not be familiar with AVOW diagrams and who might not recognize the mathematical validity of such an approach. The pedagogical reason for this decision was that we felt that the value of using the diagrams would come from helping the students gain a better conception of the circuit rather than giving them a better calculation tool. Students' difficulties stemmed from designing an overall problem solving strategy, not from being unable to use formulas and calculations.

### 4.1.1 Lesson One: March 22, 2007

The first lesson of this unit began on the last day of classes before spring break. As a result, the class was shorter than normal and it was intended to introduce the unit on circuits and provide a bridge from the previous electrostatics unit.

Mr. Burns began the class by defining current as the rate of flow of electrical charge. He introduced the formula where I is current, q is charge and t is time. From their previous unit of study of electrostatics, students were already familiar with the symbol q for charge measured in coulombs and t for time measured in seconds. The ampere was defined as one coulomb per second. Mr. Burns then presented the following assertions.

1. Current is directly proportional to voltage: $I \alpha V$
2. Current is inversely proportional to resistance: $I \alpha \frac{1}{R}$
3. Resistance is the ability of a material to stop/slow the current flow.

Students were then provided with the relationship: $R \alpha \frac{\rho l}{A}$ Where ρ is the resistivity of the material, *l* is the length of the wire, and A is the cross-sectional area of the wire. This relationship was used to show that the resistance of a wire increases with the length of the wire and decreases with the cross-sectional area. Household wires and power lines were given as examples for wires that are thick and therefore have less resistance. Students were told that the unit for resistance is the ohm and that the symbol is Ω. Ohm's law was given in two forms: $I = \frac{V}{R}$ and $V = IR$

Finally, the concept of power was introduced in the context of electric current. Students had used the relationship $P = \frac{W}{t}$ in previous units where P is power in watts, W is work in joules, and t is time measured in seconds. They had also used $P = \frac{\Delta E}{t}$, where ΔE signifies the change in energy. Students were reminded that a watt is equal to one joule per second. The relation $P = IV$ was then introduced and justified through the use of dimensional analysis. The formulas $P = IV$ and $V = IR$ were then combined to show that $P = \frac{V^2}{R}$ and $P = I^2R$.

This lesson was then concluded and students were dismissed for their spring break. Mr. Burns formatively assessed student understanding of this lesson by asking questions throughout his presentation and using the students' responses to identify which ideas appeared to be understood and which points needed further clarification.

### 4.1.2 Lesson Two: April 2, 2007

The second lesson was longer than the first and it introduced the concept of a circuit. Circuit schematic diagrams were introduced and explained. Elements were defined as being in series if there is only one current path and in parallel if there is more than one current path. Circuits that have parallel and series elements were also introduced and described as combination circuits.

Mr. Burns was careful to highlight the importance of the conservation of current and the conservation of energy at the outset of his explanations and frequently referred to these ideas in his teaching. When discussing current, Mr. Burns was careful to differentiate between electron flow and conventional current and to emphasize that both concepts are valid ways to describe current flow. Mr. Burns makes a habit of explaining that current can be described as flowing in either direction, thus discouraging sequential reasoning.

Mr. Burns then described a circuit as having a voltage source, such as a battery or cell, that acts to supply energy to the circuit and at least one electrical device, such as a bulb or resistor, that consumes the energy supplied by the battery.

As a very experienced physics teacher, Mr. Burns is aware of most of the misconceptions that students have about electricity and he has many strategies that he uses to attempt to correct them. Once he had described the physical appearance of a circuit Mr. Burns asked the students how they would describe the motion of electrons around the circuit. One student suggested that the electrons closer to the battery push on the other electrons in the wire at points further from the battery, not unlike the way that toothpaste is squeezed from a tube. This suggestion reflected the conception of batteries as a source of current rather than a source of potential difference. In order to correct this conception Mr. Burns revisited his previous unit on electrostatics and reminded the students of the force acting on charged particles that are between two charged parallel plates. On a diagram of a circuit, Mr. Burns drew an electric field induced by the battery and showed that electrons at all points in the circuit will experience the same force due to this electric field. Thus, when the circuit is closed, any electron in the circuit will act as a result of that field and not from the interaction with other electrons.

Mr. Burns then added another parallel resistor to the circuit and asked the students which way electrons would flow. One student suggested that the electron decides which path to take. Mr. Burns responded by saying that an electron cannot "decide" which path to take. On his diagram, Mr. Burns showed two current paths with a total current of 10 A. Through one path he showed a current of 3 A and 7 A through the other. Another student then suggested that the currents should split equally. Mr. Burns then explained that in the case where the resistances for the two paths are different, that fewer electrons will follow the path of greater resistance and more electrons follow the path of less resistance. Therefore, if only 3 A flowed through one path, it is because that path has a greater resistance than the path with 7 A flowing through it.

A different student then suggested that electrons should take the "shortest" path through the circuit. Mr. Burns assured the student that the physical length of the path does not determine the path taken by the electron. Before moving on to his next topic, Mr. Burns emphasized that the sum of the current through each path must be the same as the total current through the circuit.

Next, Mr. Burns introduced Kirchhoff's Voltage Rule (where the sum of the individual voltage drops in the circuit is equal to the total voltage of the circuit) and tracked the voltage drop across different circuit elements that were in series. He showed three resistors in series connected to a battery that supplied 9 V. The first resistor had a voltage drop of 6 V, the second had a drop of 1 V and the third, therefore, must have a drop of 2 V. He explained this by referring to the law of conservation of energy and the law of conservation of charge. Energy supplied by the battery must be the same as the energy consumed by the circuit, and the current into the circuit must be the same as the current coming out of the circuit. In order to emphasize the combination of these two ideas, he used joules per coulomb (J/C) in his discussion of potential difference instead of volts. To add further clarity, he then derived the conversion factor for J/C to J/electron to show that the amount of energy for each electron is directly related to the amount of energy for each unit of charge. It followed then that if energy and current are both conserved then potential difference also must be conserved since the measure of two of potential difference, current, and energy defines the third. The total voltage consumed along any current path must add up to the total voltage provided by the battery.

Mr. Burns then led his students through an example that demonstrated parallel resistors and concluded that resistors in parallel must have equal potential difference. The lesson closed with students practicing some simple calculations involving P=IV and V=IR.

### 4.1.3 Lesson Three: April 3, 2007

The third lesson in the unit introduced AVOW diagrams. The lesson began by summarizing parallel circuits as having more than one current path, series circuits having only one current path, and combination circuits as having series parts and parallel parts. The students were also introduced to the formulas for calculating the equivalent resistance of parallel and series resistors.

The first example in this lesson showed a circuit with one resistor. The circuit was solved using conventional methods and then the AVOW diagram for the circuit was introduced. The example was used to define the dimensions of the AVOW diagram and to illustrate how those dimensions reflect the relationships between current (width of the rectangle), voltage (height of the rectangle), resistance (slope of the diagonal), and power (area of the rectangle). The AVOW diagrams were then modified to illustrate how changing one dimension changes the others.

Students were very quick to answer questions about how other dimensions would be affected by a change in one dimension. For example, when a student asked what would happen if the power used by a resistor were reduced with the voltage remaining constant, she identified that the current must be reduced. Further prompting resulted in students recognizing that this would mean that the resistance of the resistor would have to be increased. It was clear that students were able to make this connection without having to use formulas.

Mr. Burns then asked the students about the brightness of different light bulbs. He used 100 W, 60 W, and 40 W bulbs as examples and asked students to rate their relative brightness. Stipulating equal voltages, Mr. Burns asked students to draw AVOW diagrams for each bulb and then comment on the resistances of the various bulbs. All the observed students made similar drawings to the one shown in Figure 4.5. Mr. Burns then drew similar diagrams on the board and he emphasized that the bulb with the lowest resistance, as shown by the diagonal with the shallowest slope, used the greatest amount of power.

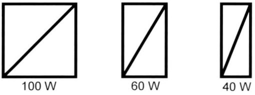



Figure 4.5. AVOW diagrams for three different light bulbs.

The next sample circuit included two different bulbs in series as shown in figure 4.6. The circuit was first solved algebraically and then an AVOW diagram for the circuit was constructed. Mr. Burns' general method for solving circuits algebraically is to attempt to find the total potential difference across the circuit, the total resistance of the circuit, and

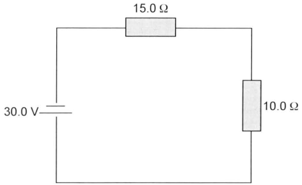



Figure 4.6. Circuit diagram for two light bulbs in series.

the total current through the circuit. Once this is achieved, the potential difference across each resistor can be determined and then the current through each can be calculated. Students were shown how to draw a chart to keep track of the information given in the question and the results of their calculations. The chart is shown in figure 4.7. The number **1** refers to the resistor number 1, number **2** refers to resistor number 2 and **Total** refers to the entire circuit.

| | V | I | R | P |
|---|---|---|---|---|
| **1** | | | **10.0 Ω** | |
| **2** | | | **15.0 Ω** | |
| **Total** | **30.0 V** | | | |

Figure 4.7. Table for recording circuit parameters.

Since the resistors are in series, the total resistance can be found by $R_T = R_1 + R_2$.

Figure 4.8 shows this value entered in the table.

| | V | I | R | P |
|---|---|---|---|---|
| 1 | | | 10.0 Ω | |
| 2 | | | 15.0 Ω | |
| Total | 30.0 V | | *25.0 Ω* | |

Figure 4.8. Table for recording circuit parameters.

The current for the entire circuit was then calculated from the formula $V = IR$ and figure 4.9 shows this value entered in the table.

| | V | I | R | P |
|---|---|---|---|---|
| 1 | | | 10.0 Ω | |
| 2 | | | 15.0 Ω | |
| Total | 30.0 V | *1.2 A* | 25.0 Ω | |

Figure 4.9. Table for recording circuit parameters.

Since the resistors are in series, the current through each is the same as shown in Figure 4.10.

| | V | I | R | P |
|---|---|---|---|---|
| 1 | | *1.2 A* | 10.0 Ω | |
| 2 | | *1.2 A* | 15.0 Ω | |
| Total | 30.0 V | 1.2 A | 25.0 Ω | |

Figure 4.10. Table for recording circuit parameters.

The formula $V = IR$ was then used to calculate the potential difference for each of the resistors and the values are shown in Figure 4.11. Finally, the power for each resistor and the total circuit was calculated using $P = IV$ and the results are shown in figure 4.12.

| | V | I | R | P |
|---|---|---|---|---|
| **1** | *12.0V* | **1.2 A** | **10.0 Ω** | |
| **2** | *18.0 V* | **1.2 A** | **15.0 Ω** | |
| **Total** | **30.0 V** | **1.2 A** | **25.0 Ω** | |

Figure 4.11. Table for recording circuit parameters.

This chart is used so that students can confirm many of the relationships that exist in a DC circuit. For example, potential difference across the resistors in series sums to the total potential difference across the circuit and the power used by the resistors sums to the total power used in the circuit. This chart method allows students to organize their data about the circuit and to prompt subsequent problem solving steps.

| | V | I | R | P |
|---|---|---|---|---|
| **1** | *12.0V* | **1.2 A** | **10.0 Ω** | *14.4 W* |
| **2** | *18.0 V* | **1.2 A** | **15.0 Ω** | *21.6 W* |
| **Total** | **30.0 V** | **1.2 A** | **25.0 Ω** | *36.0 W* |

Figure 4.12. Completed table of circuit parameters.

The AVOW diagram method was then introduced with the following teaching sequence. Mr. Burns began by drawing a box representing the entire circuit as shown in Figure 4.13. The AVOW diagram was not used to solve the circuit at this point, but rather to illustrate what an AVOW diagram might look like for this circuit.

Mr. Burns then proceeded to split the box to represent the two resistors. He used a meter-stick to suggest different locations to make the split and asked students for input as to where to split the box. Since students knew that the resistor with lower resistance would use more power, they suggested an unequal split. When a student expressed

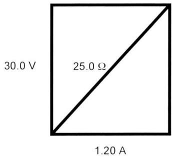



Figure 4.13. AVOW diagram for the complete circuit.

concern about which resistor should be at the top of the box and which one should be at the bottom, Mr. Burns assured her that it did not make a difference since current can be visualized as either conventional current or electron flow and as a result, the order of the resistors is irrelevant. Figure 4.14 shows the diagrams that Mr. Burns drew for the students.

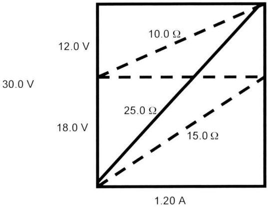



Figure 4.14. AVOW diagram for a circuit showing two resistors.

Students were able to show that all of the relationships between the circuit parameters established with the original algebraic solution were represented by the AVOW diagram. Students experienced little difficulty with this activity. A parallel circuit, as shown in figure 4.15, was then introduced and solved algebraically using the chart method described earlier. While solving the circuit, a student expressed concern about the equivalent resistance of the circuit being lower than the resistance of either resistor. Mr. Burns addressed this concern by describing a highway with a construction delay. He asked the student to imagine what would happen to the traffic flow if some of the cars could be detoured around the construction delay. The student understood that traffic would flow easier along two paths and that the traffic would flow faster using both paths than using just one.

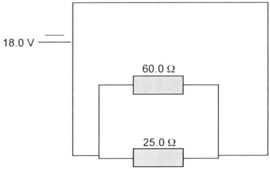



Figure 4.15. Circuit diagram for a parallel circuit.

After solving the circuit using traditional algebraic methods, Mr. Burns asked his students to draw an AVOW diagram for this circuit starting from the outline of a box that he had drawn for them. As the students attempted their drawings, I moved around the room and observed 10 students drawing correct diagrams, one student drawing a diagram that was in series and one student drawing a diagram with three resistors but I was not able to observe all of the students in the class. Mr. Burns noted that most students that he had observed had split their boxes vertically, and when he asked the class why they chose to draw their resistors this way, the reply was that the voltages across the resistors must be equal. Mr. Burns then asked how the diagram should be divided and the students explained that the split should be proportional to the currents that they had calculated algebraically. Figure 4.16 shows the AVOW diagram for the circuit used in this example.

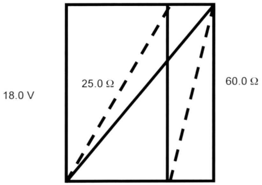



Figure 4.16. AVOW diagram for a parallel circuit.

The students were then asked to label their AVOW diagrams and there was a discussion about how the dimensions of the AVOW diagram represent the parameters of the circuit. Students appeared comfortable with this representation.

A combination circuit was then introduced but not solved. Mr. Burns summarized series elements as boxes stacked on top of each other and parallel elements as side-by-side boxes. He then encouraged students to sketch AVOW diagrams for circuits using approximate scales rather than algebraically solving the circuit prior to drawing the diagram. He provided two more simple examples and all of the observed students were able to draw correct diagrams.

### 4.1.4 Lesson Four: April 4, 2007

Once three lessons had been completed, the emphasis of the lessons shifted away from teacher-directed to student-centered problem solving. Students were presented with circuit diagrams and required to produce the AVOW diagram and then solve the circuit. Students adopted the strategy of building AVOW diagrams by first sketching a box and then subdividing the box into parallel or series sections. They then labeled the dimensions that had been given and then used the AVOW diagram to identify which dimensions could be determined from the given information. Students found that solving circuits in this manner made it easy to keep track of the information that they had been given and how that information related to all of the other dimensions of the circuit. Students generally found that solving circuits in this manner to be quite straightforward. In this class, students solved circuits with up to five resistors.

### 4.1.5 Subsequent Lessons

The remainder of the unit consisted of students practicing solving circuits as well as a laboratory activity where students constructed series and parallel circuits and measured current and voltage for each resistor and for the entire circuit. In the lab, the measured values were compared to predicted values. Additionally, several quizzes were administered during the course of the unit in order to provide feedback to the students, Mr. Burns, and myself. At the end of the unit, students wrote a unit exam and then finally students wrote the DIRECT 1.0 test.

### 4.1.6 Samples of Student Work

Figure 4.17 shows one quiz that Mr. Burns used to assess his students' work. This student response illustrates the typical problem solving strategy used by the students on this quiz. All of the students who wrote this quiz were able to construct correct AVOW diagrams for the given circuit and all of the students were able to correctly solve for all of the circuit parameters. Figure 4.18 shows a less formal example of another student's work. This student response, which was not collected for evaluation, does not include the detailed workings that Mr. Burns required from his students in his summative assessment activities. In solving the given circuit, this student included two AVOW diagrams, one to show the organization of the circuit and another larger one to show the equivalent resistances of groups of resistors. It can be seen that the resistances of resistors 2 and 3 appear to be equal in the smaller AVOW diagram but their differences are shown in the larger diagram. However, the diagonals of resistors 2 and 4 in the larger diagram do not have the same slope even though they have the same resistance. This is an indication of how difficult it is to construct a perfectly proportioned AVOW diagram.

# Circuits Quiz 2A

1. What is the heat produced in a conductor in 75.0 s if there is a current of 12.7 A and a resistance of 8.50Ω? How many electrons would have moved past a point in the wire during this time?

q = ?  E = ?  t = 75.0s  I = 12.7A  R = 8.50 Ω

E = PT = IVT
E = I(IR)T = (I)²RT

E = (12.7A)²(8.50 Ω)(75.0s) = 102828.375 J

E = 1.03 × 10⁵ J

q = E/T = 102827.375 J / 75.0s = 1370.965 C

#e⁻ = 8.57 × 10²¹ e⁻

2. If electricity costs $0.0800/kWh then how much would it cost to run three 100W lightbulbs on a porch for 8 hours a night, 365 days a year?

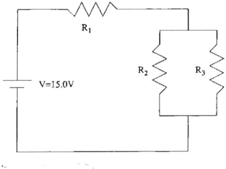
E = Pt = (0.300 kw)(2920h) = 876 kwh

cost = $0.0800/kwh · 876 kwh = $70.08

P = 0.1 kw × 3 = 0.300 kw
T = 8h · 365 · 2920h

3. Calculate $R_t$, $V_t$, $I_t$, Vdrop for each resistor, and I for each resistor given:

$R_1$ = 20.0Ω
$R_2$ = 60.0Ω
$R_3$ = 50.0Ω



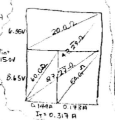

V_T = 15.0V

R_T = 20.0 Ω + (60.0 Ω⁻¹ + 50.0 Ω⁻¹)⁻¹
= 20.0 Ω + 27.27 Ω
R_T = 47.3 Ω

I_T = 15.0V/47.3 Ω = 0.317307... A
I_T = 0.317 A

Vdrop₁ = I_T R₁ = 0.317A · 20.0 Ω
= 6.35 V

Vdrop₂/₃ = I_T R₂/₃ = 0.317A · 27.27 Ω
= 8.65V




| | V | I | R |
|---|---|---|---|
| 1 | 6.35V | 0.317A | 20.0Ω |
| 2 | 8.65V | 0.144A | 60.0Ω |
| 3 | 8.65V | 0.173A | 50.0Ω |
| T | 15.0V | 0.317A | 47.3Ω |

3) I₁ = V_T/R_I = 0.317 A

I₃ = V₃/R₃ = 8.65V/50.0Ω = 0.173 A

I₂ = V₂/R₂ = 8.65V/60.0Ω = 0.144... A

Figure 4.17. Quiz used as assessment on April 10, 2007.

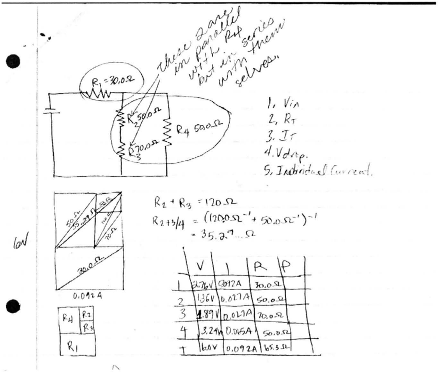



Figure 4.18. Sample of one student's work.

### 4.1.7 Overall Impressions

Mr. Burns observed that while presenting this unit using AVOW diagrams, he took about two days longer than usual but he did not attribute the extra time to the addition of AVOW diagrams as the length each unit varies from year to year. Mr. Burns also noted that, in his lessons, he was able to discuss circuits with his students from a more qualitative perspective than in the past. An example of this is being able to discuss with students how changing one circuit parameter affects the other parameters without resorting to algebra. This is an ability that Cheng and Shipstone (2003b) expect to arise from the use of AVOW diagrams. Students were noticeably more adept at predicting how the power used by a resistor would change based on changes in the circuit than students in previous classes. Mr. Burns indicated that he would include AVOW diagrams in future efforts to teach students about DC circuits.

**4.2 DIRECT 1.0 Results**

DIRECT 1.0 is a test designed to identify student conceptions of DC circuits. Table 4.1 shows the responses given by the 28 students in the Central High School study group. Correct answers are shown in bold. The number of possible answers for each question ranged from three to five. One student left three questions blank, another student left two questions blank, and one student left one question blank. Each value in Table 4.1 indicates the fraction of the entire sample that selected each answer. The fractions for the questions that were left blank by these students reflect this missing data.

While the entire DIRECT 1.0 test was administered to the study group, nine questions were selected as the focus of interviews with students. These questions were selected because AVOW diagrams could be applied to the questions. The questions selected for the interviews were: 2, 5, 6, 14, 15, 17, 21, 26, and 29. Questions from the test that were not selected could not have AVOW diagrams meaningfully applied to them. For example, several questions asked students to interpret diagrams of bulbs, batteries, and wires. Other questions tested theoretical knowledge about circuits. See Appendix B for the complete test.

Table 4.1

*Collected Results for DIRECT 1.0 Test*

| | Fraction of Central High School students selecting each answer | | | | |
|---|---|---|---|---|---|
| Question | A | B | C | D | E |
| 1 | 0.29 | 0.00 | 0.32 | **0.39** | 0.00 |
| 2 | 0.04 | **0.64** | 0.32 | 0.00 | 0.00 |
| 3 | 0.00 | 0.04 | **0.43** | 0.07 | 0.46 |
| 4 | 0.11 | 0.00 | 0.21 | **0.29** | 0.39 |
| 5 | 0.29 | **0.64** | 0.07 | 0.00 | 0.00 |
| 6 | 0.25 | 0.11 | 0.07 | 0.14 | **0.43** |
| 7 | **0.71** | 0.07 | 0.21 | 0.00 | 0.00 |
| 8 | 0.00 | 0.11 | **0.89** | 0.00 | 0.00 |
| 9 | 0.07 | 0.04 | 0.04 | **0.86** | 0.00 |
| 10 | 0.00 | 0.00 | 0.54 | 0.04 | **0.39** |
| 11 | **0.32** | 0.00 | 0.29 | 0.39 | 0.00 |
| 12 | 0.54 | 0.14 | **0.04** | 0.18 | 0.11 |
| 13 | **0.86** | 0.04 | 0.00 | 0.00 | 0.11 |
| 14 | 0.25 | **0.54** | 0.21 | 0.00 | 0.00 |
| 15 | 0.25 | 0.00 | **0.75** | 0.00 | 0.00 |
| 16 | 0.25 | 0.21 | **0.54** | 0.00 | 0.00 |
| 17 | 0.04 | 0.11 | 0.43 | **0.36** | 0.07 |
| 18 | 0.00 | 0.00 | **0.25** | 0.71 | 0.00 |
| 19 | 0.00 | 0.04 | **0.86** | 0.07 | 0.04 |
| 20 | 0.04 | 0.21 | **0.75** | 0.00 | 0.00 |
| 21 | 0.04 | 0.21 | 0.11 | **0.50** | 0.11 |
| 22 | 0.00 | **0.18** | 0.14 | 0.07 | 0.61 |
| 23 | 0.07 | 0.04 | **0.50** | 0.36 | 0.00 |
| 24 | 0.61 | 0.04 | 0.11 | **0.18** | 0.07 |
| 25 | **0.79** | 0.00 | 0.21 | 0.00 | 0.00 |
| 26 | 0.21 | 0.36 | 0.00 | **0.39** | 0.04 |
| 27 | 0.07 | **0.54** | 0.11 | 0.25 | 0.00 |
| 28 | 0.50 | 0.04 | 0.32 | **0.14** | 0.00 |
| 29 | 0.29 | **0.11** | 0.18 | 0.25 | 0.14 |

*Note:* The correct answers are shown in bold.

### 4.2.1 Question 2

Question 2 targets two misconceptions. The first misconception is that the battery supplies constant current regardless of circuit configuration and the second is that current is consumed. The question is shown in figure 4.19 and the correct answer for this question is B. If the student views the battery as a source of constant current, then the power delivered to resistor A should not be affected by any changes to the circuit and the student will select answer A. Answer C does not discriminate between students who are using the battery as a constant current source conception or a consumption model using conventional current.

2) **How does the power delivered to resistor A change when resistor B is added as shown in circuits 1 and 2 respectively?**

**(A) Increases**
**(B) Decreases**
**(C) Stays the same**

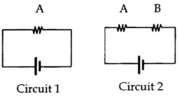



Figure 4.19. DIRECT 1.0 question 2.

The correct AVOW diagram for question 2 is shown in figure 4.20. In this diagram the slopes of the diagonals of each resistor are the same to indicate that the resistances of each resistor are the same. The area of each resistor indicates the power used by each resistor.

The fraction of students from the study group that answered this question correctly was 0.64 and two students from the study group were interviewed about this question.

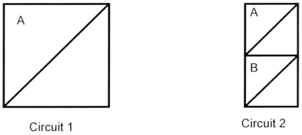



Figure 4.20. Correct AVOW diagram for resistors in series.

Christine's answer to this question was C. While this response could indicate sequential reasoning—where it is believed that changes occurring later in the current stream do not affect elements earlier in the current stream—her correct answer to question 8 did not indicate that she maintained this conception. In her interview, Christine drew AVOW diagrams with resistors correctly in series but the resistances of the resistors in her second diagram were not equal to the resistors in the first. Christine's drawing is shown in figure 4.21.

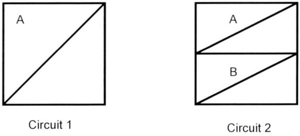



Figure 4.21. Christine's AVOW diagram for two resistors in series.

Christine's diagram was consistent with a battery that supplied constant current. Christine was then reminded that the instructions indicated that the resistances for each resistor should be the same. I asked her if the resistance of the resistor in her first diagram was the same as the resistances in her second diagram. She was able to recognize that they were different but she was unable to correct her diagram. She suggested lowering the dividing line between resistor A and B in order to increase the steepness of the resistance of resistor A. It was pointed out that this would further decrease the resistance of resistor B. I suggested to her that the vertical line on the right side of the diagram could be shifted to the left in order to increase the steepness of both of the diagonals. At this point, Christine was able to draw a more suitable diagram for the second circuit. Once the diagram was drawn, she was able to identify that the current in the second circuit was smaller than the current in the first and that the total power in the second circuit was lower than the power in the first circuit. She was then able to use her diagrams to correctly answer the question.

Like Christine, Jennifer's original answer to this question was also C. In her interview, Jennifer drew the AVOW diagrams for this question with the resistors correctly in series but her diagrams were similar to Christine's in that her diagram for the second circuit had the same width and area as her diagram for the first circuit. As a result, the resistor in the first diagram had a greater resistance than the resistors in the second diagram. Jennifer was not very confident in her abilities to draw AVOW diagrams and she seemed very flustered in her interview. After she drew her first diagram, I asked if all of the resistors had the same resistance and she was able to identify that they did not but when I asked if she could change the diagram to make all of the resistances the same, she suggested that she should have drawn the resistors in parallel. I assured her that the resistors should be in series and that she had drawn her resistors in series.

I asked Jennifer how resistance was shown in AVOW diagrams. She replied that slope represented resistance and when I asked if her slopes were too high or too low, she knew that her slopes were too low. Jennifer was hesitant to attempt a second drawing so I drew the correct diagram for her. Once the diagram was drawn, she easily selected the correct answer. She said that the diagram helped her because "if you remember that power is the area, then you're good."

It is interesting to note that both of these students began their drawings for the second circuit by drawing a rectangle similar to the rectangle that they drew for the first circuit. In teaching this unit, Mr. Burns and I had not demonstrated a process for comparing two similar circuits using AVOW diagrams. Instead, the focus of using AVOW diagrams was to investigate one particular circuit. In all classroom examples of AVOW diagrams, the rectangle for the entire circuit was drawn first and then divided according to the arrangements of the resistors in the circuit and this seems to be the approach used by the students in their interviews.

### 4.2.2 Question 5

Question 5 is shown in Figure 4.22. This question tests if the student knows that adding a resistor in series increases the overall resistance and adding a resistor in parallel decreases the overall resistance. Remembering and applying Kirchhoff's Laws allows students to answer this question.

5) **Compare the resistance of branch 1 with that of branch 2. A branch is a section of a circuit. Which has the least resistance?**

(A) Branch 1
(B) Branch 2
(C) Neither, they are the same

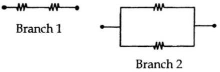



Figure 4.22. DIRECT 1.0 question 5.

Answer B is the correct answer but students might select answer C if they believe that two resistors will result in the same resistance regardless of their configuration. The appropriate AVOW diagrams are shown in Figure 4.23 with the equivalent resistance shown for each circuit with a hollow black line.

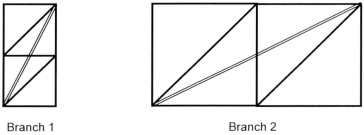



Figure 4.23. Correct AVOW diagrams for DIRECT 1.0 question 5.

The fraction of students from the study group correctly answering this question was 0.64 and four students who had answered this question incorrectly were interviewed.

Lisa's original answer to this question was A. In her interview, Lisa was asked to draw AVOW diagrams for each branch in this question and her sketches are reproduced in figure 4.24.

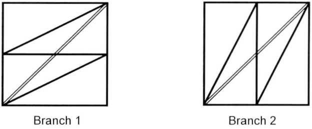



Figure 4.24. Lisa's AVOW diagram for DIRECT 1.0 question 5.

Prior to asking Lisa to draw the AVOW diagrams, she was reminded that all the resistors in this test should be considered to have the same resistance. Lisa correctly drew the branches in series and in parallel but in her drawing, the resistances were not the same. When asked if the resistances of the resistors in the first branch were the same as the resistors in the second branch she said that they were. Since the resistances that she had drawn were not the same, I asked her how resistance was represented in the diagrams. She replied, "The diagonal—oh, they're different but they're the same. You said that they are the same, didn't you?" It was suggested that she try to modify her diagrams so that the slopes for each resistor would be equal but after a few brief attempts, Lisa gave up on her efforts to draw a correct AVOW diagram. I then sketched appropriate diagrams for her without the diagonals that represent overall resistance. She was not able to use the diagrams to determine which would have the lowest overall resistance until I sketched in the diagonal representing total resistance in one of the diagrams.

When I asked about her difficulty in drawing the AVOW diagrams for this question she replied, "I think maybe it was just because this is wider and I just always make them the same box shape versus widening it out or whatever." In their attempts to draw diagrams for question 2, Christine and Jennifer also used diagrams that were the same height-to-width ratio for each diagram.

Randy's original answer to this question was C. However, in the interview when I presented the question to him again, he chose answer A. He was asked to draw diagrams to represent the two branches in the question and when he did, he drew diagrams that were similar to Lisa's and he did not draw diagonals to represent total resistance. The overall shapes for each of his branches were similar to one another but his drawings were quickly sketched and not very neat. As a result, it is unclear if he had intentionally drawn the second branch wider than the first. For both diagrams, Randy, just like Christine, Jennifer, and Lisa, drew the rectangles representing the entire circuit first and then filled in the resistors as required. When Randy was asked which branch would have the lower resistance, he quickly chose Branch 1 even though each of his diagrams had similar shapes. I asked him why he chose that circuit and he said, "Because the slope is less." Since it appeared as though the overall slopes would be about equal, I asked Randy which slope would be less when the diagonals were drawn in. Without drawing any slopes, he changed his answer to say that the total resistance was the same for both branches.

Randy was then reminded that each resistor on the test should have the same resistance and was asked if his diagrams represented this. He agreed that they did not but he was unsure about how to modify his diagrams in order to correct them. I asked if he should make his rectangles taller and he said, "No" but did not make any more attempts to make a correct drawing. When I sketched a correct diagram and Randy confirmed that all of the resistors displayed the same resistance, he was able to correctly identify which branch had the lowest resistance.

Erin's original answer to this question was A. In her interview, the diagrams that she drew did not show resistance diagonals and, like the other students, she drew the outline of her diagrams before filling in the details. Her drawings also did not show resistors with equal resistance. Using her diagrams, she selected answer B but was unable to use her diagrams to demonstrate that the resistances were different. I asked if her diagrams showed equal resistance for each resistor and she replied, "Well, if my diagrams were in proportion they would be. The slopes would be the same." Erin displayed confidence in her reasoning and her ability to draw correctly scaled diagrams for this question.

Tammy's original answer to this question was A. She said that she drew an AVOW diagram for this question when she wrote the test and an inspection of her test paper shows that she drew diagrams on the test paper similar to the ones that were drawn in her interview. The diagrams that she drew were similar to the diagrams drawn by the other students that were interviewed about this question.

In her diagrams, the resistors in Branch 1 had lower resistances than the resistors in Branch 2. Since her resistors in Branch 1 had lower resistances, she concluded that Branch 1 would also have a lower resistance. When she was then reminded that all of the resistors should have the same resistance, she changed her answer to say that the resistances of both branches should be the same.

I asked Tammy if she knew how to use Kirchhoff's rule for resistors in series to find the total resistance. She said, "You add them." Then she said, "So branch 2 is going to be lower, because you do the inverse." I then drew properly scaled diagrams and Tammy confirmed that Branch 2 would have a lower resistance. It is evident from Tammy's interview she confused the total resistance of the branches with the resistances of the individual resistors.

### 4.2.3 Question 6

Question 6, as shown in figure 4.25, tests the concept of potential difference and checks if students know that potential difference across each resistor in a series sums to the total potential difference in the entire circuit.

6) **Rank the potential difference between points 1 and 2, points 3 and 4, and points 4 and 5 in the circuit shown below from highest to lowest.**

**(A) 1 and 2; 3 and 4; 4 and 5**
**(B) 1 and 2; 4 and 5; 3 and 4**
**(C) 3 and 4; 4 and 5; 1 and 2**
**(D) 3 and 4 = 4 and 5; 1 and 2**
**(E) 1 and 2; 3 and 4 = 4 and 5**

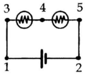



Figure 4.25. DIRECT 1.0 question 6.

The correct answer for this question is E. Answers A and B might be chosen if a student believes that the first element in a circuit removes more voltage than subsequent elements in the circuit. Answer A would be chosen by a student using sequential reasoning with conventional current and Answer B would be chosen by a student using sequential reasoning with electron flow. Answer D is the reverse of the correct answer with the potential differences ranked from lowest to highest.

The correct AVOW diagram for this question is given in figure 4.26. The fraction of students from the study group answering this question correctly was 0.43 and four students who had answered this question incorrectly were interviewed.

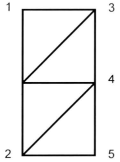



Figure 4.26. AVOW diagram for DIRECT 1.0 question 6.

Larry's original answer to question 6 was A. Larry was able to correctly draw an AVOW diagram for this question. When asked about this question, Larry was confused as to why the number 4 was listed twice. He did not realize that he was looking at the potential difference between points 3 and 4, and points 4 and 5. Once Larry understood the question, he quickly reasoned out the correct rankings of the potential differences. He was, however, unable to select the correct answer from the list of answers provided due to a difficulty in interpreting the multiple-choice answers as presented.

Christine's original answer to question 6 was D. Christine was able to correctly draw an AVOW diagram for this question. When prompted, she was able to correctly label points 1 through 5. She correctly identified the potential difference between points 1 and 2 as being the largest and between 3 and 4, and 4 and 5 as being equal to each other and smaller than between points 1 and 2. Like Larry, Christine also had difficulty interpreting the multiple-choice answers.

Randy's original answer to question 6 was D. Randy was able to correctly draw an AVOW diagram for this question and when prompted, he was able to label it correctly. He had no difficulty in correctly indicating the ranking of the potential differences between the labeled points. Randy claimed to have no difficulty interpreting the multiple-choice answers.

Jennifer's original answer to question 6 was A. Since she had displayed reluctance to draw a diagram for a previous interview question, I sketched a diagram for this question for her. Once the drawing was complete, she was able to correctly identify which parts of the diagram represented the potential difference between the given points and to rank them accordingly.

### 4.2.4 Question 14

Question 14, as shown in Figure 4.27, is like question 5 in that it tests students' knowledge of how the arrangement of resistors affects the overall resistance of a section of a circuit. The correct answer for this question is B but students will choose Answer A if they reason that an additional resistor in the circuit will increase the total resistance regardless of the configuration of the resistors.

**14) How does the resistance between the endpoints change when the switch is closed?**

**(A) Increases**
**(B) Decreases**
**(C) Stays the same**

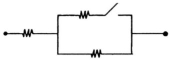


Figure 4.27. DIRECT 1.0 question 14.

The fraction of students from the study group answering this question correctly was 0.54 and two students who had answered the question incorrectly were interviewed. The AVOW diagrams that illustrate the circuit with the switch open and with the switch closed are shown in Figure 4.28. The hollow line shows the equivalent resistance for each example of the circuit.

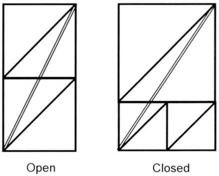



Figure 4.28. Correct AVOW diagram for DIRECT 1.0 question 14.

Christine's original answer to this question was C. Christine had a great deal of difficulty drawing the AVOW diagrams for this circuit. When she was unable to start a diagram, she was asked if the resistors in the diagram with the open switch were in parallel or in series. She incorrectly identified the resistors in the open circuit as being in parallel but once she realized that they were in series she was able to draw the AVOW diagram. She was then able to draw the AVOW diagram for the closed circuit but the resistances for each resistor were not all equal. It is not clear if her drawing of the circuit with the closed switch was intentionally or accidentally correct. Once the drawings were complete, she was able to infer that the total resistance decreased but she was not confident about her answers to this question.

Randy's original answer to this question was A. Randy easily drew AVOW diagrams for both the open and closed switches but the resistances of his resistors were not the same. When Randy was questioned about the unequal resistors, he said that they were equal. When I pointed out that the slopes were not the same, he maintained that the resistances were equal anyway. This was taken as an indication that Randy was not interested in continuing the interview so the point was not pressed.

### 4.2.5 Question 15

Question 15 tests students' conceptions about potential difference in parallel and series circuits. The question is shown in figure 4.29. The correct answer for this question is C and the appropriate AVOW diagram with bulb A as part of the circuit and with bulb A removed are shown in figure 4.30. The fraction of students answering this question correctly was 0.71.

**15) What happens to the potential difference between points 1 and 2 if bulb A is removed?**

**(A) Increases**
**(B) Decreases**
**(C) Stays the same**

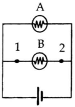



Figure 4.29. DIRECT 1.0 question 15.

The three students that I chose to interview about this question were selected because they had answered it incorrectly. However, in all of the interviews, they recognized their error before the use of AVOW diagrams could be prompted. Kerry was unable to answer the question because he did not realize that potential difference and voltage are synonymous. Once he understood the question, he quickly answered it correctly.

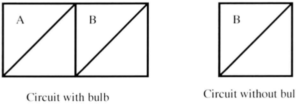



Figure 4.30. Correct AVOW diagram for DIRECT 1.0 question 15.

Jason's original answer to this question was A. In the interview, Jason read this question and then repeated his original answer of A. The following is the transcript from the interview about this question. My part of the interview is in bold.

**What is another word for potential difference?**

Voltage.

**Okay, let's assume that the battery supplies 12 volts,**

Yes.

**How many volts is bulb B removing?**

Oh, 12.

**And A?**

12.

**And if we take A out?**

It would still be 12.

**So do you want to change your answer?**

Yes.

**Why is it easier if we put numbers in there?**

For like, potential difference?

**Yes.**

I don't know. Easier to understand? You can tell where it's going to.

Larry's original answer to this question was A. When Larry was shown this question, he recalled that he had selected A but immediately recognized his error. The following is the transcript of the interview for this question and my part of the interview is shown in bold.

I picked A didn't I? Because they stay the same because they are in parallel.

**Yup. So what were you thinking when you first put it down?**

More power to B because A is out of there.

### 4.2.6 Question 17

Question 17, as shown in figure 4.31 tests how students conceive of current. The correct answer for this question is D. Answers A, B, and C could be selected if the student was using a current consumption conception. Answer E might be chosen if the student confuses current with voltage. The AVOW diagram for this circuit is shown in figure 4.32.

**17) Rank the currents at points 1, 2, 3, 4, 5, and 6 from highest to lowest.**

**(A) 5, 1, 3, 2, 4, 6**
**(B) 5, 3, 1, 4, 2, 6**
**(C) 5 = 6, 3 = 4, 1 = 2**
**(D) 5 = 6, 1 = 2 = 3 = 4**
**(E) 1 = 2 = 3 = 4 = 5 = 6**

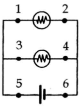



Figure 4.31. DIRECT 1.0 question 17.

The fraction of students answering this question correctly was 0.36 and two students who had answered this question incorrectly and one who had answered correctly were interviewed about this question.

Jennifer's original answer to this question was B. Jennifer admitted that the multiple-choice responses to these questions were difficult to understand. I clarified the question by pointing out that we were looking for the current at each of the six points identified in the diagram. Jennifer at first suggested that the currents were all the same and then quickly corrected herself by saying, "No wait, that's in series, never mind. They are not the same."

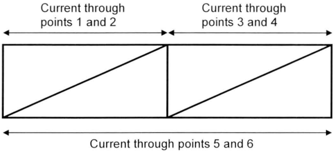



Figure 4.32: Correct AVOW diagram for DIRECT 1.0 question 17.

I asked Jennifer to draw an AVOW diagram for this circuit. She identified that the resistors were in parallel but balked at making a drawing. I drew a diagram for her and she agreed that it represented two resistors in parallel. Once the drawing was made, she was able to identify which dimensions represented the current through each resistor and through the entire circuit. Using the diagram, Jennifer was correctly able to rank the order of the current through each resistor and through the entire circuit. She said that the diagram was helpful in answering this question once it had been drawn.

Lisa's original answer to this question was E. Lisa was easily able to draw an AVOW diagram for this circuit and label the current flowing through each bulb. Based on this drawing, she was able to correctly rank the order of current through each point. Lisa admitted that she first chose E because she thought that all of the currents would be the same but when she changed her answer, she was not certain if C or D represented her ranking. She said that she found the format of the multiple-choice answers to be confusing.

Brad originally answered this question correctly. Brad was easily able to draw an AVOW diagram for this circuit but he concluded that it would be difficult to label the points 1 through 6 on the diagram. Brad correctly justified his answer to this question without using the diagram but was able to demonstrate how the diagram could be used to illustrate the answer.

### 4.2.7 Question 21

This question tests if students understand how resistors in series affect the power used by the circuit. Question 21 is shown in figure 4.33 and the correct answer is D. Answers B and C might be selected if the student is using a current consumption conception and answer E would be selected if a student did not believe that the arrangement of the resistors had any effect at all on the behaviour of the circuit.

**21) Compare the energy delivered per second to the light bulb in circuit 1 with the energy delivered per second to the light bulbs in circuit 2. Which bulb or bulbs have the least energy delivered to it per second?**

(A) A
(B) B
(C) C
(D) B = C
(E) A = B = C

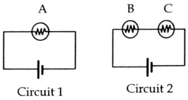



Figure 4.33. DIRECT 1.0 question 21.

The correct AVOW diagrams for each circuit is shown in figure 4.34. The fraction of students answering this question correctly was 0.54. Only one student was interviewed about this question due to an error that I made in assigning interview questions. Once the error was discovered, I was unable to recruit any more interview volunteers.

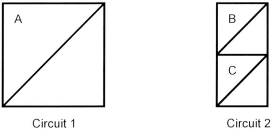



Figure 4.34. Correct AVOW diagram for DIRECT 1.0 question 21.

Tammy's original answer to this question was B. Tammy was able to draw the AVOW diagrams for this question but was unable to use the diagram to answer the question. I asked her if the energy delivered to a bulb was related to any of the dimensions of an AVOW diagram. She suggested that energy was related to voltage and cited the formula $V=\Delta E/q$. This formula is used to calculate the potential difference between two charged plates. I suggested that that formula might not be useful in this context. I reminded her that energy could be found by multiplying power by time ($E=Pt$), and that we could modify the question to ask which bulb has the least power. Once this modification was made, Tammy quickly decided that bulbs B and C would receive less power than bulb A. Tammy suggested that the question would have been easy if it had asked for the bulb with the most *power*.

### 4.2.8 Question 26

This question is designed to test students' conception of both conservation of current and potential difference in a series circuit. The question is shown in Figure 4.35. The correct answer is D. Choosing A or B implies a current consumption conception. Answer C suggests that current is shared among the elements of a circuit and if the resistance of resistor C is increased then its reduction in current will be taken up by the two bulbs. Answer E suggests that one element of a circuit will not have an effect on any other elements in that circuit.

**26) If you increase the resistance C, what happens to the brightness of bulbs A and B?**

**(A) A stays the same, B dims**
**(B) A dims, B stays the same**
**(C) A and B increase**
**(D) A and B decrease**
**(E) A and B remain the same**

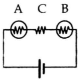



Figure 4.35. DIRECT 1.0 question 26.

The correct AVOW diagrams for the circuit before and after the resistance of C is increased are shown in Figure 4.36. The fraction of students answering this question correctly was 0.39 and four students were interviewed about this question.

Erin's original answer to this question was B. Erin drew an AVOW diagram for the circuit and when asked how she could use the diagram to answer the question, she stated that she could redraw the diagram with different proportions. She then drew a modified AVOW diagram. I asked her what would happen to bulbs B and C. Her response was, "The power would decrease so they would probably be dimmer."

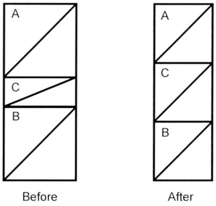



Figure 4.36. Correct AVOW diagram for DIRECT 1.0 question 26.

I asked Erin about her original answer to the question where she said that only bulb A would dim. She replied "I think that the way I was thinking about it, it was not logical in the slightest from what we learned but that this would still have the same amount of power before it hits this, therefore that one would have less." She said that after using the AVOW diagrams she could see that her original answer was "totally wrong."

Larry's original answer to this question was A. Before drawing an AVOW diagram, Larry asked if he could treat the light bulbs and the resistor the same. I replied that the resistances of each light bulb were equal but that the value of the resistor was going to change. Larry decided that he was going to draw the resistance for C larger than for the bulbs. Once the drawing was complete, I asked him what would happen to the brightness of A and B if the resistance of C was increased. Larry did not draw a second diagram. Instead, he immediately replied that they would get dimmer. When questioned about his original answer, he said, "I know exactly what I thought. I thought this would hit the volts first and it would still get its normal amount. I was thinking in volts instead of resistance, instead of ohms." He then admitted that he had not used an AVOW diagram in his initial attempt to answer the question.

Lisa's original answer to this question was B. Lisa was able to draw and label an AVOW diagram for the circuit before the resistance of the resistor was increased but she did not include the diagonal lines to represent resistance. I asked her what would happen to the bulbs when the resistance of C was increased and she said that they would get brighter. I asked her to draw the diagonals to represent resistance and after doing so, she expressed surprise at her realization that the bulbs would get dimmer. She was able to draw a second AVOW diagram to justify her answer. When I asked her about her original answer she said, "I don't know why I said that. Maybe because I thought that since A would, like, the same amount of, I don't know, current would go through all of them, the same amount of voltage, go through A but then more would go through C so there is less to go through B and then I confused it and said that it would get brighter, or something."

Jason originally incorrectly answered this question as B. He was able to draw the AVOW diagram for this question and once the diagram was drawn he was able to determine the correct answer. I asked him if this was the same as his original answer and he said that he remembered it to be the same answer.

### 4.2.9 Question 29

Question 29 tests students' conceptions of potential difference and power in series and parallel circuits. This question is shown in figure 4.37 and the correct answer is B.

Selecting answer A suggests that students are reasoning both sequentially and with a battery that supplies constant current. Sequential reasoning implies that since the switch is past bulb A, it will have no effect on the bulb. If the battery provides a constant source of current, then closing the switch causes bulbs B and C to share the current and as a result, bulb B dims.

**29) What happens to the brightness of bulbs A and B when the switch is closed?**

**(A) A stays the same, B dims**
**(B) A brighter, B dims**
**(C) A and B increase**
**(D) A and B decrease**
**(E) A and B remain the same**

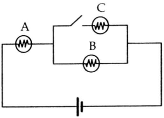



Figure 4.37. DIRECT 1.0 question 29.

Selecting answer D suggests that students are using a constant current model where current will be shared between three bulbs instead of two. This will result in bulbs A and B becoming dimmer.

To select answer E, students might reason that since bulbs B and C are in parallel, they should be the same brightness. If they were the only bulbs in the circuit, closing the switch would not cause bulb B to change in brightness. Thus, if bulb B does not change, then neither should bulb A.

The correct answer for this question is B and it is best illustrated with the AVOW diagram for the open and closed version of the circuit as shown in figure 4.38. The fraction of students answering this question correctly was 0.15 and three students who had answered incorrectly were interviewed about this question.

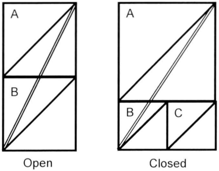



Figure 4.38. Correct AVOW diagram for DIRECT 1.0 question 29.

Jason's original answer to this question was D. Jason was able to draw an AVOW diagram for this circuit but the resistances for the bulbs were not the same. When I asked him to visualize what would happen when the switch was closed, he correctly reasoned that the area of bulb A would increase and he suggested that the area of B would also increase. When I asked Jason to justify his answer, he suggested that the area of bulb B might remain the same. At this point I suggested that he try to draw an AVOW diagram with resistances for all three bulbs being equal.

Jason attempted to draw a new diagram but he was unsuccessful so I drew one for him. When looking at the diagram, Jason first suggested that bulb A would still have the same area in the first diagram as in the second but then he agreed that the area for bulb A had increased and that the area for bulb B had decreased.

Brad's original answer to this question was A. Brad drew two AVOW diagrams but in the second diagram, the resistances of bulbs B and C were not the same as bulb A. I asked him if he could modify his diagram to correct this but was unable to achieve the correct proportions. I suggested that he draw a third diagram and he was able to draw a sufficiently accurate diagram. Once this diagram was drawn, Brad was able to determine the correct answer to this question.

Erin's original answer to this question was B. Erin was one of only three students in this study group to correctly answer this question. I asked if she had sketched an AVOW diagram when she had written the test and she said that she had not and that she simply thought about the question in the same way that she had thought about question # 14. When I asked her to draw an AVOW diagram for this question she was easily able to do so.

Kerry originally answered C to this question. In his interview about this question, Kerry was unable to draw the correct AVOW diagram but was able to correctly answer the question once I drew the diagram for him. It took me two attempts to draw a correct diagram for Kerry in his interview and this caused him to remark, "See, that's the problem with the AVOW diagram right there! It's like a guess and check thing" but later in his interview he conceded "That's a good way of doing it." At one point in his interview Kerry expressed a preference for quantitative solutions to circuit problems but he also said that AVOW diagrams were useful because it was easier to remember how to draw a picture than it was to remember formulas.

### 4.3 Teacher Observations

Mr. Burns and I have taught DC circuits to grade 12 students for a combined total of sixteen years. The benefits and limitations of incorporating the AVOW diagrams into the unit were discussed and the decision was made to use the diagrams and to evaluate their use. The observations and interpretations made with respect to AVOW diagrams were made against a backdrop of years of teaching experience.

#### 4.3.1 Impressions of AVOW Diagrams

When I first began to use AVOW diagrams, I was pleased to discover the completeness of the analogy. All of the relations that were required to describe the attributes of a simple DC circuit were present graphically and when any dimension changed, the impact of that change could be seen on the other dimensions. I found that in order to explain these diagrams to others, I had to build the analogy step by step so that the utility of the diagrams could be understood. A basic knowledge of circuits, including the concept of current, voltage, resistance, and power was required before using these diagrams.

While observing Mr. Burns' use of the diagrams in his teaching, I found that he was able to quickly illustrate to his students and discuss with his students how the attributes of DC circuits are related. For example, he could ask what would happen to current if the voltage were increased, or what would happen to the power if the resistance were decreased. While this can be done algebraically or numerically, the diagrams provided a natural and fluid means to justify and illustrate the behaviour of a circuit.

Mr. Burns' initial reaction to the use of the diagrams was somewhat skeptical. In our school and in provincial assessments, questions about circuits are often quantitative in nature and his students traditionally were very successful with these assessments. While preparing the unit for the incorporation of AVOW diagrams, Mr. Burns shared my enthusiasm for the completeness of the diagrams and felt that they would be a good addition to his teaching of circuits. This belief continued as he progressed through the unit and he concluded that he would in all likelihood continue to use the diagrams in his teaching.

### 4.3.2 Suggested Modifications and Future Use of AVOW Diagrams

Interviews with students identified a number of difficulties that occurred when using AVOW diagrams. Students often failed to make use of an AVOW diagram unless prompted, students had difficulty drawing AVOW diagrams with consistent resistances for resistors, and students had difficulty drawing AVOW diagrams to reflect a circuit before and after a change had been made.

Conceptual change theory suggests that in order for students to make use of a new concept, they must discover the utility of the concept. In this unit, students made use of AVOW diagrams to solve DC circuits but they were not presented with many questions similar to the ones found on the DIRECT 1.0 test. It is possible that if students are exposed to more qualitative assessments and are taught to invoke the AVOW analogy, that they would make better use of the diagrams in those situations.

It is possible, with practice, to improve the mechanics of drawing AVOW diagrams but drawing diagrams with constant slopes remains challenging, particularly when attempting to draw before and after diagrams to represent changes in a circuit. One could make use of triangles from a geometry set to maintain constant slopes and it is possible to use computer draw programs to make the diagrams, but adding tools might detract from the quick and intuitive use of these diagrams. The strategy that I have found that works best for me is to make a preliminary sketch and then make a second sketch that corrects the problems with the preliminary one.

Before these diagrams could be adopted as a general strategy for teaching electric circuits, these concerns need to be addressed but they do not seem to be insurmountable. I would caution against any approach that makes the use of the diagrams rigid or contrived. The diagrams are a tool for understanding circuits and students should use them because they find them helpful, not because the teacher requires their use. Exact proportions are not necessary to communicate important relationships as long as students and teachers maintain an appreciation of the limitations of their drawing abilities.

A final modification that I would suggest would be to create an animated display that allows AVOW diagrams to be manipulated by students and teachers in real time. Use of such a display could help develop important visualization skills.

### 4.4 Summary

The use of AVOW diagrams was easily incorporated into a unit on DC circuits. The diagrams were used as a tool to illustrate and discuss the relationships among the parameters of a circuit. The diagrams did not replace any alternative presentations that would have been otherwise used in the unit and the incorporation of the diagrams did not significantly add to the duration of the unit.

The class that used the AVOW diagrams was given a diagnostic test, DIRECT 1.0, and their responses to the test were used as the basis for interviews with students who volunteered to be interviewed about the diagrams and the test.

Students said that the diagrams had been useful in their learning and that they would advocate their continued use. Teachers found that the students were able to understand the diagrams and were interested in using the diagrams to discuss and explore the attributes of DC circuits.

# Chapter 5: Conclusions

This chapter will use the data presented in chapter 4 to address the research questions. Each research question will be addressed individually and then recommendations about the further use of AVOW diagrams will be presented and suggestions for further study will be made.

## 5.1 How Can the AVOW Diagram Analogy Be Used to Teach About DC Circuits in the Context of a Typical Classroom?

Cohen, Eylon, and Ganiel (1983) encouraged investigation of "methods designed to develop the understanding of functional relationships between the variables that characterize electric circuits" (p. 412). Three issues that they describe are:

- Students using complicated and poorly understood algorithms for solving DC circuits quantitatively.
- Students are unable to reason about circuits qualitatively.
- Student reasoning that focuses on current rather than voltage.

AVOW diagrams can be a way of organizing quantitative data about circuits in a way that helps students to organize their quantitative problem solving strategies. The diagrams also provide students with a qualitative model of the circuit that allows them to predict how changes in one parameter will affect the others. Finally, the structure of the diagrams themselves requires that students focus on voltage at least as much as current. This research project indicates that it is possible to successfully use AVOW diagrams in conjunction with other methods to teach students about DC circuits and to address these three concerns. This section will focus on the practical use of AVOW diagrams and the empirical support for the use of the AVOW diagram analogy.

### 5.1.1 Teacher Preparation and Presentation

In order to successfully use AVOW diagrams, the teacher needs to be familiar with DC circuits. While AVOW diagrams provide a way of thinking about the relationships between the parameters of a DC circuit, they do not provide explanations for those relationships. If teachers do not have proper conceptions of electricity, it is unlikely that their students will develop them. Teachers need to understand how AVOW diagrams work. In this project, Mr. Burns learned how to use the diagrams very quickly. It is reasonable to expect that other teachers will be able to learn how to use them in a similar time. Furthermore, teachers must have a plan for incorporating the diagrams into their lessons.

While there are many ways to approach the topic of DC circuits, a typical direct instruction presentation can be divided into four stages. In the first stage, the parameters of a DC circuit are explained qualitatively. For example, since lower resistance allows electricity to flow more easily, increasing the resistance will cause less current to flow. As another example, since voltage causes current to flow, increasing the voltage will result in greater current.

In the second stage, mathematical formulas are used to describe the relationships among circuit parameters. Formulas such as Ohm's law: V=IR and P=IV are used by teachers and students to relate voltage, current, power and resistance. Once the basic relationships are understood, the concept of resistors in series and in parallel can then added.

The third stage of teaching DC circuits must address the conceptual differences between parallel and series circuits. Two analogies that are commonly used to explain these situations are the flowing water analogy and the crowded corridor analogy that were described in chapter 2. Gentner and Gentner (1983) described the difficulty associated with using these two analogies—students may generate two different predictions for the same situation depending on which analogy the student chooses to make use of or adopt.

In the final stage, formulas are used to algebraically represent the relationships in complicated circuits that contain multiple resistors in parallel and in series. Students use $V_{total} = V_1 + V_2 + V_3$, $I_{total} = I_1 = I_2 = I_3$, and $R_{total} = R_1 + R_2 + R_3$ to calculate with resistors in series and $V_{total} = V_1 = V_2 = V_3$, $I_{total} = I_1 + I_2 + I_3$, and $\frac{1}{R\ total} = \frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3}$ to calculate with resistors in parallel. Research described in chapter 2 indicates that students are able to use these formulas to quantitatively solve circuits but that they have difficulties reasoning qualitatively about these circuits. Mr. Burns and I have found that Cohen, Eylon, and Ganiel's (1983) observation that students do not understand the algorithms used to solve complicated circuits applies to our students prior to the use of AVOW diagrams.

Mr. Burns used AVOW diagrams in each of these stages. In the first stage, he introduced students to the diagrams by constructing a simple box diagram and related its dimensions to the circuit parameters. He was then able to explore how changing one parameter affected the others. In the second stage, he showed how the formulas P=IV and V=IR can be derived from an AVOW diagram. Using these simple diagrams, his students were able to quickly solve for unknown parameters in single resistor circuits.

When it was time to introduce series and parallel circuits, Mr. Burns drew circuit diagrams in order to describe how current might flow around a circuit with more than one resistor. He was careful to remind the students about the necessity to ensure that current and energy are both conserved. Students were taught that current splits at parallel branches and that the split is in proportion to the resistances of each branch. They were also taught that two resistors in series must each have the same current pass through them. Students were taught that any current path must have a total voltage drop that is equal to the voltage provided by the battery. When students were invited to suggest what an AVOW diagram might look like for parallel and series resistors, it was observed that students were quick to adopt these representations and that they were able to do so without making any significant errors.

In the fourth stage, Mr. Burns used AVOW diagrams with labels to show the values of given parameters to encourage students to decide which values could be calculated next in order to solve the circuit. Based on our experiences as classroom teachers, Mr. Burns and I knew that students are often frustrated at this point in the traditional approach to teaching DC circuits. Students often do not know which steps will lead them to their final answer and they lack the experience required to inform them which parameters can be solved in order to lead them to the final solution. As a result, students get frustrated and they give up. When presented with labeled AVOW diagrams, students could easily see the relationships between different parameters. It is evident from the diagrams, for example, that the voltages across parallel resistors are the same and that the current through series resistors are also the same. They are able to see how the sum of the current through two parallel resistors will equal the current through a resistor that is in series with both. They are also able to see that two resistors that are in series with each other and in parallel to a third resistor will have a sum of voltages that are equal to the voltage across the third resistor. While teachers often easily recall these characteristics of complex circuits and while students are able to understand and explain these characteristics, students still find it difficult to incorporate these characteristics into their problem solving strategies—they often fail to see how they can lead to the final solution. We observed that this difficulty did not present itself when students used labeled AVOW diagrams.

In classroom presentations, Mr. Burns discussed DC circuits qualitatively and students were able to successfully contribute and participate in these discussions. The tests and the quizzes used in this unit, however, did not include many qualitative questions about circuits and there were no test and quiz questions similar to the ones on the DIRECT 1.0 test. Informal assessment indicated that the students were capable of answering qualitative questions but most of the paper-and-pencil assessments for this unit were quantitative in nature. The standardized test that students wrote at the end of the course also emphasized quantitative solutions for circuit problems. The results from the DIRECT 1.0 test indicate that it is likely that students could benefit from the incorporation of more assessment items that require qualitative reasoning. Learning activities and experiences should align with assessment.

### 5.1.2 Use of AVOW Diagrams as an Analogy

The AVOW diagram analogy for DC circuits has been explained in earlier sections. In this project, it is clear that students were able to identify the dimensions of AVOW diagrams that mapped on to parameters of DC circuits and were able to make simple predictions about the effect of changing one of the parameters on the other parameters. All areas of DC circuits that are covered by the curriculum can be described using AVOW diagrams and there are no cases where the analogy does not hold. Gentner's (1982) analogy characteristics of base specificity, clarity, richness, systematicity, scope and validity are easily met by the AVOW diagrams in this context. Base specificity depends on students' understanding of the analogy's base which in this case is the AVOW diagrams. Students demonstrated that they remembered and understood the meanings of the dimensions of the diagrams as well as how the diagrams related to a real circuit. Clarity describes how well the base domain maps onto the target domain. When properly constructed, AVOW diagrams behave in the same way and follow the same rules as DC circuits. An analogy is considered rich if there are a large number of attributes that map from one domain to the other. AVOW diagrams include all of the characteristics of DC circuits that students need to understand in order to successfully complete this teaching unit. Systematicity is achieved when the relationships in both domains are related in the same way. AVOW diagrams are designed in such a way that they are highly systematic. Finally, the scope and validity of an analogy is determined by the different situations for which the analogy holds. AVOW diagrams accurately represent DC circuits for all of the situations studied in this unit.

While most analogies do not fully represent the target domain, AVOW diagrams come very close. Previous analogies used for teaching about DC circuits require the use of one analogy (usually flowing water) to reason about series resistors and another (crowded hallways) to reason about parallel resistors. AVOW diagrams are suitable for both of those contexts, as well as for circuits that combine series and parallel resistors.

Treagust, Harrison, and Venville (1996) found that students sometimes needed to be prompted to make use of analogies that they have learned. Once the analogy was recalled, student performance increased. This finding was supported by this project. In most cases, students who answered questions incorrectly were able to correctly answer the questions once they were either given AVOW diagrams or prompted to draw their own AVOW diagrams. It was disappointing that they did not spontaneously choose to use the diagrams. Students may need to be reminded that questions about circuits are often more complex than they seem and that their attempts to answer these questions without using the careful reasoning fostered by tools like AVOW diagrams will often be wrong. The data from this study suggest that students often do not use analogies because the questions that they are asked appear to be easier to answer than they actually are.

Gabel and Sherwood (1980) suggested that more capable students might not make as much use of analogies as students with less formal reasoning ability. In this project, Brad provided an example of this. In his interview, Brad indicated that he understood how to use AVOW diagrams but he did not habitually use them as his own conceptions almost always led him to the correct answer. Other students in their interviews however, found that they were able to answer questions successfully only after drawing AVOW diagrams.

Duit, Roth, Kormorek, and Wilbers (2001) identified some dangers of using analogies for teaching science. One is that students and teachers may have different conceptions of the base domain. In the flowing water analogy, for example, students may not have a clear understanding of the way that water flows. If this is not addressed, students might draw incorrect conclusions about the target domain. Interviews identified that students were able to read AVOW diagrams to find the qualitative or quantitative values of the different parameters of a circuit. Students could recognize and build diagrams with resistors in series, parallel, and in combination. Students were able to predict how the rest of the parameters would change in response to the change of one parameter. However, while students were easily able to keep track of height, width, and area and how they related to voltage, current, and power, there were difficulties with slope representing resistance. In the diagrams that they drew, students' slopes (resistances) changed when questions stated that they should not. Furthermore, students had difficulty recognizing that the resistance indicated by their diagrams had changed.

## 5.2 How Do Students Use AVOW Diagrams to Reason About DC Circuits?

Students can use a variety of analogies, conceptions, and strategies for reasoning about DC circuits. AVOW diagrams are just one analogy that students can use in their thinking. For students' use of the diagrams to be successful, there are a number of criteria that must be met. They must understand the analogy, they must be able to use the analogy to make predictions about circuits, and they must choose to use the analogy when appropriate. Furthermore, it is important that the use of the diagrams do not lead to inappropriate conceptions. That is, students that use the AVOW diagrams should be able to answer questions about DC circuits at least as well as students who do not use AVOW diagrams.

It was clear that students were able to understand AVOW diagrams that had been drawn for them. In each of the interviews, students were able to recognize AVOW diagram representations of current, voltage, resistance and power although some students needed to be reminded that the slope of the diagonal in an AVOW diagram represented resistance. Students were able to draw diagrams to represent a single circuit but they were sometimes unable to draw appropriate diagrams that compared circuits before and after a parameter had been changed. There was one student that expressed frustration with the qualitative nature of AVOW diagrams. The group of students that were interviewed mirrored the class in ability and achievement. The interview group ranged from a student who rarely made any mistakes on evaluations to one who just met the minimum criteria for passing the course but the bulk of the students were the type that would be expected to be enrolled in an academic science class.

When students were interviewed about questions that they had answered incorrectly on the DIRECT 1.0 test, their incorrect responses indicated that they either did not use AVOW diagrams or that they used AVOW diagrams incorrectly. The interviews recorded nine instances where students were able to draw correct AVOW diagrams when prompted and were then able to correctly answer the question using the diagrams. There were also nine occasions where the students were unsuccessful in drawing a diagram but once the diagram was drawn, they were able to use the diagram to answer the question correctly. There were three situations where students were unable to draw the diagram and even when the diagram was drawn, were unable to determine the correct answer.

This result implies that students would have done better on this test if they had spontaneously used AVOW diagrams. It was observed that the primary difficulty that students had when drawing diagrams was maintaining constant resistances for their resistors. This could be due to the fact that they generally drew the box for the total circuit first and then fit the resistors inside the box. Mr. Burns and I did not have the same difficulty in drawing the diagrams but it is not clear if this difference between teachers and students is because we had more practice in drawing the diagrams or if there is some other more fundamental difference between our use of the diagrams.

### 5.3 How Do Students Use AVOW Diagrams Within the Context of Conceptual Change?

Posner, Strike, Hewson, and Gertzog (1982) said that conceptual change occurs when students experience dissatisfaction with their current conception and are presented with an alternative conception that is intelligible, plausible, and fruitful. Since all of the students in this class were able to understand and use AVOW diagrams to solve DC circuits, it can be concluded that they found the diagrams to be intelligible and plausible. In her interview Tammy said, "Well, it's so much to just remember and memorize and how things are related to each other. Just draw a diagram and it makes it easier." This indicates that she found the AVOW diagrams to be fruitful as well.

Tao and Gunstone (1999) showed that students who hold alternative conceptions might change those conceptions when faced with conceptual conflict in one context but that they may revert to their original conception in another context. In this study, Erin provides an example of this. Even though she was very comfortable in her use of AVOW diagrams, it was revealed in her interview that she did not use the diagrams to reason about one of the questions that she had been unable to answer correctly. Once she was prompted to use the diagrams, she was able to determine the correct answer. This situation was repeated in several of the interviews but a way of encouraging students to use AVOW diagrams by their own choice was not uncovered in this research project. One method of encouragement that I would try in the future would be to require that students sketch an AVOW diagram of the circuit before attempting to find a solution. Careful attention to the details of a question at the onset of the solution should reveal the complexities that students consistently overlook.

Conceptual change seems to be a gradual process (Tao & Gunstone, 1999; Vosniadou et al., 2001; Vosniadou, 2003) with the new conception gaining status as it repeatedly proves to be superior to prior conceptions. Unfortunately, status did not seem to lead to utilization. While students never demonstrated that they doubted the results suggested to them by AVOW diagrams, they still tried to use other conceptions unless they were prompted to use the diagrams. Students eventually developed sufficient skill in solving quantitative problems that they no longer needed AVOW diagrams to develop their problem solving strategy. Qualitative problems were not posed as often as quantitative ones and students were never formally required to use AVOW diagrams to explain their answers to qualitative problems. As a result, students did not often spontaneously use AVOW diagrams for the type of qualitative problems posed in the DIRECT 1.0 test.

Limon (2001) and Mason (2001) suggested that conceptual change does not have to be prompted only by anomalous data but might also be encouraged by the use of analogies, metaphors, and discussion. It has been observed in this study that AVOW diagrams facilitate a greater amount of discussion about circuits than a more quantitative approach. When she was asked in her interview about using AVOW diagrams, Erin said, "they were pretty easy once you got the hang of it, once you realized how everything worked, then yeah they were a lot easier to check your answers and make sure that everything worked the way that you thought it was going to." The AVOW diagram analogy appears to be a useful way to think and reason about DC circuits.

Limon (2001) also said that conceptual change might be confounded when students do not recognize that they are presented with data that is in conflict with their conceptions. Several times in their interviews, students were surprised when their reasoning was shown to be incorrect once they had drawn an AVOW diagram. In Erin's interview about question 26, she indicated that she had reasoned sequentially but as soon as she had drawn an AVOW diagram, she recognized that she had been "totally wrong."

Cobern (1994) found that the complete replacement of old conceptions with new ones to be an unrealistic goal. The results of this project indicate that even though students have access to a conception that they know is very useful, they do not always choose to use that conception. It was not clear why students did not choose to always use the AVOW diagrams. Perhaps the diagrams would be used more if they were shown in questions on formal assessments and if there were a greater emphasis placed on qualitative rather than quantitative problems.

### 5.4 Recommendations for the Further Use of AVOW Diagrams

The use of AVOW diagrams should be an integral part of the teaching of this unit. The instructional sequence described in this investigation successfully incorporated AVOW diagrams from the very start of the unit. It is not clear what would happen if teachers tried to superficially tack on AVOW diagrams to their usual approach to teaching circuits. Mr. Burns referred to AVOW diagrams each time he worked through an example in his notes and lessons.

Emphasis should be placed on qualitative rather than quantitative questions about circuits in both lessons and assessments. Students have difficulties reasoning qualitatively and assessing their ability to do so will encourage the use of AVOW diagrams over the use of formulas and calculations. Included in this recommendation would be setting aside time to practice drawing AVOW diagrams for questions similar to the ones found on the DIRECT 1.0 test.

Students should be encouraged to think about how they think about circuits. Identifying when students are using misconceptions and drawing attention to their use of misconceptions should make them more aware of the way that they sometimes make incorrect assumptions. This greater awareness should lead to an increased use of correct conceptions.

### 5.5 Suggestions for Future Study

One question that arose again and again in my mind as I studied my results was why students failed to use AVOW diagrams in situations where they would have been useful. Students were willing to use them when they were prompted but they rarely chose to use the diagrams on their own. Attempting to answer this question could be a fruitful area of inquiry.

Another area of inquiry could be the use of AVOW diagrams with younger students. Circuits are introduced to students in grade 6 and studied again in grade 9. At both of these levels, students are exposed to the concepts of voltage, current, resistance, and power as well as series and parallel circuits. Since students at this level do not quantitatively analyze the circuits, AVOW diagrams could provide an effective way for students and teachers to discuss the way that the circuit parameters influence each other.

A third area for further study would be to attempt to perform a follow up study with a group of students who had been taught to use AVOW diagrams. Since the literature shows that students often revert to previous conceptions, it would be interesting to see if students are able to retain and spontaneously use the AVOW diagram analogy to reason about DC circuits.

### 5.6 Summary

This study set out to investigate what happens when a new way of representing DC circuits is introduced to a physics class. It is evident that AVOW diagrams can be successfully used as one way to teach about DC circuits. The diagrams did not introduce any difficulties to the teaching of this unit and many students found them to be particularly useful. It was also evident that the diagrams do not rectify all of the difficulties that arise when students learn about electricity, though no approach could be expected to do so.

Many of the obstacles to learning about electricity described in the literature were also found in this study. The students in this study exhibited the conceptions that had been previously identified and their reaction to Mr. Burns' attempts to help them embrace scientifically acceptable conceptions was in line with what had been previously reported. While AVOW diagrams alone are not the answer to the challenge of teaching DC circuits, it has proven to be a valuable addition to the approaches available to teachers.

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## Appendix A

There are many analogies that are used to teach students about DC circuits. Cheng and Shipstone (2003a) developed AVOW diagrams as a law-encoding diagram that captures all of the relevant relationships between current (amperes), potential difference (volts), resistance (ohms), and power (watts) in a DC circuit. The diagram provides an analogy that students can use to think about DC circuits. In addition to correctly illustrating the relationships among the parameters of a DC circuit, it is impossible to represent the most common student misconceptions of electricity. The simplest AVOW diagram consists of a rectangle that represents the load on a DC circuit. The load can be either a light bulb or a resistor but not other circuit elements such as capacitors or transistors. The width of the rectangle represents the current through the circuit and the height of the rectangle represents the potential difference across the circuit. The power used by a circuit can be calculated by determining the product of the current and the voltage ( $P = IV$ ). With respect to the AVOW diagram, this means that the power used by the circuit is represented by the area of the rectangle.

Ohm's law states that the current flowing through a circuit is proportional to the voltage across the circuit and inversely proportional to the resistance of the circuit. Ohm's law is expressed mathematically as $V = IR$. This formula can be rearranged to the form: $R = \frac{V}{I}$ and this expression can be used to determine the slope of the diagonal of the rectangle that represents the circuit as shown in figure A1.

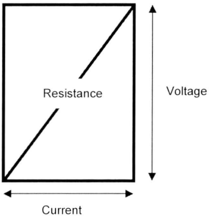



Figure A1. AVOW diagram of a circuit with one resistor.

Generally, wires are assumed to have no resistance in most physics problems and thus, if represented in an AVOW diagram, would have no height and it would not be possible to include them in the diagram. As a result, the box shown in figure A1 can be assumed to represent one resistor or bulb in a DC circuit. A conventional schematic for such a circuit is shown in figure A2.

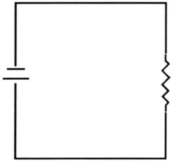


Figure A2. A schematic diagram of a DC circuit with one resistor.

A mapping of the analog (AVOW diagram) and the target (DC circuit) is given in figure A3.

| **AVOW Diagram** (Analog) | | **DC circuit** (Target) |
|---|---|---|
| Rectangle | compared with | Load in circuit |
| Width of rectangle | compared with | Current through circuit |
| Height of rectangle | compared with | Voltage across circuit |
| Area of rectangle | compared with | Power used by circuit |
| Slope of diagonal of rectangle | compared with | Resistance of circuit |

Figure A3. Mapping relations between AVOW diagrams and DC circuits.

A simple circuit with two resistors in series and its AVOW diagram representation are shown in figure A4 and a circuit with two parallel resistors is shown in figure A5.

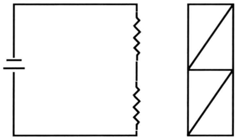


Figure A4. A DC series circuit and the AVOW diagram for the circuit.

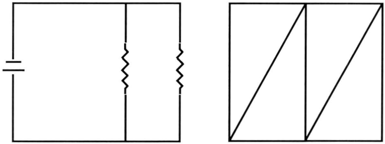


Figure A5. A parallel DC circuit and its AVOW diagram.

One condition that must be met when combining rectangles in an AVOW diagram is that the complete diagram must be rectangular and have no gaps. Thus the diagrams in figure A6 would not be acceptable diagrams.

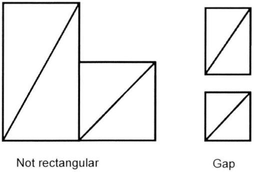



Figure A6. Incorrect AVOW diagrams.

When AVOW diagrams are used to represent DC circuits with more than one resistor, several additional features of the analog can be mapped onto the target. The mapping relationships are shown in figure A7.

| **AVOW Diagram** (Analog) | | **DC circuit** (Target) |
|---|---|---|
| Rectangle | compared with | Resistor in circuit |
| Constant width of each rectangle | compared with | Current that flows into the resistor is equal to the current that flows out of the resistor. |
| Stacked rectangles for resistors in series | compared with | The current through the first resistor is the same current that flows through the second resistor and the total resistance of resistors in series is greater than the resistance of the individual resistors. |
| Side by side rectangles for resistors in parallel | compared with | The voltages across each resistor in parallel are equal and the total resistance of resistors on parallel is less than the resistance of the individual resistors. |
| Combined area of rectangles | compared with | Total power used by the circuit. |

Figure A7. Mapping relationships for circuits with multiple resistors.

AVOW diagrams model DC circuits in such a way that they are not compatible with most of the common misconceptions that students hold about electricity. These misconceptions include current attenuation models, local reasoning and sequential reasoning.

One form of an attenuation model suggests that bulbs in series will consume current and that the bulbs later in the series will be dimmer than earlier bulbs. This is shown in figure A8.

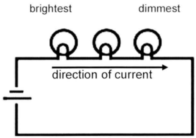



Figure A8. Attenuation model of light bulbs in series.

The brightness of a bulb is proportional to the power used by the bulb, therefore, the brightness of the bulb can be modeled by the area of a rectangle in an AVOW diagram. figure A9 shows the correct AVOW diagram for this circuit and the two AVOW diagrams that could explain the decreased brightness of each subsequent bulb.

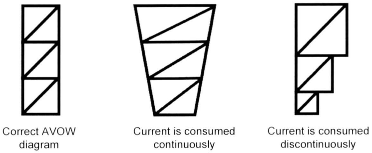



Figure A9. AVOW diagrams to explain current consumption model.

The diagram in the shape of a trapezoid assumes that current decreases continuously and seems more sensible than the second incorrect AVOW diagram where current disappears very abruptly. Both of the incorrect AVOW diagrams violate the condition that the complete diagram must be a rectangle. In practice, a non-rectangular AVOW diagram would imply that current is not conserved. In order to overcome a current consumption conception of electricity, a student must accept that an AVOW diagram must be rectangular and that the AVOW diagram is a valid representation of DC circuits.

Evidence that supports the AVOW diagram can be demonstrated by showing first that three bulbs in series exhibit identical brightness as predicted by the equal areas of the rectangles in the AVOW diagrams. If students believe that they can perceive a difference in the brightness of the bulbs (sometimes an artifact caused by non-identical bulbs), reversing the polarity of the power supply has no effect on the relative intensities of the bulbs. This observation is also supported by the correct AVOW diagram.

A more sophisticated model of the current consumption model concedes that each of the bulbs will exhibit the same brightness but maintains that the amount of current that enters the circuit from the power supply is greater than the amount of current that returns. A rectangular AVOW diagram cannot be drawn that represents this conception since the width (current) at the top of the diagram must be the same as the width at the bottom of the diagram.

Local reasoning occurs when students believe that current will split equally at each branch irrespective of the resistances of each branch. For a circuit with two resistors in parallel and its AVOW diagram see figure A10. As long as the resistances of each branch are identical, the current will split equally.

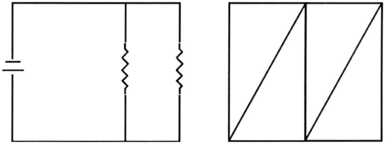


Figure A10. A parallel circuit and the AVOW diagram for two equivalent resistors.

Figure A11 illustrates the case where the resistances are different and the AVOW diagram on the left correctly shows that more current flows through the branch with the least resistance. The diagram on the right shows the AVOW diagram that illustrates what would happen if the current did divide evenly between the two branches.

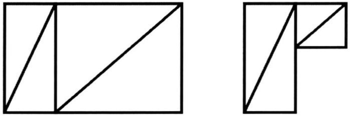


Figure A11. Correct and incorrect AVOW diagrams for parallel and unequal resistors.

Again, the principal that the overall AVOW diagram must be rectangular is not observed. In order for the current to split evenly in such a situation, the potential differences across each parallel branch would not be the same. That situation would violate the law of conservation of energy.

Sequential reasoning can be illustrated by using the circuit in figure A12.

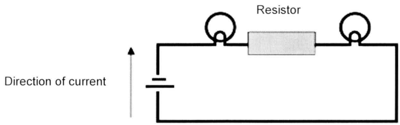



Figure A12. A circuit to illustrate sequential reasoning.

If sequential reasoning is used then the brightness of the second bulb will decrease if the resistance of the resistor is increased. The brightness of the first bulb will not change. AVOW diagrams that show the original circuit and the modified circuit are shown in figure A13.

The incorrect AVOW diagram suggests that changing the resistance of the resistor has somehow caused the resistance of the second bulb to decrease. Since the resistance of a bulb is a physical property of the bulb and is independent of the circuit, this representation cannot be true.

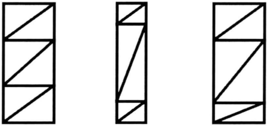
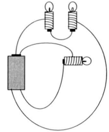



Figure A13. AVOW diagrams to illustrate sequential reasoning.

Students who succumb to sequential reasoning often use a current consumption model. The trapezoidal AVOW diagram in figure A9 could be used to support sequential reasoning but that diagram violates the constraint that the diagram must be a rectangle.

AVOW diagrams can be used to represent any DC circuit and as long as the rules of construction are followed, then the constructed diagram can not be used to support any of the common misconceptions that students have about DC circuits.

# Appendix B



**D**etermining and
**I**nterpreting
**R**esistive
**E**lectric Circuits
**C**oncepts
**T**est    Version 1.0

## *Instructions*

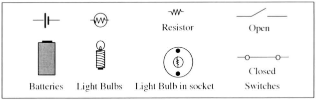
**Wait until you are told to begin**, then turn to the next page and begin working. Answer each question as accurately as you can. There is only one correct answer for each item. Feel free to use a calculator and scratch paper if you wish.

Use a #2 pencil to **record you answers** on the computer sheet, but please **do not write in the test booklet**.

You will have approximately one hour to complete the test. If you finish early, check your work before handing in both the answer sheet and the test booklet.

## *Additional comments about the test*

All light bulbs, resistors, and batteries should be considered identical unless you are told otherwise. The battery is to be assumed ideal, that is to say, the internal resistance of the battery is negligible. In addition, assume the wires have negligible resistance. Below is a key to the symbols used on this test. Study them carefully before you begin the test.





North Carolina State University
Department of Physics
Raleigh, NC 27695-8202

1) Are charges used up in a light bulb, being converted to light?

(A) Yes, charges moving through the filament produce "friction" which heats up the filament and produces light.

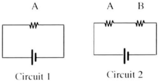
(B) Yes, charges are emitted.

(C) No, charge is conserved. It is simply converted to another form such as heat and light.

(D) No, charge is conserved. Charges moving through the filament produce "friction" which heats up the filament and produces light.

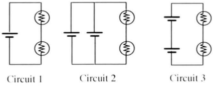
2) How does the power delivered to resistor A change when resistor B is added as shown in circuits 1 and 2 respectively?

(A) Increases
(B) Decreases
(C) Stays the same

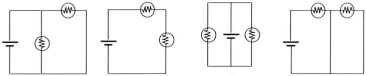



3) Consider the circuits shown below. Which circuit or circuits have the greatest energy delivered to it per second?

(A) Circuit 1
(B) Circuit 2
(C) Circuit 3
(D) Circuit 1 = Circuit 2
(E) Circuit 2 = Circuit 3



4) Consider the following circuits.

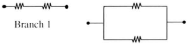


A B C D

Which circuit(s) above represent(s) a circuit consisting of two light bulbs in parallel with a battery?
(A) A
(B) B
(C) C
(D) A and C
(E) A, C, and D

5) Compare the resistance of branch 1 with that of branch 2. A branch is a section of a circuit. Which has the least resistance?

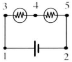
(A) Branch 1
(B) Branch 2
(C) Neither, they are the same



Branch 1 Branch 2

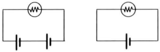
6) Rank the potential difference between points 1 and 2, points 3 and 4, and points 4 and 5 in the circuit shown below from highest to lowest.

(A) 1 and 2; 3 and 4; 4 and 5
(B) 1 and 2; 4 and 5; 3 and 4
(C) 3 and 4; 4 and 5; 1 and 2
(D) 3 and 4 = 4 and 5; 1 and 2
(E) 1 and 2; 3 and 4 = 4 and 5




7) Compare the brightness of the bulb in circuit 1 with that in circuit 2. Which bulb is brighter?

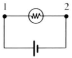
(A) Bulb in circuit 1
(B) Bulb in circuit 2
(C) Neither, they are the same



Circuit 1 Circuit 2

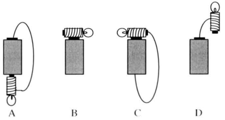
8) Compare the current at point 1 with the current at point 2. Which point has the larger current?

(A) Point 1
(B) Point 2
(C) Neither, they are the same



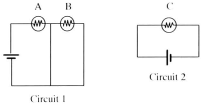

9) Which circuit(s) will light the bulb?

(A) A
(B) C
(C) D
(D) A and C
(E) B and D




10) Compare the brightness of bulbs A and B in circuit 1 with the brightness of bulb C in circuit 2. Which bulb or bulbs are the brightest?

(A) A
(B) B
(C) C
(D) A = B
(E) A = C



11) Why do the lights in your home come on almost instantaneously?

(A) Charges are already in the wire. When the circuit is completed, there is a rapid rearrangement of surface charges in the circuit.

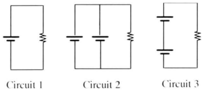
(B) Charges store energy. When the circuit is completed, the energy is released.

(C) Charges in the wire travel very fast.

(D) The circuits in a home are wired in parallel. Thus, a current is already flowing.

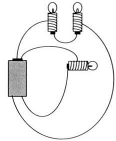
12) Consider the power delivered to each of the resistors shown in the circuits below. Which circuit or circuits have the least power delivered to it?

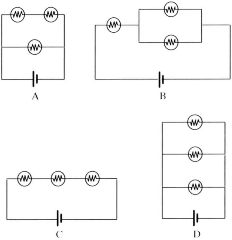
(A) Circuit 1
(B) Circuit 2
(C) Circuit 3
(D) Circuit 1 = Circuit 2
(E) Circuit 1 = Circuit 3



13) Which schematic diagram best represents the realistic circuit shown below?

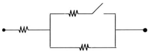
(A) A
(B) B
(C) C
(D) D
(E) None of the above





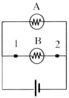
14) How does the resistance between the endpoints change when the switch is closed?

(A) Increases
(B) Decreases
(C) Stays the same



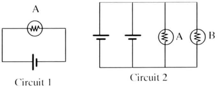
15) What happens to the potential difference between points 1 and 2 if bulb A is removed?

(A) Increases
(B) Decreases
(C) Stays the same



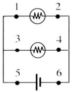

16) Compare the brightness of bulb A in circuit 1 with bulb A in circuit 2. Which bulb is dimmer?

(A) Bulb A in circuit 1
(B) Bulb A in circuit 2
(C) Neither, they are the same

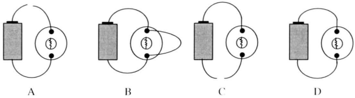



17) Rank the currents at points 1, 2, 3, 4, 5, and 6 from highest to lowest.

(A) 5, 1, 3, 2, 4, 6
(B) 5, 3, 1, 4, 2, 6
(C) 5 =6, 3 = 4, 1 =2
(D) 5 = 6, 1 = 2 = 3 = 4
(E) 1 = 2 = 3 = 4 = 5 = 6



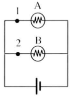
18) Which circuit(s) will light the bulb?




(A) A
(B) B
(C) D
(D) B and D
(E) A and C

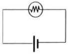
19) What happens to the brightness of bulbs A and B when a wire is connected between points 1 and 2?

(A) Increases
(B) Decreases
(C) Stays the same
(D) A becomes brighter than B
(E) Neither bulb will light



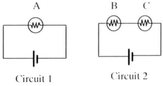

20) Is the electric field zero or non-zero inside the tungsten bulb filament?

(A) Zero because the filament is a conductor.
(B) Zero because there is a current flowing.
(C) Non-zero because the circuit is complete and a current is flowing.
(D) Non-zero because there are charges on the surface of the filament.



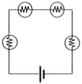
21) Compare the energy delivered per second to the light bulb in circuit 1 with the energy delivered per second to the light bulbs in circuit 2. Which bulb or bulbs have the least energy delivered to it per second?

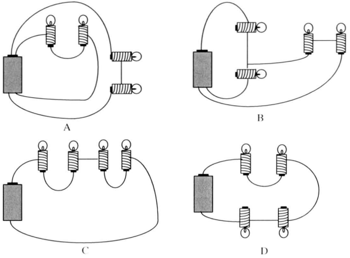
(A) A
(B) B
(C) C
(D) B = C
(E) A = B = C




22) Which realistic circuit(s) represent(s) the schematic diagram shown below?

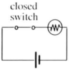
(A) B
(B) C
(C) D
(D) A and B
(E) C and D





23) Immediately after the switch is opened, what happens to the resistance of the bulb?

(A) The resistance increases.
(B) The resistance decreases.
(C) The resistance stays the same.
(D) The resistance goes to zero.

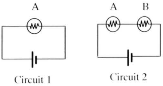



24) If you double the current through a battery, is the potential difference across a battery doubled?

(A) Yes, because Ohm's law says $V = IR$.
(B) Yes, because as you increase the resistance, you increase the potential difference.
(C) No, because as you double the current, you reduce the potential difference by half.
(D) No, because the potential difference is a property of the battery.
(E) No, because the potential difference is a property of everything in the circuit.

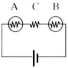
25) Compare the brightness of bulb A in circuit 1 with bulb A in circuit 2. Which bulb is brighter?

(A) Bulb A in circuit 1
(B) Bulb A in circuit 2
(C) Neither, they are the same

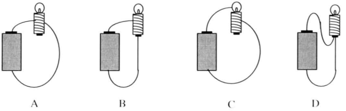



26) If you increase the resistance C, what happens to the brightness of bulbs A and B?

(A) A stays the same, B dims
(B) A dims, B stays the same
(C) A and B increase
(D) A and B decrease
(E) A and B remain the same



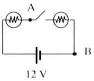
27) Will all the bulbs be the same brightness?




(A) Yes, because they all have the same type of circuit wiring.
(B) No, because only B will light. The connections to A, C, and D are not correct.
(C) No, because only D will light. D is the only complete circuit.
(D) No, C will not light but A, B, and D will.

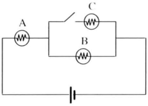
28) What is the potential difference between points A and B?

(A) 0 V
(B) 3 V
(C) 6 V
(D) 12 V




29) What happens to the brightness of bulbs A and B when the switch is closed?

(A) A stays the same, B dims
(B) A brighter, B dims
(C) A and B increase
(D) A and B decrease
(E) A and B remain the same



Appendix C

Dear Parent or Guardian:

My name is David Brothen and I am a teacher at Hunting Hills High School. I am also a graduate student in the Faculty of Education at Memorial University working on my Master's thesis. My thesis deals with the use of analogies when teaching DC circuits. Analogies are often used in teaching about electric circuits but research indicates that most analogies do not work very well. Mr. Burns has agreed to present a new analogy for teaching DC circuits in his Physics 30 class this semester. This analogy has been tested in the UK and appears to be an effective and useful one. Both Mr. Burns and I agree that this analogy will likely be effective and useful in our classes as well.

In order to test this hypothesis, Mr. Burns will include this new analogy in his unit on DC circuits and I will observe how students use this analogy to learn about and understand DC circuits. Students will also be observed as they complete a laboratory assignment where various DC circuits are constructed and analyzed. At the end of the unit, a standardized diagnostic test of student conceptions of DC circuits will be administered. Scores on this test will be compared to established norms. Finally, individual students will be invited to be interviewed where they will be questioned about their conceptions of DC circuits and of the usefulness of the new analogy. The test contains 29 multiple-choice questions and should take about 30 minutes of class time. The interviews will take place at lunch or after school and will take no longer than 20 minutes.

The unit of instruction on electricity will begin in March and will last for about two weeks. The standardized test will be administered at the end of this unit and interviews will take place in the week after the test is administered.

As a teacher at Hunting Hills, it is possible that I personally know your child and may have taught him or her in the past. This means that your child will not be anonymous to me. However, your child's identity will not be revealed to anyone else. Information about your child will be presented in such a way that his or her identity is concealed. Information from this research will be used to complete my Master's thesis and then might be shared at conferences or submitted for publication.

The data collected for this study will consist of observation notes, interview audiotapes, a completed multiple-choice test, and a lab write-up. I will transcribe audiotapes and student names will be replaced with unique identification numbers. Student names will be removed from tests and lab write-ups and also replaced by identification numbers. No one else will have access to list of names and identification numbers.

The incorporation of new teaching techniques is an important aspect of teaching practice. This study goes beyond normal practice in that I will be observing Mr. Burns's students and will be formally investigating the effects of the new teaching technique. We believe that the introduction of this new analogy will improve the teaching and learning of DC circuits and as such would use it in the course of our normal practice even if this study were not taking place. Research protocols require that participants be informed of the foreseeable risks and benefits of participating in this research. Since none of the proposed activities lay outside the range of normal teaching practice, the risk involved in participating in this research is minimal. The benefit of this research is the development of a way to improve the teaching and learning of DC circuits.

Your child may decline to answer any individual questions or stop the interview/activity at any time. The Interdisciplinary Committee for Ethics in Human Research has approved the proposal for this research. If you have any questions or concerns about the research that are not dealt with by me, you may contact the Chairperson of that Committee through the Committee's secretary, Ms. Eleanor Butler, at the Office of Research, Memorial University at 709-737-8368. The results of my research will be made available to you upon request.

All recordings made during the interview will be held in a secure location and destroyed upon completion of the study.

The findings of this study will be published in my Master's thesis but neither your child nor the school will be named.

If you are in agreement with having your child participate in this study, please sign the attached consent form and return one copy to the Mr. Burns. The other is for you. If you have any questions or concerns, please do not hesitate to contact me at Hunting Hills High School, 403-342-6655 ext 2521. If at any time you wish to speak with a resource person not associated with the study, please contact the Associate Dean, Graduate Programmes, at 709-737-3402.

I would appreciate it if you would please return this sheet by February 28, 2007.

Sincerely,

David Brothen

Appendix D

# PHYSICS 20–30

## A. PROGRAM OVERVIEW

### RATIONALE AND PHILOSOPHY

Physics is the study of matter and energy and their interactions. Through the study of physics, learners are given an opportunity to explore and understand the natural world and to become aware of the profound influence of physics in their lives. Learning is facilitated by relating the study of physics to what the learners already know, deem personally useful and consider relevant. Learning proceeds best when it originates from a base of concrete experiences presenting an authentic view of science in the context of physics. In Physics 20–30, students learn physics in relevant contexts and engage in meaningful activities. This facilitates the transfer of knowledge to new contexts. Students are encouraged to participate in lifelong learning about physics and to appreciate it as a scientific endeavour with practical impact on their own lives and on society as a whole.

Physics, as with all sciences, is an experimental discipline requiring creativity and imagination. Methods of inquiry characterize its study. In Physics 20–30, students further develop their ability to ask questions, investigate and experiment; to gather, analyze and assess scientific information; and to test scientific laws and principles and their applications. In the process, students exercise their creativity and develop their critical thinking skills. Through experimentation, and problem-solving activities that include the integration of technology and independent study, students develop an understanding of the processes by which scientific knowledge evolves.

The Physics 20–30 program places students at the centre. Students are active learners and will assume increased responsibility for their learning as they work through the program. A thorough study of physics is required to give students an understanding that encourages them to make appropriate applications of scientific concepts to their daily lives and prepares them for future studies in physics. Students are expected to participate actively in their own learning. An emphasis on the key concepts and principles of physics provides students with a more unified view of the sciences and a greater awareness of the connections among them.

These science learnings will take varying amounts of time to acquire, depending on the individual learning styles and abilities of students. While each course is designed for approximately 125 hours, instructional time can be modified to meet the individual needs of students. Some students will require more than 125 hours, while others will require less.

**GOALS**

The major goals of the Physics 20–30 program are:

- to develop in students an understanding of the interconnecting ideas and principles that transcend and unify the natural science disciplines
- to provide students with an enhanced understanding of the scientific world view, inquiry and enterprise
- to help students attain the level of scientific awareness essential for all citizens in a scientifically literate society
- to help students make informed decisions about further studies and careers in science
- to provide students with opportunities for acquiring knowledge, skills and attitudes that contribute to personal development.

Physics 20–30 is an academic program that helps students better understand and apply fundamental concepts and skills. The focus is on helping students understand the physics principles behind the natural events they experience and the technology they use in their daily lives. The program encourages enthusiasm for the scientific enterprise and develops positive attitudes about physics as an interesting human activity with personal meaning. It develops in students the knowledge, skills and attitudes to help them become capable of, and committed to, setting goals, making informed choices and acting in ways that will improve their own lives and life in their communities.

# B. LEARNER EXPECTATIONS

## GENERAL LEARNER EXPECTATIONS

The general learner expectations outline the many facets of scientific awareness and serve as the foundation for the specific learner expectations covered in section C. The general learner expectations are developed in two categories: *program* expectations and *course* expectations.

### PROGRAM GENERAL LEARNER EXPECTATIONS

The *program* general learner expectations are broad statements of science attitudes, knowledge, skills and science, technology and society (STS) connections that students are expected to achieve in all of the senior high school science programs. These *program* general learner expectations are further refined through the *course* general learner expectations and then developed in specific detail through the study of individual units in each of Physics 20 and Physics 30. All expectations follow a progression from Science 10 through to Physics 30, and though listed separately, are meant to be developed in conjunction with one another, within a context.

### ATTITUDES

*Students will be encouraged to develop:*

- enthusiasm for, and a continuing interest in, science
- affective attributes of scientists at work; such as, respect for evidence, tolerance of uncertainty, intellectual honesty, creativity, perseverance, cooperation, curiosity and a desire to understand
- positive attitudes toward scientific and technological skills involving process skills, mathematics, and problem solving
- open-mindedness and respect for the points of view of others
- sensitivity to the living and nonliving environment
- appreciation of the roles of science and technology in our understanding of the natural world.

### KNOWLEDGE

**Science Themes**

*Students will be expected to demonstrate* an understanding of themes that transcend the discipline boundaries, and show the unity among the natural sciences, including:

- Change: how all natural entities are modified over time, how the direction of change might be predicted and, in some instances, how change can be controlled
- Diversity: the array of living and nonliving forms of matter and the procedures used to understand, classify and distinguish those forms on the basis of recurring patterns
- Energy: the capacity for doing work that drives much of what takes place in the Universe through its variety of interconvertible forms
- Equilibrium: the state in which opposing forces or processes balance in a static or dynamic way
- Matter: the constituent parts, and the variety of states of the material in the physical world
- Systems: the interrelated groups of things or events that can be defined by their boundaries and, in some instances, by their inputs and outputs.

**SKILLS**

*Students will be expected to develop* an ability to use thinking processes associated with the practice of science for understanding and exploring natural phenomena, problem solving and decision making. Students will also be expected to use teamwork, respect the points of view of others, make reasonable compromises, contribute ideas and effort, and lead when appropriate to achieve the best results. These processes involve many skills that are to be developed within the context of the program content.

Students will also be expected to be aware of the various technologies, including information technology, computer software and interfaces that can be used for collecting, organizing, analyzing and communicating data and information.

The skills framework presented here assumes that thinking processes often begin with an unresolved problem or issue, or an unanswered question. The problem, issue or question is usually defined and hypotheses formulated before information gathering can begin. At certain points in the process, the information needs to be organized and analyzed. Additional ideas may be generated—for example, by prediction or inference—and these new ideas, when incorporated into previous learning, can create a new knowledge structure. Eventually, an outcome, such as a solution, an answer or a decision is reached. Finally, criteria are established to judge ideas and information in order to assess both the problem-solving process and its outcomes.

The following skills are not intended to be developed sequentially or separately. Effective thinking is nonlinear and recursive. Students should be able to access skills and strategies flexibly; select and use skills, processes or technologies that are appropriate to the tasks; and monitor, modify or replace them with more effective strategies.

- Initiating and Planning
  - identify and clearly state the problem or issue to be investigated
  - differentiate between relevant and irrelevant data or information
  - assemble and record background information
  - identify all variables and controls
  - identify materials and apparatus required
  - formulate questions, hypotheses and/or predictions to guide research
  - design and/or describe a plan for research, or to solve a problem
  - prepare required observation charts or diagrams, and carry out preliminary calculations
- Collecting and Recording
  - carry out the procedure and modify, if necessary
  - organize and correctly use apparatus and materials to collect reliable data
  - observe, gather and record data or information accurately according to safety regulations; e.g., Workplace Hazardous Materials Information System (WHMIS), and environmental considerations
- Organizing and Communicating
  - organize and present data (themes, groups, tables, graphs, flow charts and Venn diagrams) in a concise and effective form
  - communicate data effectively, using mathematical and statistical calculations, where necessary
  - express measured and calculated quantities to the appropriate number of significant digits, using SI notation for all quantities
  - communicate findings of investigations in a clearly written report
- Analyzing
  - analyze data or information for trends, patterns, relationships, reliability and accuracy
  - identify and discuss sources of error and their affect on results

- identify assumptions, attributes, biases, claims or reasons
- identify main ideas

• Connecting, Synthesizing and Integrating

- predict from data or information, and determine whether or not these data verify or falsify the hypothesis and/or prediction
- formulate further, testable hypotheses supported by the knowledge and understanding generated
- identify further problems or issues to be investigated
- identify alternative courses of action, experimental designs, and solutions to problems for consideration
- propose and explain interpretations or conclusions
- develop theoretical explanations
- relate the data or information to laws, principles, models or theories identified in background information
- propose solutions to a problem being investigated
- summarize and communicate findings
- decide on a course of action

• Evaluating the Process or Outcomes

- establish criteria to judge data or information
- consider consequences and biases, assumptions and perspectives
- identify limitations of the data or information, and interpretations or conclusions, as a result of the experimental/research/project/design process or method used
- evaluate and suggest alternatives and consider improvements to the experimental technique and design, the decision-making or the problem-solving process
- evaluate and assess ideas, information and alternatives

## CONNECTIONS AMONG SCIENCE, TECHNOLOGY AND SOCIETY

### Science, Technology and Society (STS)

*Students will be expected to demonstrate* an understanding of the processes by which scientific knowledge is developed, and of the interrelationships among science, technology and society, including:

- the central role of evidence in the accumulation of knowledge, and the ways proposed theories may be supported, modified or refuted
- the inability of science to provide complete answers to all questions
- the functioning of processes or products based on scientific principles
- the ways in which science advances technology and technology advances science
- the use of technology to solve practical problems
- the limitations of scientific knowledge and technology
- the influence of the needs, interests and financial support of society on scientific and technological research
- the ability and responsibility of society, through science and technology, to protect the environment and use natural resources judiciously to ensure quality of life for future generations.

## FURTHER READING

For a more detailed discussion on how to integrate thinking and research skills into the science classroom, refer to the publications: *Teaching Thinking: Enhancing Learning*, 1990 and *Focus on Research: A Guide to Developing Students' Research Skills*, 1990.

For further reading on integrating science, technology and society into the classroom, refer to the publication: *STS Science Education: Unifying the Goals of Science Education*, 1990.

**COURSE GENERAL LEARNER EXPECTATIONS**

The *course* general learner expectations are specific to each of Physics 20 and Physics 30 providing a bridge between the *program* general learner expectations and the specific learner expectations for each unit of study.

The attitudes expectations refer to those predispositions that are to be fostered in students. These expectations encompass attitudes toward science, the role of science and technology, and the contributions of science and technology toward society. The knowledge expectations are the major physics concepts in each course. The skills expectations refer to the thinking processes and abilities associated with the practice of science, including understanding and exploring natural phenomena, and problem solving. The connections among science, technology and society expectations focus on: the processes by which scientific knowledge is developed; the interrelationships among science, technology and society; and links each course to careers, everyday life and subsequent studies of physics.

Although itemized separately, the attitudes, knowledge, skills and STS connections are meant to be developed together within one or more contexts.

**Physics 20–30**

Attitudes

*Students will be encouraged to:*

- appreciate the role of empirical evidence and models in science, and accept the uncertainty in explanations and interpretations of observed phenomena
- value the curiosity, openness to new ideas, creativity, perseverance and cooperative hard work required of scientists, and strive to develop these same personal characteristics
- appreciate the role of science and technology in advancing our understanding of the natural world, be open-minded and respectful of other points of view when evaluating scientific information and its applications, and appreciate that the application of science and technology by humankind can have beneficial as well as harmful effects and can cause ethical dilemmas
- show a continuing interest in science, appreciate the need for computational competence, problem-solving and process skills when doing science, and value accuracy and honesty when communicating the results of problems and investigations
- appreciate the simplicity of, and similarity among, scientific explanations for complex, physical phenomena.

**Physics 20**

*Students will be able to:*

Knowledge

- compare and contrast scalar and vector quantities; and apply the concept of field to quantitatively explain, in terms of its source, direction and intensity, the gravitational effects of objects and systems
- describe, quantitatively, analyze and predict mechanical energy transformations, using the concepts of conservation of energy, work and power
- describe, quantitatively, analyze and predict motion with constant velocity, constant acceleration and uniform circular motion of objects and systems, using the concepts of kinematics, dynamics, Newton's laws of motion and the law of universal gravitation
- use the principles of simple harmonic motion and energy conservation to relate the concepts of uniform linear and circular motion to the behaviour and characteristics of mechanical waves

- describe, quantitatively, analyze and predict the behaviour of light, using the concepts of geometric and wave optics, and graphical and mathematical techniques

Skills

- perform investigations and tasks of their own and others' design that have a few variables and yield direct or indirect evidence; and provide explanations based upon scientific theories and concepts

- collect, verify and organize data into tables of their own design, and graphs and diagrams of others' design, using written and symbolic forms; and describe findings or relationships, using scientific vocabulary, notation, theories and models

- analyze and interpret data that yield straight- and curved-line graphs; and use appropriate SI notation, fundamental and derived units, and formulas; and determine new variables, using the slopes of, and areas under graphs, plot corresponding graphs, and derive mathematical relationships among the variables

- use mathematical language of ratio and proportion, numerical and algebraic methods, two-dimensional vector addition in one plane, and unit analysis to solve single- and multi-step problems; and to communicate scientific relationships and concepts

Connections Among Science, Technology and Society

- apply cause and effect reasoning to formulate simple relationships for a given instance in which scientific evidence shapes or refutes a theory; and describe the limitations of science and technology in answering all questions and solving all problems, using appropriate and relevant examples

- describe and explain the design and function of technological solutions to practical problems, using scientific principles; and relate the ways in which physics and technology advance one another, using appropriate and relevant examples

- explain for a given instance how science and technology are influenced and supported by society, and the responsibility of society, through physics and technology, to protect the environment and use natural resources wisely

- identify subject-related careers and apply the knowledge and skills acquired in Physics 20 to everyday life and to related and new concepts in subsequent studies of physics.

**Physics 30**

*Students will be able to:*

Knowledge

- compare and contrast scalar and vector quantities and fields; and apply the concept of field to quantitatively explain, in terms of their source, direction and intensity, electric, gravitational and magnetic effects on objects and systems

- explain, quantitatively, analyze and predict physical interactions among objects and systems, using the concepts of conservation of energy and momentum

- describe, quantitatively, analyze and predict the behaviour of electric charges in electric and/or magnetic fields, using the principles of kinematics, dynamics, conservation of energy and electric charge, electrostatics and electromagnetism

- explain, quantitatively, analyze and predict the motor and generator effect involving a single conductor; and use relevant electromagnetic principles to explain the design and function of simple electric motors, generators, meters, transformers and other simple electromagnetic devices

- illustrate, using biophysical, industrial and other examples, technological applications of electromagnetic theories and effects; and describe, quantitatively, analyze and predict the functioning of simple resistive direct current circuits, using Ohm's law and Kirchhoff's rules

- explain, quantitatively, the characteristics and behaviours of the various constituents of the electromagnetic spectrum, and algebraically solve problems, using the relationship among speed, wavelength and frequency of electromagnetic waves

- explain, citing empirical evidence, the development of an atomic theory contingent upon wave–particle duality of matter and statistical probability, and its technological application

Skills

- perform and evaluate investigations and tasks of their own and others' design that have multiple variables and yield direct or indirect evidence; and provide explanations and interpretations, using scientific theories and concepts

- collect, verify and organize data into tables, graphs and diagrams of their own design, using written and symbolic forms; and describe findings or relationships and make predictions, using scientific vocabulary, notation, theories and models

- analyze, interpret and evaluate data that yield straight- and curved-line graphs; and use appropriate SI notation, fundamental and derived units, and formulas; and determine new variables using the slopes of, and areas under graphs, plot corresponding graphs, and use curve-straightening techniques to infer mathematical relationships among variables

- use mathematical language of ratio and proportion, numerical and algebraic methods, two-dimensional vector addition in one plane, unit analysis, and derived algebraic algorithms to solve multi-step, nonroutine problems; and communicate scientific relationships and concepts

Connections Among Science, Technology and Society

- apply cause and effect reasoning to formulate relationships for a range of instances in which scientific evidence shapes or refutes a theory; and explain the limitations of science and technology in answering all questions and solving all problems, using appropriate and relevant examples

- describe and evaluate the design and function of technological solutions to practical problems, using scientific principles or theories; and relate the ways in which physics and technology advance one another, using appropriate and relevant examples

- explain and evaluate for a given instance, and from a variety of given perspectives, how science and technology are influenced and supported by society; and assess the ability and responsibility of society, through physics and technology, to protect the environment and use natural resources wisely

- identify subject-related careers and apply the knowledge and skills acquired in Physics 30 to everyday life and to related and new concepts in post-secondary studies of physics.

## SPECIFIC LEARNER EXPECTATIONS

### LEARNING CYCLE

The specific learner expectations consist of the knowledge, skills and attitudes that are to be addressed in Physics 20–30. The use of the learning cycle allows students to progress, from:

- an introduction framing the lesson in an STS connection relevant to the lives of the learners, and makes connections between past and present learning experiences, as well as anticipates activities to focus students' thinking on the learning outcomes of the activity

TO

- the experiential exploration of new content that provides students with a common base of experiences within which they identify and develop key concepts, processes and skills

THROUGH

- a hypothesis-building phase where concepts are developed to describe a particular aspect of their experiential exploration, and opportunities are provided to communicate their conceptual understanding, or demonstrate their skills or behaviours

TO

- an elaboration phase that extends understanding of key concepts and allows further opportunities to practise desired skills and problem-solving strategies

TO

- an application phase where the hypotheses, vocabulary and patterns previously developed are applied to new situations and related to key concepts and principles of science

TO

- a final evaluation of the significance of the new learning in an STS context to assess their understanding and abilities, and provide opportunities for evaluation of student progress toward achieving the curriculum standards.

In Physics 20–30, students examine phenomena in a variety of topics to show the relationships among all the sciences. Wherever possible, examples should be framed in the context of the learners' own experiences to enable them to make the connections between scientific knowledge and the society around them, the technology that societies have developed, and the nature of science itself.

### PROGRAM OVERVIEW

The Physics 20–30 program emphasizes the science themes: *change*, *diversity*, *energy*, *equilibrium*, *matter* and *systems* as they relate to physics. These themes provide a means of showing the connections among the units of study in both courses of the program, and provide a framework for students to learn how individual sections of the program relate to the big ideas of science.

In addition to developing a solid understanding of fundamental science concepts and principles, Physics 20–30 has the goal of educating students about the nature of science and technology, and the interaction between physics and technology. Students must be aware of the tremendous impact of physics and associated technology on society, but at the same time, they must be aware of the roles and limitations of the physical sciences, science in general, and of technology in problem solving in a societal context.

**PHYSICS 20**

*Energy* is the science theme common to all units in Physics 20, with *change*, *diversity*, *equilibrium*, *matter* and *systems* also playing a role. *Energy* in its many forms causes *change* and determines the kind of change *matter* and *systems* undergo.

The major concepts allow connections to be drawn among the four units of the course and among all eight units in the two courses in the program.

Physics 20 consists of four units of study:

Unit 1: Kinematics and Dynamics
Unit 2: Circular Motion and Gravitation
Unit 3: Mechanical Waves
Unit 4: Light.

An examination of motion, the causes of motion and their relationship to *energy changes* in *systems* emphasizes the science theme of *change* in Unit 1. In Unit 2, the principles of *change* in and conservation of *energy* motion are extended to circular motion, and lead into an investigation of gravitation and *equilibrium* in planetary *systems*. Unit 3 considers the transfer of *energy* through *matter* by means of mechanical waves, and the characteristics of waves are studied in the context of sound. Unit 4 focuses on the nature of light, a visible form of *energy* and one of the *diverse* forms of electromagnetic radiation.

**PHYSICS 30**

The *diversity* of *energy* and *matter* are the predominant themes of the Physics 30 course.

The major concepts allow connections to be drawn among the four units of the course and among all eight units in the two courses in the program.

Physics 30 consists of four units of study:

Unit 1: Conservation Laws
Unit 2: Electric Forces and Fields
Unit 3: Magnetic Forces and Fields
Unit 4: Nature of Matter.

Physics 30 expands upon the concepts and skills introduced in Science 10 and Physics 20. In Unit 1, students emphasize the science theme of *equilibrium*, as exemplified by the fundamental phenomenon of conservation of *energy* and momentum in isolated *systems* in the physical universe. In Unit 2, the electrical nature of *matter* in its *diverse* forms is examined. Unit 3 investigates the *diversity* and magnetic nature of *matter*, and electromagnetic interactions and technological applications. In Unit 4, the quantum concept of *energy* and *matter* is investigated via the study of the electric nature of the atom, the photoelectric effect and the wave–particle duality of radiation; as well, the applications of nuclear energy and the radioactive nature of the atom are studied.

# PHYSICS 30

## UNIT 1
## CONSERVATION LAWS

### OVERVIEW

**Science Themes:** *Energy*, *Equilibrium* and *Systems*

In Unit 1, students investigate *energy* and *equilibrium* in the physical world, in a study of the conservation of *energy* and momentum.

In this unit, the *energy* concepts from Science 10, Unit 4: Change and Energy; and Physics 20, Unit I: Kinematics and Dynamics, are recalled and extended. The vector nature of momentum is explored through the algebraic and graphical solution of conservation of linear momentum problems. The principles learned are reinforced by analyzing common and practical physical interactions in isolated *systems*. This unit provides a foundation for further study of mechanics in subsequent units and for post-secondary studies in physics.

The two **major concepts** developed in this unit are:

- conservation of *energy* in an isolated *system* is a fundamental physical concept
- momentum is conserved when objects interact in an isolated *system*.

In this unit, *students will develop* an ability to use the **skills** and **thinking processes** associated with the practice of science, emphasizing:

- initiating and planning
- collecting and recording
- organizing and communicating
- analyzing data from physical interactions
- connecting, synthesizing and integrating to relate the data to the laws and principles of conservation of energy and momentum
- evaluating the process or outcomes of activities investigating the concepts of conservation of energy and momentum.

The **STS connections** in this unit illustrate:

- the functioning of products or processes based on scientific principles
- the use of technology to solve practical problems
- the influence of the needs, interests and financial support of society on scientific and technological research.

### ATTITUDES

*Students will be encouraged to:*

- appreciate the need for computational competence in quantifying conservation of energy and momentum
- accept uncertainty in the descriptions and explanations of conservation in the physical world
- be open-minded in evaluating potential applications of conservation principles to new technology
- appreciate the fundamental role the principles of conservation play in our everyday world
- appreciate the need for simplicity in scientific explanations of complex physical interactions and the role conservation laws play in many of these explanations
- appreciate the need for accurate and honest communication of all evidence gathered in the course of an investigation related to conservation principles
- appreciate the need for empirical evidence in interpreting observed conservation phenomena
- appreciate the restricted nature of evidence when interpreting the results of physical interactions.

| MAJOR CONCEPT | KNOWLEDGE |
|---|---|
| | *Students should be able to demonstrate an understanding that:* |
| 1. Conservation of *energy* in an isolated *system* is a fundamental physical concept. | • mechanical energy interactions involve changes in kinetic and potential energy, by extending energy concepts from Science 10, Unit 4, and the mechanical energy concepts and problem-solving methods studied in Physics 20, Unit 1, and by:<br>• describing energy and mass as scalar quantities<br>• relating the conservation of mass and energy in a qualitative analysis of Einstein's concept of mass–energy equivalence<br>• defining mechanical energy as the sum of kinetic and potential energy<br>• solving conservation problems, using algebraic and/or graphical analysis<br>• analyzing and solving, quantitatively, kinematics and dynamics problems, using mechanical energy conservation concepts by extending previous problem-solving methods. |

| SKILLS | STS CONNECTIONS |
|---|---|
| *Students should be able to demonstrate the skills and thinking processes associated with the practice of science, by:* | *Students should be able to demonstrate the interrelationships among science, technology and society, by:* |
| | • understanding that changes in kinetic and potential energy occur in mechanical energy interactions; and analyzing and solving, quantitatively, kinematic and dynamics problems, using mechanical energy concepts, and algebraic and/or graphical analyses; and by gathering, and graphically analyzing, relevant data inferring mathematical relationships, within the context of: |
| • designing and performing experiments demonstrating the law of conservation of energy, and the relationship between kinetic and mechanical potential energy<br>• using free-body diagrams (force diagrams) in organizing and communicating the solutions of conservation problems<br>• analyzing data graphically, using curve-straightening techniques, to infer mathematical relationships. | • investigating and reporting the application of conservation principles in research and design<br>OR<br>• any other relevant context. |

| MAJOR CONCEPT | KNOWLEDGE |
|---|---|
| | *Students should be able to demonstrate an understanding that:* |
| 2. Momentum is conserved when objects interact in an isolated *system*. | • conservation laws provide a simple means to explain interactions among objects, by:<br>• describing momentum as a vector quantity<br>• defining momentum as a quantity of motion equal to the product of the mass and the velocity of an object<br>• relating Newton's laws of motion, quantitatively, to explain the concepts of impulse and a change in momentum<br>• explaining, quantitatively, using vectors, that momentum appears to be conserved during one- and two-dimensional interactions in one plane among objects (the sine and cosine rules are not required)<br>• defining, comparing and contrasting elastic and inelastic collisions, using quantitative examples<br>• comparing scalar and vector conservation laws. |

| SKILLS | STS CONNECTIONS |
|---|---|
| *Students should be able to demonstrate the skills and thinking processes associated with the practice of science, by:* | *Students should be able to demonstrate the interrelationships among science, technology and society, by:* |
| | • understanding that the law of conservation of momentum provides a means to explain interactions among objects; and explaining, quantitatively, using vectors and one- and two-dimensional interactions in one plane; and by obtaining and analyzing empirical evidence to demonstrate the conservation of momentum, and estimating and predicting results of interactions, within the context of: |
| • performing and analyzing experiments demonstrating the conservation of momentum and the principle of impulse<br><br>• approximating, estimating and predicting results of interactions, based on an understanding of the conservation laws. | • assessing the role conservation laws and the principle of impulse play in the design and use of injury prevention devices in vehicles and sports; e.g., air bags, child restraint systems, running shoes, helmets<br><br>OR<br><br>• analyzing how the need for decreasing momentum over a long period has influenced the design of ropes used in such activities as "bunji" jumping and mountain climbing<br><br>OR<br><br>• investigating and reporting on a technology developed to improve the efficiency of energy transfer in a response to reconcile the energy needs of society with its responsibility to protect the environment and to use energy judiciously<br><br>OR<br><br>• investigating and reporting on a safety device that results in a cost saving to consumers and society, in terms of the problem addressed and its impact on quality of life<br><br>OR<br><br>• any other relevant context. |

## UNIT 2
## ELECTRIC FORCES AND FIELDS

### OVERVIEW

**Science Themes:** *Diversity*, *Energy* and *Matter*

In Unit 2, the *diversity* of *matter* is highlighted as its electric nature is considered in the context of electrical interactions and electric energy.

This unit covers the principles of electrostatics and how to describe the interaction of electric charges mathematically from empirical data. The concepts from Physics 20, Unit 1: Kinematics and Dynamics, are extended to charged particle dynamics. The concept of field, introduced in Physics 20, Unit 2: Circular Motion and Gravitation, is applied to electrical phenomena. The unit concludes with the consideration of electric *energy* and simple direct current (DC) circuits. This unit provides a foundation for further study of electrical principles in subsequent units and for post-secondary studies in physics.

The four **major concepts** developed in this unit are:

- the laws governing electrical interactions are used to explain the behaviour of electric charges at rest
- Coulomb's law relates electric charge to electric force
- electric field theory is a model used to explain how charges interact
- electric circuits facilitate the use of electric *energy*.

In this unit, *students will develop* an ability to use the **skills** and **thinking processes** associated with the practice of science, emphasizing:

- initiating and planning
- collecting and recording
- organizing and communicating
- analyzing data from electrical interactions
- connecting, synthesizing and integrating to relate the data to the laws and principles of electric forces and fields
- evaluating the process or outcomes of activities investigating the concepts of electric forces and fields.

The **STS connections** in this unit illustrate:

- the central role of evidence in the accumulation of knowledge, and the ways proposed theories may be supported, modified or refuted
- the functioning of products or processes based on scientific principles
- the ways in which science advances technology and technology advances science
- the use of technology to solve practical problems
- the ability and responsibility of society, through science and technology, to protect the environment and use natural resources judiciously to ensure quality of life for future generations.

### ATTITUDES

*Students will be encouraged to:*

- appreciate the need for computational competence in quantifying electrical interactions
- accept uncertainty in the descriptions and explanations of electrical phenomena in the physical world
- be open-minded in evaluating potential applications of electrical principles to new technology
- appreciate the fundamental role the principles of electricity play in our everyday world
- appreciate the need to follow safe practices when working with electricity
- foster a responsible attitude to environmental and social change as related to the use and production of electrical *energy*
- appreciate the restricted nature of evidence when interpreting the results of electrical interactions.

| MAJOR CONCEPT | KNOWLEDGE |
|---|---|
| | *Students should be able to demonstrate an understanding that:* |
| 1. The laws governing electrical interactions are used to explain the behaviour of electric charges at rest. | • the electrical model of matter is fundamental to the explanation of electrical interactions, by extending from Physics 20, Unit 1, and by:<br>• describing matter as containing discrete positive and negative particles<br>• explaining electrical interactions in terms of the law of conservation of charge<br>• explaining electrical interactions in terms of the law of electric charge (two types of charge: like charges repel, unlike charges attract)<br>• comparing the methods of transferring charge: conduction and induction. |

| SKILLS | STS CONNECTIONS |
|---|---|
| *Students should be able to demonstrate the skills and thinking processes associated with the practice of science, by:* | *Students should be able to demonstrate the interrelationships among science, technology and society, by:* |
| | • understanding that the electrical model of matter is fundamental to the explanation of electrical phenomena; and explaining electrical interactions in terms of the law of conservation of charge and the law of electric charge; and by investigating, empirically, and explaining electrostatics, using the electric nature of matter, within the context of: |
| • performing an activity demonstrating the electrical nature of matter, using methods of electrification, and describing observations in terms of the laws of electrostatics<br><br>• using safe practices when conducting electrical experiments. | • assessing how the principles of electrostatics are used to solve problems in industry and technology, and improve upon quality of life; e.g., telephones, photocopiers, electrostatic air cleaners, precipitators<br><br>OR<br><br>• investigating natural and artificial electrical discharge and the need for grounding in terms of scientific principles and the inability of science to provide complete answers to all questions<br><br>OR<br><br>• any other relevant context. |

| MAJOR CONCEPT | KNOWLEDGE |
|---|---|
| | *Students should be able to demonstrate an understanding that:* |
| 2. Coulomb's law relates electric charge to electric force. | • Coulomb's law explains the relationships among force, charge and separating distance, by:<br>• explaining, qualitatively, the principles pertinent to Coulomb's torsion balance experiment<br>• explaining, quantitatively, using Coulomb's law and vectors, the electrostatic interaction between discrete point charges<br>• comparing the inverse square relationship as it is expressed by Coulomb's law and Newton's universal law of gravitation. |

| SKILLS | STS CONNECTIONS |
|---|---|
| *Students should be able to demonstrate the skills and thinking processes associated with the practice of science, by:* | *Students should be able to demonstrate the interrelationships among science, technology and society, by:* |
| | • understanding that the relationships among force, charge and separating distance is explained by Coulomb's law; and explaining, quantitatively, using Coulomb's law and vectors, the electrostatic interaction between discrete point charges; and by gathering and analyzing relevant data inferring the mathematical relationships among force, charge and separating distance, within the context of: |
| • performing an experiment demonstrating the relationships among magnitude of charge, electric force and distance<br><br>• inferring the mathematical relationships among force, charge and separating distance from empirical evidence. | • comparing and contrasting the experimental designs used by Coulomb and Cavendish, in terms of the role of technology in advancing science<br><br>OR<br><br>• any other relevant context. |

| MAJOR CONCEPT | KNOWLEDGE |
| --- | --- |
| | *Students should be able to demonstrate an understanding that:* |
| 3. Electric field theory is a model used to explain how charges interact. | • the concept of field is applied to electric interactions, by extending from Physics 20, Unit 2, the definition of field, and by:<br>• comparing scalar and vector fields<br>• comparing forces and fields<br>• explaining, quantitatively, using vector addition, electric fields in terms of intensity (strength) and direction relative to the source of the field<br>• explaining, quantitatively, using vector addition, electric fields in terms of intensity (strength) and direction relative to the effect on an electric charge<br>• predicting, using algebraic and/or graphical methods, the path followed by a moving electric charge in a uniform electric field, using kinematics and dynamics concepts<br>• explaining electrical interactions, quantitatively, using the conservation laws of energy and charge. |

| SKILLS | STS CONNECTIONS |
|---|---|
| *Students should be able to demonstrate the skills and thinking processes associated with the practice of science, by:* | *Students should be able to demonstrate the interrelationships among science, technology and society, by:* |
| | • understanding the concept of field as related to electrical interactions; and explaining, quantitatively, using vector addition electric fields in terms of intensity and direction relative to the source of the field and its effect on an electric charge; and by plotting electric fields, using field lines and linking centripetal force to the electric force, within the context of: |
| • plotting electric fields, using field lines, for fields induced by discrete point charges, combinations of discrete point charges (like and oppositely charged) and charged parallel plates<br><br>• relating the electric force, using Newton's second law, to the motion of an electric charge following a curved path in an electric field. | • evaluating electric field theory as a model used to explain the behaviour of electric charges in terms of supporting experimental evidence<br><br>OR<br><br>• explaining, qualitatively, how the problem of protecting sensitive components in a computer from electric fields is solved<br><br>OR<br><br>• any other relevant context. |

| MAJOR CONCEPT | KNOWLEDGE |
| --- | --- |
| | *Students should be able to demonstrate an understanding that:* |
| 4. Electric circuits facilitate the use of electric *energy*. | • Ohm's law and Kirchhoff's rules are fundamental to explaining simple electric circuits, by:<br>• defining current, potential difference, resistance and power, using appropriate terminology<br>• defining the ampere as a fundamental SI unit, and relating the coulomb and second to it<br>• distinguishing between conventional and electron flow current<br>• explaining Ohm's law as an empirical, rather than a theoretical, relationship<br>• quantifying electrical energy and power dissipated in a resistor, using Ohm's law<br>• explaining Kirchhoff's current and voltage rules as a logical consequence of the laws of conservation of energy and charge<br>• analyzing, quantitatively, simple series and/or parallel DC circuits in terms of the variables of potential difference, current and resistance, using Kirchhoff's rules and/or Ohm's law (solutions requiring Kirchhoff's rules to be limited to networks containing two power supplies and three branch currents). |

| SKILLS | STS CONNECTIONS |
|---|---|
| *Students should be able to demonstrate the skills and thinking processes associated with the practice of science, by:* | *Students should be able to demonstrate the interrelationships among science, technology and society, by:* |
| | • understanding and analyzing, quantitatively, simple series and parallel circuits in terms of Ohm's law and Kirchhoff's rules; and quantifying electrical energy and power dissipated in a resistor, using Ohm's law; and by determining, from empirical and theoretical evidence the relationships among electric energy/power, current, resistance and voltage, within the context of: |
| • determining, from empirical and theoretical evidence, the relationships among electric energy/power, current, resistance and voltage<br>• performing an experiment to explain the relationships among current, voltage and resistance<br>• designing, analyzing and solving simple resistive DC circuits<br>• drawing diagrams of simple resistive DC circuits, using accepted symbols for circuit components<br>• designing and performing an experiment demonstrating the heating effect of electric energy. | • analyzing common technological applications of electricity to solve practical problems in daily life; e.g., toasters, hair dryers, light fixtures<br>OR<br>• comparing and contrasting electrical energy with other energy sources with respect to such factors as cost, energy potential, risks and benefits to society, safety concerns and their impact on the quality of life of future generations<br>OR<br>• analyzing the use of series and parallel networks in household circuits in terms of the problems addressed<br>OR<br>• investigating the need for and the functioning of circuit breakers in household circuits<br>OR<br>• analyzing the risks of electric shock in terms of scientific principles<br>OR<br>• investigating the requirements and potential of careers, supported by societal needs and interests, involving electricity<br>OR<br>• any other relevant context. |

# UNIT 3
# MAGNETIC FORCES AND FIELDS

## OVERVIEW

**Science Themes:** *Diversity* and *Matter*

In Unit 3, the *diversity* of *matter* is highlighted as its magnetic nature is considered in the context of electric and magnetic interactions.

The concept of field, introduced in Physics 20, Unit 2: Circular Motion and Gravitation, is applied to magnetic phenomena. The concepts from Physics 20, Unit 1: Kinematics and Dynamics, are applied to charged particle dynamics in magnetic fields. The principles of electromagnetism introduced in Science 9, Unit 4: Electromagnetic Systems are further applied to an investigation of the functioning of electric motors, generators and transformers. The unit concludes with the consideration of the characteristics of the electromagnetic spectrum and alternating current (AC) circuits. This unit provides a foundation for further study of electromagnetic principles in Unit 4 and for post-secondary studies in physics.

The three **major concepts** developed in this unit are:

- magnetic field theory is a model used to describe magnetic behaviour
- electromagnetism pervades the Universe
- electromagnetic radiation is a physical manifestation of the interaction of electricity and magnetism.

In this unit, *students will develop* an ability to use the **skills** and **thinking processes** associated with the practice of science, emphasizing:

- initiating and planning
- collecting and recording
- organizing and communicating
- analyzing data from electromagnetic interactions
- connecting, synthesizing and integrating to relate the data to the laws and principles of magnetic forces and fields
- evaluating the process or outcomes of activities investigating the concepts of magnetic forces and fields.

The **STS connections** in this unit illustrate:

- the central role of evidence in the accumulation of knowledge, and the ways proposed theories may be supported, modified or refuted
- the ways in which science advances technology and technology advances science
- the use of technology to solve practical problems
- the influence of the needs, interests and financial support of society on scientific and technological research
- the ability and responsibility of society, through science and technology, to protect the environment and use natural resources judiciously to ensure quality of life for future generations.

## ATTITUDES

*Students will be encouraged to:*

- appreciate the need for computational competence in quantifying electromagnetic phenomena
- accept uncertainty in the descriptions and explanations of electromagnetic phenomena in the physical world
- be open-minded in evaluating potential applications of electromagnetic principles to new technology
- appreciate the parallelism in the characteristics of electrical, gravitational and magnetic phenomena
- appreciate the fundamental role the principles of electricity and magnetism play in our everyday world
- appreciate the need to follow safe practices when working with electricity
- appreciate the restricted nature of evidence when interpreting the results of electromagnetic interactions.

| MAJOR CONCEPT | KNOWLEDGE |
|---|---|
| | *Students should be able to demonstrate an understanding that:* |
| 1. Magnetic field theory is a model used to describe magnetic behaviour. | • field theory can be used to describe magnetic interactions, by extending from Physics 20, Unit 1 and Physics 20, Unit 2, and by:<br>• explaining the source of magnetic characteristics of matter in terms of magnetic domains<br>• comparing the magnetic properties of Earth with those of artificial magnets<br>• explaining magnetic interactions in terms of vector fields<br>• comparing gravitational, electric and magnetic fields in terms of their sources and directions. |

| SKILLS | STS CONNECTIONS |
|---|---|
| *Students should be able to demonstrate the skills and thinking processes associated with the practice of science, by:* | *Students should be able to demonstrate the interrelationships among science, technology and society, by:* |
| | • understanding that magnetic interactions are described using field theory; and comparing and contrasting gravitational, electric and magnetic fields and interactions in terms of their source, direction and vectors; and by using field lines to show the shape and orientation of magnetic fields due to a variety of sources, within the context of: |
| • plotting magnetic fields, using field lines to show the shape and orientation of the magnetic fields resulting from magnetic poles or current-carrying conductors. | • evaluating magnetic field theory as a model to describe and predict observations of magnetic behaviour based on supportive evidence<br><br>OR<br><br>• discussing contemporary developments in the areas of electricity and magnetism, and their immediate and potential impact on daily life; e.g., superconductivity<br><br>OR<br><br>• investigating and reporting the affects of magnetism on the behaviour of living organisms in terms of the limitations of scientific knowledge and technology and in terms of quality of life<br><br>OR<br><br>• any other relevant context. |

| MAJOR CONCEPT | KNOWLEDGE |
|---|---|
| | *Students should be able to demonstrate an understanding that:* |
| 2. Electromagnetism pervades the Universe. | • magnetic forces and fields are described in relation to electric currents, by extending electromagnetic concepts from Science 9, Unit 4, and by:<br>• demonstrating how the discoveries of Oersted and Faraday form the foundation of the theory relating electricity to magnetism<br>• describing a moving charge as the source of a magnetic field; and predicting the orientation of the magnetic field from the direction of motion<br>• predicting, quantitatively, how a uniform electric and/or magnetic field affects a moving electric charge, using the relationships among charge, motion and field direction<br>• relating and explaining, qualitatively, the interaction between a magnetic field and a moving charge as to how a magnetic field affects a current-carrying conductor<br>• predicting, quantitatively, the effect of an external magnetic field on a current-carrying conductor<br>• describing the effects of moving a conductor in an external magnetic field, using the analogy of a moving charge in a magnetic field<br>• predicting, quantitatively, the effects of a magnetic field on a moving conductor<br>• predicting, quantitatively, and verifying, the effects of changing one, or a combination, of the variables in the relationship $\frac{N_p}{N_s} = \frac{V_p}{V_s} = \frac{I_s}{I_p}$<br>• explaining the relationship between, and calculating, the effective and maximum values of, voltage and current in AC devices, given appropriate information<br>• discussing, qualitatively, Lenz's law in terms of conservation of energy; describing, giving examples, situations where Lenz's law applies. |

| SKILLS | STS CONNECTIONS |
|---|---|
| *Students should be able to demonstrate the skills and thinking processes associated with the practice of science, by:* | *Students should be able to demonstrate the interrelationships among science, technology and society, by:* |
| | • understanding that magnetic forces and fields are related to electric currents; and predicting, quantitatively, the effect of a uniform electric and/or magnetic field on a moving electric charge, and explaining the motor and generator effects; and by analyzing empirical evidence of magnetic field–current interactions, within the context of: |
| • designing, performing and analyzing experiments demonstrating magnetic field–current interactions<br><br>• predicting, using the LHR or RHR (hand rules), the relative directions of motion, force and field in electromagnetic devices<br><br>• relating the magnetic force, using Newton's second law, to the motion of an electric charge following a curved path in a magnetic field. | • identifying and analyzing the application of electromagnetic interactions in the functioning of several types of technology<br><br>OR<br><br>• explaining, qualitatively, the design and function of AC and DC motors, generators, meters and other simple electromagnetic devices, using correct scientific terminology<br><br>OR<br><br>• assessing the impact of the transformer and alternating current on the generation, transmission and use of electrical energy, and on quality of life<br><br>OR<br><br>• evaluating, objectively, electromagnetic biomedical technology, in terms of solving practical problems and the influence of the needs, interests and financial support of society for its development, such as magnetic resonance imaging (MRI) or positron emission tomography (PET)<br><br>OR<br><br>• analyzing the parallels among gravitational, electrical and magnetic phenomena in terms of empirical evidence, and evaluating the role the conservation laws play in the accumulation of knowledge<br><br>OR<br><br>• any other relevant context. |

| MAJOR CONCEPT | KNOWLEDGE |
|---|---|
| | *Students should be able to demonstrate an understanding that:* |
| 3. Electromagnetic radiation is a physical manifestation of the interaction of electricity and magnetism. | • Maxwell's theory of electromagnetism expanded on Oersted's and Faraday's generalizations, by:<br>• stating that electromagnetic radiation is the result of accelerating electric charges, and demonstrates wavelike behaviour<br>• comparing and contrasting the constituents of the electromagnetic spectrum on the basis of frequency, wavelength and energy<br>• solving problems algebraically, using the relationships among speed, wavelength, frequency, period and/or distance, of electromagnetic waves<br>• comparing and contrasting natural and technological processes by which the major constituents of the electromagnetic spectrum are produced<br>• explaining, qualitatively, Maxwell's theory of electromagnetism<br>• explaining the propagation of electromagnetic radiation in terms of perpendicular electric and magnetic fields, varying with time, travelling away from their source at the speed of light<br>• explaining, qualitatively, how different types of electromagnetic radiation interact with matter, including biological effects; e.g., microwaves, ultraviolet radiation, X-rays. |

| SKILLS | STS CONNECTIONS |
|---|---|
| *Students should be able to demonstrate the skills and thinking processes associated with the practice of science, by:* | *Students should be able to demonstrate the interrelationships among science, technology and society, by:* |
| | • understanding that electromagnetic radiation is a physical manifestation of the interaction of electricity and magnetism; and explaining the propagation of electromagnetic radiation in terms of electric and magnetic fields; and by demonstrating the wavelike behaviour of electromagnetic radiation; and by predicting the conditions required for electromagnetic radiation emission, within the context of: |
| • performing experiments, and/or using simulations, demonstrating the wavelike behaviour of electromagnetic radiation<br><br>• predicting the conditions required for electromagnetic radiation emission. | • evaluating the risks and benefits of using electromagnetic radiation in technological solutions to practical problems; in terms of the quality of life, the limitations of science and technology, and societal needs, interests and financial support<br><br>OR<br><br>• researching, reporting on and evaluating the use of electromagnetic radiation technology in such scientific fields as biology, chemistry, medicine, astronomy, in terms of societal needs, interests and financial support, and the contribution to the accumulation of scientific knowledge<br><br>OR<br><br>• investigating the requirements and potential of careers, supported by societal needs and interests, involving electromagnetism<br><br>OR<br><br>• any other relevant context. |

# UNIT 4
# NATURE OF MATTER

## OVERVIEW

**Science Themes:** *Energy* and *Matter*

In Unit 4, students investigate the science themes of *energy* and *matter*, as the electric nature of *matter* is considered in the context of developing and understanding of quantum concepts, atomic theory and nuclear processes.

Building on previous learning from Science 10, Unit 3: Energy and Matter in Chemical Change, the discovery of the electron and the development of the quantum model of the atom is studied. The study of the photoelectric effect and the photon model of light provides a link to Physics 20, Unit 4: Light, where the wave model of light is emphasized. The unit concludes with the study of radiation, the characteristics of fission and fusion reactions, quantization of *energy* and how *energy* levels in nature support modern atomic theory. This unit provides a foundation for post-secondary studies in related areas.

The four **major concepts** developed in this unit are:

- the atom has an electric nature
- the photoelectric effect requires the adoption of the photon model of light
- nuclear fission and fusion are nature's most powerful *energy* sources
- *energy* levels in nature support modern atomic theory.

In this unit, *students will develop* an ability to use the **skills** and **thinking processes** associated with the practice of science, emphasizing:

- initiating and planning
- collecting and recording
- organizing and communicating
- analyzing data from experiments, empirical and theoretical evidence for the electron and quantum concepts
- connecting, synthesizing and integrating to relate the data to a theoretical model of the atom, and to the principles of the wave–particle duality of *matter*
- evaluating the process or outcomes of activities investigating quantum concepts and the wave–particle duality of matter.

The **STS connections** in this unit illustrate:

- the central role of evidence in the accumulation of knowledge, and the ways proposed theories may be supported, modified or refuted
- the inability of science to provide complete answers to all questions
- the functioning of products or processes based on scientific principles
- the ways in which science advances technology and technology advances science
- the use of technology to solve practical problems
- the limitations of scientific knowledge and technology
- the ability and responsibility of society, through science and technology, to protect the environment and use natural resources judiciously to ensure quality of life for future generations.

## ATTITUDES

*Students will be encouraged to:*

- appreciate that models are modified as new and/or conflicting evidence is presented
- appreciate the role of mathematics in assessing the risks and benefits of radioactivity and the commercial use of nuclear *energy*.

| MAJOR CONCEPT | KNOWLEDGE |
|---|---|
| | *Students should be able to demonstrate an understanding that:* |
| 1. The atom has an electric nature. | • the discovery of the electron contributed to the formulation of quantum concepts and atomic models, by extending from Science 10, Unit 3, and by:<br>• explaining how the discovery of cathode rays contributed to the development of atomic models<br>• explaining Thomson's experiment and the significance of the results<br>• deriving the relationship $\frac{q}{m} = \frac{v}{BR}$, using circular motion and charged particles in electric and magnetic field concepts<br>• explaining Millikan's experiment and its significance relative to charge quantization<br>• relating the electronvolt, as a unit of energy, to the joule. |

| SKILLS | STS CONNECTIONS |
|---|---|
| *Students should be able to demonstrate the skills and thinking processes associated with the practice of science, by:* | *Students should be able to demonstrate the interrelationships among science, technology and society, by:* |
| | • understanding and explaining how technological advances and experimental evidence contributed to the formulation of models of the atom; and by determining the charge to mass ratio of the electron, and the mass of an electron and/or ion, given appropriate empirical data, within the context of: |
| • performing an experiment, or using simulations, to determine the charge to mass ratio of the electron<br><br>• determining, in quantitative terms, the mass of an electron and/or ion, given appropriate empirical data. | • analyzing how the identification of the electron and its characteristics is an example of the interaction of science and technology<br><br>OR<br><br>• evaluating how, in the scientific process, discoveries are often missed by investigators failing to identify and/or correctly interpret evidence; e.g., X-rays<br><br>OR<br><br>• any other relevant context. |

| MAJOR CONCEPT | KNOWLEDGE |
| --- | --- |
| | *Students should be able to demonstrate an understanding that:* |
| 2. The photoelectric effect requires the adoption of the photon model of light. | • the quantum concept is required to explain adequately some natural phenomena, by extending from Physics 20, Unit 4, and by:<br>• explaining the necessity for Planck to introduce the quantum of energy concept to explain blackbody radiation<br>• defining the photon as a quantum of electromagnetic radiation<br>• describing how Hertz discovered the photoelectric effect while investigating electromagnetic waves<br>• explaining the photoelectric effect in terms of the intensity and wavelength of the incident light and surface material<br>• assessing the assumptions made by Einstein in explaining the photoelectric effect<br>• defining threshold frequency as the minimum frequency giving rise to the photoelectric effect; and work function as the energy binding an electron to a photoelectric surface<br>• explaining the relationship between the kinetic energy of a photoelectron and stopping voltage<br>• using Einstein's equation, quantitatively, to describe photoelectric emission<br>• describing the photoelectric effect as a phenomenon that supports the notion of the wave–particle duality of electromagnetic radiation<br>• explaining X-ray production as an inverse photoelectric effect, and predicting, quantitatively, the short wavelength limit of X-rays produced, given appropriate data<br>• explaining, qualitatively, the Compton effect and the de Broglie hypothesis applying the laws of mechanics, conservation of momentum and energy, to photons, as another example of wave–particle duality. |

| SKILLS | STS CONNECTIONS |
|---|---|
| *Students should be able to demonstrate the skills and thinking processes associated with the practice of science, by:* | *Students should be able to demonstrate the interrelationships among science, technology and society, by:* |
| | • understanding that an adequate explanation of some natural phenomena requires the quantum concept; and describing the photoelectric effect as evidence for the notion of wave–particle duality of electromagnetic radiation; and by investigating, empirically, the photoelectric effect, within the context of: |
| • performing an experiment demonstrating the photoelectric effect and interpreting the data obtained<br><br>• predicting and verifying the effect that changing the intensity and/or frequency of the incident radiation or the material of the photocathode has on photoelectric emission. | • analyzing, in general terms, the functioning of various technological applications of the photoelectric effect to solve practical problems; e.g., automatic door openers, burglar alarms, light meters, smoke detectors<br><br>OR<br><br>• discussing why the photoelectric effect could not be explained, using the wave model of electromagnetic radiation, and thus required a new hypothesis<br><br>OR<br><br>• identifying industrial and scientific uses of X-rays; e.g., X-ray examination of welds, crystal structure analysis<br><br>OR<br><br>• any other relevant context. |

| MAJOR CONCEPT | KNOWLEDGE |
| --- | --- |
| | *Students should be able to demonstrate an understanding that:* |
| 3. Nuclear fission and fusion are nature's most powerful *energy* sources. | • the processes of nuclear fission and fusion are nature's most powerful energy sources, by:<br><br>• using the isotope notation to describe and identify common nuclear isotopes, and determine the number of each nucleon of an atom<br>• describing the nature and behaviour of alpha, beta and gamma radiation<br>• writing nuclear equations for alpha and beta decay<br>• performing simple, nonlogarithmic, half-life calculations<br>• predicting the particles emitted by a nucleus from the examination of representative transmutation equations<br>• explaining, qualitatively, how radiation is absorbed by matter, and compare and contrast the biological effects of different types of radiation<br>• comparing and contrasting the characteristics of fission and fusion reactions<br>• explaining, qualitatively, the importance of Einstein's concept of mass–energy equivalence<br>• relating, qualitatively, the mass defect of the nucleus to the energy released in nuclear reactions. |

| SKILLS | STS CONNECTIONS |
|---|---|
| *Students should be able to demonstrate the skills and thinking processes associated with the practice of science, by:* | *Students should be able to demonstrate the interrelationships among science, technology and society, by:* |
| | • understanding that the processes of nuclear fission and fusion are nature's most powerful energy sources; and describing the nature of particle radiation and nuclear decay, and explaining, qualitatively, the importance of the concept of mass–energy equivalence in nuclear reaction processes; and by analyzing empirical nuclear decay data, and performing a risk/benefit analysis of a nuclear energy application, within the context of: |
| • using library resources to research and report on selected scientists who contributed to our understanding of the structure of the nucleus<br>• inferring radiation properties from experimental data provided<br>• graphing data for radioactive decay and interpolating values for half-life<br>• interpreting some common nuclear decay chains<br>• performing a qualitative risk/benefit analysis of a nuclear energy application. | • assessing the value to society of nuclear and particle research<br>OR<br>• evaluating the applications of radiation phenomena and technologies in research, medicine, agriculture, industry; e.g., isotope tracing, food irradiation<br>OR<br>• assessing the risks and benefits of exposure to natural background radioactivity and artificially induced radioactivity; e.g., air travellers to cosmic radiation, dental X-rays<br>OR<br>• evaluating, qualitatively, the risks and benefits of using fission and/or fusion as commercial sources of energy, in terms of the limitations of scientific knowledge and technology, and the ability and responsibility of society to protect the environment and to use natural resources judiciously to ensure quality of life for future generations<br>OR<br>• investigating the requirements and potential of careers, supported by societal needs and interests, involving nuclear physics<br>OR<br>• any other relevant context. |

| MAJOR CONCEPT | KNOWLEDGE |
| --- | --- |
| | *Students should be able to demonstrate an understanding that:* |
| 4. *Energy* levels in nature support modern atomic theory. | • the Rutherford–Bohr model of the atom represents a synthesis of classical and quantum concepts, by:<br>• explaining, qualitatively, the significance of the results of Rutherford's scattering experiment in terms of the nature and role of the nucleons; and the size and mass of the nucleus and the atom, which lead to the proposal of a planetary model of the atom<br>• explaining why Maxwell's theory of electromagnetism predicts the failure of a planetary model of the atom<br>• describing why each element has a unique line spectrum, and comparing and contrasting the characteristics of continuous and line spectra<br>• explaining, qualitatively, the conditions necessary to produce line emission and line absorption spectra<br>• explaining the quantum implications of the line absorption and the line emission spectra, and determining any variable in the Balmer equation $\frac{1}{\lambda} = R_H\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$<br>• explaining Bohr's concept of "stationary states" and their relationship to line spectra of atoms; and using the frequency/wavelength of an emitted photon to determine the energy difference between states<br>• explaining the relationship between hydrogen's absorption spectrum and its energy levels<br>• describing how the Bohr atom can be used to predict the ionization energy of hydrogen, and to calculate the allowed radii of the hydrogen atom<br>• describing how the Rutherford–Bohr model has been further refined, by applying quantum concepts to a purely mathematical model based on probability and waves<br>• comparing and contrasting, qualitatively, the Rutherford, the Bohr and the quantum model of the atom. |

## SKILLS

*Students should be able to demonstrate the skills and thinking processes associated with the practice of science, by:*

- observing representative line spectra of selected elements
- predicting the conditions necessary to produce and observe line emission and line absorption spectra
- predicting the potential energy transitions in the hydrogen atom, using a labelled diagram showing the energy levels.

## STS CONNECTIONS

*Students should be able to demonstrate the interrelationships among science, technology and society, by:*

- understanding that the Rutherford–Bohr model offers a restricted explanation of the structure of the atom, and that a mathematical model provides a fuller explanation of the empirical evidence of energy levels within the atom; and by observing line spectra and predicting potential energy transition in an atom, within the context of:
  - investigating and reporting on the use of line spectra in the study of the Universe and the identification of substances

    OR

  - describing the functioning of lasers in terms of energy level transitions and resonance

    OR

  - investigating and reporting on the application of spectra concepts in the design and functioning of lighting devices; e.g., street lights, signs

    OR

  - analyzing how quantum concepts led to technological advances that benefit society; e.g., semiconductors, electron microscopes, computers

    OR

  - investigating and reporting on the contributions made by scientists to the development of the early quantum theory; e.g., Hertz, Planck, Einstein, Bohr, Compton, Davisson, Germer

    OR

  - any other relevant context.

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