KING'S College LONDON

PIPER (Promoting and Interpreting Physics Education Research)

Electro-motive force (EMF)

INTRODUCTION

The aim of the PIPER project is to engage teachers, teacher trainers and CPD providers in accessing and working with the best available evidence as they refine and justify their practice. This monograph focuses on the topic of EMF which is possibly one of the most commonly taught physics topics in the UK and elsewhere. While there are many teaching resources available and advice on how to teach the topic is not in short supply, there is also a growing body of research that can provide a source of knowledge about what teaching strategies work (and why) and why students find particular aspects of the topic difficult.

In putting this monograph together, we have identified, assembled, filtered, and translated studies that appear to offer robust evidence gathered in contexts which may be appropriate to teachers and students in England. We have also included some material that may be less relevant but is, we believe, interesting and informative.

THE PROBLEM

Some indication of the challenge facing students who come across EMF for the first time can be gauged from what for many is their first port of call for information, Wikipedia:

> **Electromotive force**, also called **emf**[1] (denoted $\mathcal{E}$ and measured in volts), refers to voltage generated by a battery or by the magnetic force according to Faraday's Law, which states that a time varying magnetic field will induce an electric current.[2] Electromotive "force" is not considered a force, as force is measured in newtons, but a potential, or energy per unit of charge, measured in volts.

So electromotive force isn't a force, it's a potential and its measurement involves two equally challenging phenomena, energy and charge. It is, perhaps, no wonder that students find aspects of the topic difficult.

Jimenez Gomez and Fernandez Duran (1998) identify some of the problems concerned with the teaching and learning of electricity:

- Electric charge is inseparable from the mass; it has two different forms (+ve and –ve); impossible to observe directly.
- PD, EMF are abstract concepts
- Voltage is hard to understand as students don't understand the balance of pressures and pressure differences.
- There are a variety of definitions of work and potential energy;

- Most authors confuse the definition of a concept with its operative relations and its phenomenological description.
- Mathematical models are not necessarily consistent with physical models

WHAT DO STUDENTS FIND DIFFICULT?

Jimenez Gomez and Fernandez Duran (1998) highlight key issues faced by learners:

- Is 'potential' the same as 'potential difference'? What are their similarities and differences?
- Is electric potential difference work, energy, or work and energy per unit of charge?
- Is electric potential difference a magnitude of the electric field or of the electric charge that is introduced into the field?
- Is electric potential difference a magnitude of the interaction, or does it have no relation with it?
- If electric potential different is not work nor energy per unit of charge, how is it related to them?

CURRENT

Liegeois et al. (2003) point out that students often think that electrical current is the origin of potential difference and that potential difference is just a measure of electric flow, more or less synonymous with current. They also tend to view electrical current as being used up by the bulbs, resistors, etc. in the circuit bulbs. The scientific explanation sees things the other way round: potential difference results from the inequality of charges between the battery terminals which itself results from chemical reactions inside the battery. That is, the separation of positive and negative charges and their accumulation on opposite sides. Potential difference, therefore, is the origin of electric current, the origin of the motion of the free electrons in the conductor to replace the missing electrons at the positive battery terminal.

In one study, Liegeois et al. examined the understanding of potential difference in the context of current–potential difference–resistance context among 100 students aged 13-19 studying in Reims, France. Students were given 12 cards each of which had showed an electrical circuit printed. At the bottom of the card was a response scale which went from 'No potential difference' to 'High potential difference'. Participants were tested both before and after taking a course on electricity at school. Most participants (of all ages), when asked to infer potential difference from resistance and current information, only relied on current and ignored or greatly underestimated the importance of resistance information. Secondly, participants' experience of electricity lessons did not seem to change the way participants responded.

In a second study Liegeois et al. used a teaching technique with three different groups (a) twelve 14-15 year-old pupils; (b) ten 12-13 year-old pupils who had never experienced courses on electricity; and (c) nine young adults who had technical occupations. Using similar circuit cards to the previous study, participants used the response scale to indicate what they thought the PD would be for each circuit. The participants were tested and taught over seven sessions. The experiment was self-paced, and the participants did the task individually in a quiet room in the school. The results were positive – the participants learned the correct science. What was particularly interesting was that that learning was not restricted to the participants who had previously received electricity lessons. The 12-13 year-old participants learned to predict potential difference as well as the other participants.

Parallel circuits

Millar and Beh's (1993) study involved 157 15-year-old comprehensive school students nearing the end of science courses on electricity. The main aim was to investigate the relative popularity of two models of solving parallel circuit problems. Model 1 results from perceiving the circuit primarily in voltage terms, the most important feature being that both resistors have the same voltage across them. Model 2, on the other hand, sees the circuit primarily in current and resistance terms - the focus being on the total effective resistance and the current which results.

Despite having just being taught about electricity, only a minority of the students had a good understanding of voltage in simple parallel circuits. Most were unable to state with confidence that the voltage measured across each branch will be equal to the battery voltage in simple circuits of this sort. Most students addressed the problem by writing down $V=IR$ (or $I= V/R$). They then scanned the question for numbers to substitute into the equation. As there is only one voltage in the situation, this is used for *V*. *R* poses more of a difficulty as there are two resistance values. Where the question asks for the current through the upper resistor, students are less likely to perceive the lower resistor as having any bearing on the problem, and simply use the upper resistor value. This of course leads to the correct answer for current, but an analysis of the problem which is, at best, partial. If, on the other hand, the question asks for the current through the lower resistor, then the upper resistor acts as a significant distraction. Some students attempt to add the two resistors, using either the equation for addition of parallel resistors or simple addition.

Millar and Beh suggest that much more emphasis needs to be given to establishing and emphasizing basic facts about voltmeter readings across parallel branches. The fact that voltages across parallel resistors connected directly to the same voltage source are the same, needs to be explicitly emphasized, and reinforced by reference to examples such as the constant 240V across domestic mains appliances, however many are connected and switched on, and the fixed 12V across all the lamps and other devices run from the same car battery. Greater emphasis should also be given to the view of simple parallel circuits as nested monocircuits. This approach requires knowledge that the voltage across each branch is equal to the full battery voltage.

Millar and King's (1993) study involved a diagnostic test which was given to a sample of 175 15-year-old students by their normal physics teacher. All the students were preparing to take public examinations in physics and had covered the topic of electricity in their course at the time they took the test. The test focused on the prediction of voltmeter readings in circuits consisting of two resistors in series. Few students appeared to see two-resistor series circuits as 'voltage dividers'.

Suggestions for teachers:

Teaching might be more explicitly directed towards helping students to see two-resistor series circuits as 'voltage dividers'. More emphasis needs to be given to qualitative, as opposed to quantitative questions, in teaching and discussion. Students need to understand that a change at one point in a circuit can have 'global' effects.

Teachers talk about the two-resistor series circuit in terms of 'voltage division' or 'voltage sharing'. Practical work could emphasize this, by allowing students to 'discover', for a range of resistor values, that the voltages across two resistors in series always add to equal the source voltage which could lead to incorporation of the ratio rule, using pairs of resistors of different known ratios.

Teaching needs to emphasize that changing the position of the two resistors does not affect the way the total voltage is shared out; the greater voltage is always across the greater resistor.

Resistors should be referred to as 'large' and 'small', as well as being described in terms of their actual numerical resistance. If numerical values are known, then the *ratio* of resistances should be emphasized, and be seen to be the same as the voltage ratio.

ELECTROCHEMISTRY

Garnett and Treagust's (1992) study involved 32 chemistry students in their final year of secondary schooling (age 17+ years) in Perth, Western Australia. Ten teachers were nominated students based on their prior attainment in chemistry with a mix of students coming from the top, middle and bottom thirds of their classes. Each student was interviewed for 40-50 minutes after being taught the electrochemistry topic (typically taught for 7-9 weeks with 200 minutes of class exposure each week). The interviews asked students to explain aspects of electrochemical and electrolytic cells.

Garnett and Treagust grouped the emerging misconceptions into six areas: (a) identifying the anode and cathode of electrochemical cells, (b) understanding the need for a standard half-cell, (c) understanding the current flow in electrochemical cells, (d) understanding the charge on the anode and cathode, (e) identifying the anode and cathode in electrolytic cells, and (f) predicting the products of electrolysis and the magnitude of the applied electromotive force.

Suggestions for teachers:

Two features of students' learning that might help teachers. Students tended to construct or generate their own meaning for language that is used in a scientific context. Students tended tendency to overgeneralize statements and apply them too literally. Teachers are advised to say that electric currents can be described as "drifting electrons (in metal conductors) or ions (in solution)" (Garnett and Treagust, 1992, p. 1096).

Students' erroneous ideas about electrochemical cells were associated with the idea that moving electrons are always necessary for current to flow. For example, "Some students believed electrons must complete, or travel, a closed path around the cell. They envisaged electrons leaving the anode and traveling through the external circuit to the cathode-moving from the cathode into the electrolyte, moving through the solution, and being released onto the anode" (p. 1088). Many students appeared to believe that electrons move in solution so, when referring to electrolytes, teachers should explain "drifting ions are the current." Garnett and Treagust also suggest that teachers explain that the salt bridge allows positive and negative ions to drift to the cathode and anode, respectively, and therefore maintain electrical neutrality. To say that the salt bridge "completes the circuit" leaves too much to the imagination of some students.

MODELS

Various 'unscientific' models have been found to be held by young children, students and adults, and may be inadvertently reinforced in schools (Driver et al., 1994) and through everyday electrical terminology (for example, Solomonidou and Kakana, 2000) that in some cases are embedded in superseded 'scientific' models (for example, Sheils, 2012). These models have been investigated and described by researchers (Jaakkola et al., 2011, Pesman and Eryilmaz, 2010, Kucukozer and Kocakulah, 2007, Taber et al., 2006, Çepni and Keleş, 2006, Borges and Gilbert, 1999, Shipstone, 1988, Shipstone et al., 1988, Psillos et al., 1987, Driver et al., 1985, Osborne and Freyberg, 1985, Stocklmayer and Treagust, 1996) across time, age group and country, with similar findings. The most significant models are:

Sink model/Unipolar model: Only one wire is needed between the bulb and a cell (Jaakkola et al., 2011, Driver et al., 1994, Osborne and Freyberg, 1985, Shipstone, 1985). This model appears commonly in younger students being replaced by other models as they become more familiar with electric circuits (for example Çepni and Keleş, 2006);

Clashing current model: currents (positive and negative) leave from the two poles and light bulb where they clash (Jaakkola et al., 2011, Driver et al., 1994, Osborne and Freyberg, 1985);

Current consumption model/attenuation model: In a closed circuit, the cell is a source of current that is constant regardless of the components in it, and current is therefore shared among similar components, whether in series or in parallel. (Jaakkola et al., 2011, Driver et al., 1994, Osborne and Freyberg, 1985). Students view current as being 'used up' around the circuit. Notions of voltage and current are used interchangeably in this model, and students struggle with the idea that if there is no current between two points there may nonetheless be a potential difference. Some researchers view this confusion as being caused or reinforced by introducing current as the primary concept long before voltage, rather than introducing both concepts at the same time.

These models are all *'sequential'*, that is, the order of the components matters, and appear to be related to well known everyday notions of cause-and-effect. Electricity is somehow standing in unconnected wires. Such models fail to explain the instantaneous lighting of a bulb, and may hinder students from understanding that an effect at point B has a simultaneous impact on points A 'before' and point C 'after'. There are other models that are not sequential.

Local model: focussing on local changes to a circuit rather than the impact of a local change on the whole circuit (Shipstone et al., 1988, Cohen et al., 1983).

Current conserved model/Ohm model/Scientific model: current is the same all around the series circuit (Driver et al., 1994, Osborne and Freyberg, 1985) and the size of the current depends on circuit configuration and on the quantity of energy dissipated at components (Jaakkola et al., 2011, Driver et al., 1994, Osborne and Freyberg, 1985).

In general it has been found that students in lower secondary schools hold non-scientific models (Tsai et al., 2007, Çepni and Keleş, 2006). There is also evidence that young children hold models (Glauert, 2009), although establishing what they involve is problematic. While the proportion of students developing a more scientific model increases with age, non-scientific models persist among some students, including at university level. Students also tend to have difficulties with understanding parallel circuits, suggesting that series and parallel circuits should be introduced at different times.

Diagnosing the models in use by students may be problematic in part because there is evidence that students may use different models depending on the context (Tsai et al., 2007), but partly because detecting the reasoning and students' sureness of a model is not the same as predicting the right answer. Pesman and Eryilmaz (2010) addressed these issues by developing a 'three tier' multiple choice test where for each situation students predict what will happen in the circuit, select a reason, and then indicate whether they are sure or not.

WHAT CAN TEACHERS DO?

CHALLENGING STUDENTS' THINKING

One way of challenging non-scientific ideas is to introduce 'cognitive conflict' that is, examples that are not explained by non-scientific models. For example, introducing ammeters either side of components can demonstrate that current is conserved rather than used up. However, students' own models can be sufficiently powerful to trick students into apparently seeing meter readings that fit with their held model, and even when students do apparently grasp the scientific model, they may revert to non scientific models later. Thus in addition to using cognitive conflict to challenge students' models, it may be necessary to introduce students explicitly not only to the scientific model, but also to the idea of models (among others, Driver et al., 1994). The qualitative approach that uses the brightness of a bulb to indicate the strength of a current can lead to confusion because even similar-rated bulbs suffer from manufacturing differences. Consequently, they don't glow equally bright even though they have the same current flowing through them. So, choosing bulbs carefully is vital.

USING ANALOGIES

Another way of helping students develop a scientific model is through the introduction of analogies, such as the heart and blood circulation approach. As with the above models, the use of an analogy also needs to be explained – that there is a one-to-one mapping of some, but not all, characteristics (see, for example, Hart, 2008). Analogies are not necessarily helpful, however, as they require students to understand the analogous situation. For example, the commonly used water analogy is a potentially powerful analogy (see Hong, 2010).

An analogy for the discussion of current and voltage: Current electricity is often thought of as a fluid that flows in the way that water flows through pipes. If there is a lot of water in a tank that is attached to a pipe, there is more pressure for the water to be pushed through the pipe. The voltage of a battery or a live wire might be compared to the height of the water in the tank since the voltage exerts pressure on the electrons to flow through the wire. The water that flows through the pipe helps us to understand how electricity flows along wires to the load.

Source:
http://www.yale.edu/ynhti/curriculum/units/1989/7/89.07.01.x.html

The water-circuit model shows that the pressure before a constriction (a resistance) is greater than the pressure after the constriction. The biggest drawback is that it implies, wrongly, that voltage is a pressure. In some cases the analogy may later be used in reverse – for example using electricity to understand the heart circulation system.

Analogies may be most helpful when several different ones are used together (Chiu and Lin, 2005). Thus in addition to the water analogy and heart/blood circulation analogy, adding in the analogies of workers pushing a train around a track, of teaming crowds (or 'Smarties') or of a bicycle chain (Nuffield-Chelsea Curriculum Trust, 1993) may help students to grasp the underlying model. At a higher level the use of 'box' and AVOW diagrams (Cheng and Shipstone, 2003a, Cheng and Shipstone, 2003b) may also be viewed as representing models of circuits in powerful ways and need careful explanation.

The choice of analogy does not necessarily default to using the most powerful in terms of electrical understandings if the limits of analogies are explained – sometimes simple maps are better than Ordnance Survey charts. While sophisticated analogies may allow students to develop an understanding of fields, beginners (potentially including teachers unfamiliar with electricity at, say GCSE or A level) may initially need a simpler analogy to grasp (Hart, 2008, Taber et al., 2006), although there is then a question as to what simplified model to use at different points in a student's career (Mulhall et al., 2001).

Suggestions for teachers:

Students hold a range of non-scientific models of which teachers need to be aware. Students may hold more than one model at the same time, and although as they become more experienced the form of model held may become more sophisticated, they do not necessarily develop a scientific model.

The weaknesses of non-sophisticated models therefore need to be challenged through direct observation and through persistent use of electrical ideas that need scientific models of explanation.

Teachers might consider making explicit reference to how the explanatory analogies they use map to a phenomena, and use a variety of analogies.

Simple 'graspable' analogies might be more useful than more powerful ones for beginners.

USE VOLTAGE AS THE PRIMARY CONCEPT

Psillos et al. (1998) offer a theoretical argument and a possible teaching structure for using voltage as the primary concept in teaching DC circuits. As an introduction, Psillos et al highlight common misconceptions identified in the literature:

- Students do not realise that the two variables of voltage and current are necessary to interpret a simple electric circuit.
- Voltage is viewed as the property of the current
- Students do not recognise the existence of voltage between battery terminals as a necessary condition for a circuit
- Battery is thought to supply constant current to the circuit (rather than maintaining a constant voltage across terminals)

Psillos et al. explored student (age 13- 15) conceptions (N = 147) of voltage prior to instruction. They found that students were more familiar with 'volt' than 'ampere' or 'coloumb'. However, they also found confusion regarding the meaning of 'volt': students defined it variously as a measurement of electricity; a quantity of current/electricity; the force of a current; the property of a battery. The authors go on to note that secondary textbooks use PD, EMF and Voltage to interpret DC circuits and electrostatic phenomena which further contributes to the confusion.

Suggestions for teachers:

As voltage, by definition, includes both PD and EMF. Thus they propose presenting voltage as the primary concept, rather than through relationships with other variables.

Voltage = potential difference = electromotive force

A possible teaching sequence would be:

[Initial exploration with series and parallel connections of batteries and bulb]

Explain volt indication on battery as related to the brightness of the bulb;
Explain voltmeters are connected to both terminals of a battery;
Demonstrate that voltage is different from current. (e.g. voltage between terminals, even when no current in circuit);
Explore size of batteries with respect to voltage.

Subsequent steps in the teaching sequence are then:

Current, resistance and energy stored;
Static electric;
Relationships between variable, e.g. Ohm's law.

USING COMPUTER SIMULATIONS

There is evidence (Jaakkola et al., 2011, Unlu and Dokme, 2011, Zacharia, 2007) that using computer simulations (for example, the 'electricity exploration tool) together with constructing real electrical circuits may be an efficient way of teaching, and offer deeper, learning. Zacharia (2007) found that replacing a real environment with a computer simulated one helped support adults to develop a more scientific model of electric circuits.

Suggestions for teachers:

Analogy-based simulations used together with laboratory activities not only appear to be more effective than either alone, but there are no apparent differences between using simulations and real laboratory work (Unlu and Dokme, 2011).

More recently Jaakkola et al., (2011) found that getting 12-year-olds constructing real circuits *in parallel* to using simulations (but starting with a simulated construction) is a more effective strategy than that of the teacher drawing out scientific implications with simulation alone. Furthermore, teacher support, beyond explaining how to use the equipment, appears to be unnecessary when both simulation and practical work are used together: students learnt more when given the freedom to explore without a teacher's structure.

TEACHERS AND PRE-SERVICE TEACHERS' UNDERSTANDINGS OF ELECTRICAL CIRCUITS

We suggested above that some teachers may find aspects of teaching EMF challenging. Research looking at understandings of electric circuits by pre-service and in-service physics teachers (most recently in Turkey by Kucukozer and Demirci, 2008) revealed that *some* beginner teachers:

- Used current, 'voltage' and energy interchangeably;
- Believed current was consumed;
- Believed that the order of components in a series circuit affected the brightness of a bulb (ie used 'sequential' reasoning);
- Thought that having more cells in a circuit (including in parallel) meant bulbs would always be brighter;
- Saw cells as a *source* of current, and typically a constant source;
- Could not place ammeters and voltmeters correctly in a circuit.

The order in which ideas are introduced to students may also play a part in the quality of understanding. According to Smith and van Kampen (2011), curricula can either introduce current as a primary concept (such as Psillos et al., 1988, Cohen et al., 1983, Rosenthal and Henderson, 2006) or else introduce voltage first (such as McDermott and Shaffer, 1992). Others might work using analogies, although these tend to be superficial, an exception being Schwedes and Dudeck's (1996) work on the water-flow analogy. Smith and van Kampen, in their research based in Ireland, found that pre-service teachers struggled to explain satisfactorily how bulb brightness varies in more complex circuits which involve multiple loops of cells and lamps. The mainly pre-service teachers attending their course tended to use just the concepts of current and resistance to explain differing bulb brightness, rather than the necessary concept of 'voltage'. They found that by introducing the concept of potential with respect to one side of a chosen cell, together with appropriate rules, prediction and ability to explain observations were improved.

Teachers and students may hold ‘non-scientific’ models of electric circuits and these can be difficult to challenge effectively. Nonetheless, Zacharia (2007) found that using a combination of virtual and real environments supported the development to a scientific model better than real environment alone. Specifically they introduced the virtual environment after students had explored simple circuits using a real environment and found more scientific models in use in comparison to the control group who used the real environment for throughout. An alternative approach may be to offer both real and virtual environments in parallel.

Suggestions for teachers:

Common difficulties teachers face include not understanding how cells function in a circuit and what happens when they are in parallel; having limiting models (alternative conceptions or misconceptions); muddling current, ‘voltage’ and energy).

Limited models of electric circuit behaviour may be revealed through asking for explanations of bulb brightness in circuits containing multiple cells and bulbs in different loops.

Teachers (and others) need to be equipped with understandings of EMF, potential difference (p.d.), and potential as well as current and resistance.

Virtual (or simulated) environments in conjunction with real environments for practical circuit work may support the development of a more scientific model of circuits for those holding non-scientific models.

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