DISCIPLINARY KNOWLEDGE FROM A PEDAGOGICAL POINT OF VIEW

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INTRODUCTION

Many physics teacher education programmes separate the teaching of content from the teaching of pedagogy. In some cases, teachers are expected to learn the physics content by attending courses designed for science students, while pedagogy is taught by education lecturers whose highest qualification in Physics seldom exceeds a bachelors degree, if that. As a result, those who train teachers in the teaching of Physics may not have developed the ways of thinking of a physicist or an understanding of the structure of the discipline. When this approach to teacher education is followed, a crucial element of a teacher education programme is likely to be omitted, namely pedagogical content knowledge (PCK). This term was coined by Lee Shulman (1986) in his seminal article entitled "Those who understand: Knowledge growth in teaching," subsequently reprinted as part of a collection of his essays (2004). PCK is subject matter for teaching. Shulman describes PCK as follows:

> Within the category of pedagogical content knowledge I include, for the most regularly taught topics in one's subject area, the most useful forms of representations of those ideas, the most powerful analogies, illustrations, examples, explanations, and demonstrations—in a word, the ways of representing and formulating the subject that make it comprehensible to others. Since there are no single most powerful forms of representation, the teacher must have at hand a veritable armamentarium of alternative forms of representation, some of which derive from research whereas others originate in the wisdom of practice.
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> Pedagogical content knowledge also includes an understanding of what makes the learning of specific topics easy or difficult: the conceptions and preconceptions that students of different ages and backgrounds bring with them to the learning of those most frequently taught topics and lessons. If those preconceptions are misconceptions, which they so often are, teachers need knowledge of the strategies most likely to be fruitful in reorganizing the understanding of learners, because those learners are unlikely to appear before them as blank slates.

A great deal of physics education research over the past thirty years has focused on identifying students' conceptions that are different from scientific concepts. A large number of common student conceptions related to a variety of physics concepts have been well documented (Duit, 2007). These conceptions have been given various names, including preconceptions, naive conceptions, alternative conceptions and misconceptions. Whatever they are called, physics educators now accept that when students enter our classrooms they already have many ideas about the physical world, some of which we do not consider scientific. In the past two decades, researchers have identified the conditions needed for conceptual change (Hewson and Thorley, 1989) and how teachers may facilitate conceptual change (see, for example, Scott et al, 1992).

A gap in the physics education literature, however, has been identifying the various types of PCK that Shulman refers to and making them easily accessible to practitioners. In the rest this chapter I shall give examples of PCK and discuss how PCK can be incorporated into programmes for teachers.

EXAMPLES OF PCK

PCK is specific to specific topics. In this section I shall give examples of PCK for the topic of electric circuits. I have chosen this topic because it is a standard part of physics curricula at both school and university levels. As indicated in the previous section, one type of PCK is knowledge of students' alternative conceptions. Many alternative conceptions have been identified related to electric circuits (see, for example, Shipstone et al, 1988). Some of the most common and most fundamental alternative conceptions are:

- Current gets used up by elements in a circuit
- A battery is the source of the current
- A battery supplies a fixed amount of current no matter what is connected in the circuit
- Batteries go flat when all their current is used up
- Current and voltage are not clearly distinguished

While it is important to know what alternative conceptions students hold, for teachers knowing how to address them is even more important. In this section I will provide detailed examples of PCK that has been shown to help students develop sound understanding of concepts associated with electric circuits. In the first sub-section I present a teaching sequence that incorporates nine different types of PCK. In the second sub-section I present examples of several other types of PCK.

A TEACHING SEQUENCE TO ILLUSTRATE SEVERAL TYPES OF PCK

The teaching sequence presented in this section is a distillation of the key aspects of various sequences that I have used with high school students, preservice and inservice teachers and foundation level (bridging year) university students over many years. It is intended to help students develop a sound understanding of concepts associated with electric circuits at an introductory level. A number of the activities are based on the work of McDermott (1996) and Arons (1990).

In the early days of research on student conceptions (twenty to thirty years ago) physics educators often gave students "pretests" for diagnostic purposes, that is, to identify students' conceptions prior to instruction. Now that many student conceptions are well-established, such diagnosis is not necessary for research purposes, although it is still useful for teachers to be aware of their own students' preconceptions. But getting students to think about an idea before they are taught about it serves another very important purpose—generating student interest. Students often find physics classes boring. One reason may be that as teachers we often give answers to questions that students have never asked or even thought about. By asking students to write down their predictions, we give them time to think about the idea or situation coming up and commit themselves to an answer. In the process they often become interested in finding out more. Labelling the task "predictions" rather than "pretest" takes away the negative connotations of a "test", and makes it more acceptable for students to write down what they really think instead of what they think is "right".

PCK element 1: Have students write Predictions before encountering new concepts or ideas.

The electric circuits teaching sequence begins with a handout labelled Predictions 1. On the handout students are shown a picture of a screw-type light bulb, one wire and a battery. They are asked to draw pictures of two arrangements that will make the bulb light up and two that will not. After completing their predictions, students are asked to discuss their predictions with other students. The most common incorrect arrangements students draw show one or both of the following configurations:

- the wire is drawn from one terminal of the battery to the tip of the bulb;
- the wire is drawn from one end of the battery to the other end, with the tip of the bulb touching one terminal of the battery.

PCK element 2: Allow students to observe physical phenomena where possible.

At this point students are given a bulb, wire and battery and asked to set up the arrangements they drew and see whether or not the bulb lights. (This step can be done as a whole-class demonstration if there is not equipment available for student experiments.) Students eventually find that the bulb only lights when there is a continuous path from one terminal of the battery to one terminal of the bulb (the tip or the side), then to the other terminal of the bulb and back to the other terminal of the battery. Since there has to be a complete circuit for the bulb to light we make an assumption that something must be flowing. We give the "something" the name "current".

PCK element 3: Relate experimental results to everyday life where appropriate.

The everyday expression "seeing is believing" is not necessarily true when it comes to physics experiments. Just because students saw in class that for the bulb to light two connections were needed to both the battery and the light bulb does not mean that they will believe that the same applies at home. On the contrary, they know that the lamps at home have one cord that plugs into the wall at one end and into the lamp at the other end.

To help students relate the lamps in their homes to the experiments they have done in class, the teacher shows the students a piece of flex (bought from the hardware store), the same type that is commonly used for lamps and other low-current devices. The teacher pulls the two strands of the flex apart so the students can see that although there is one cord it is actually made up of two wires. The teacher also shows the students a light fitting, pointing out the two connection points. She then explains that each strand of the flex has to be connected to a different connection point of the light fitting. Similarly, each strand has to be connected at the other end to a different pin of the plug.

Students then work on exercises showing different arrangements of batteries, bulbs and wires in which they are asked to decide whether or not the bulbs will light up and why or why not.

PCK element 4: Teach representations explicitly.

Now that students have seen where the connections must be made on a real battery and bulb, they are introduced to circuit diagrams. The teacher takes care to distinguish between a picture of a circuit, which shows physical connections, and a circuit diagram, which shows electrical connections. She emphasises that a circuit diagram is an abstract representation. She also explains that circuit diagrams differ from pictures in other ways, such as using special symbols for specific circuit elements, and straight lines for electrical connections. Circuit diagrams also do not represent unique physical configurations. For example, Figure 1 shows three different configurations that can be represented by the same circuit diagram.

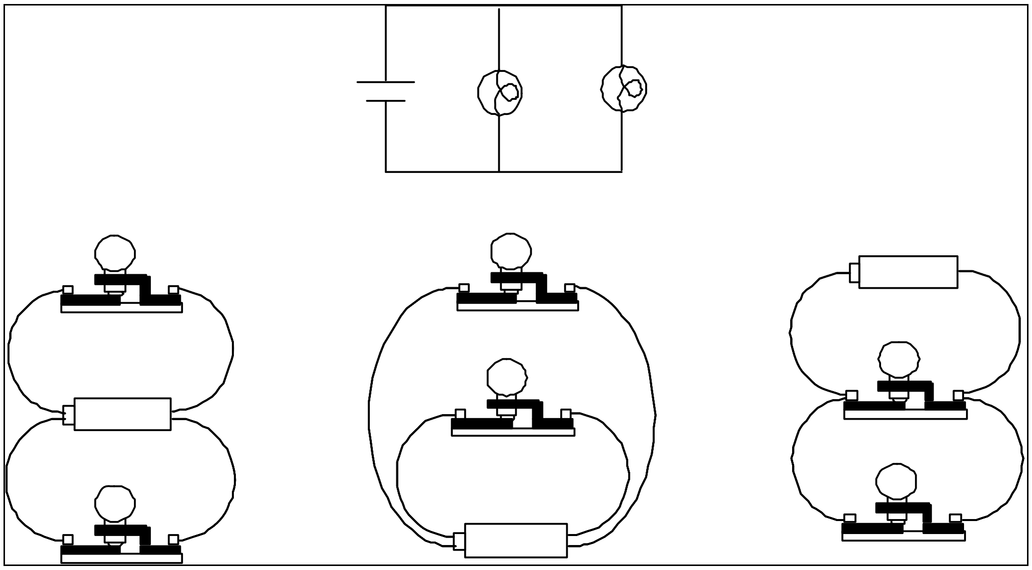


Figure 1: Three different physical configurations that can be represented by the same circuit diagram.

PCK element 5: When students must translate between different representations, give them practice in both directions.

Students are given pictures and asked to draw circuit diagrams. They are also given circuit diagrams and asked to draw pictures, showing where the connections must be made.

Next students are handed Predictions 2, which has two questions. In question 1 they are shown a picture (not a circuit diagram) of a circuit comprising two bulbs in series with a battery. They are asked to compare the brightnesses of the two bulbs. In question 2 they are asked to compare the brightnesses of each of the two bulbs in question 1 with a single bulb in series with a battery. In questions 3 they are asked to compare the current through the batteries in the two circuits.

The most common alternative conceptions are:

1. the bulb closest to the end of the battery they think the current comes from (some students say the positive end, some the negative) will be brighter than the second one because some of the current is used up and less current is left for the second bulb;
2. the bulb in the single bulb circuit will be brighter because it gets all the current and the two bulbs in series have to share it;
3. all three bulbs will have the same brightness because the current is the same through all the bulbs; this is because they are all attached to the same battery.
4. the current through the two batteries is the same.

Alternative conception 1 above reveals a misconception that current is used up when it passes through elements in a circuit. Alternative conceptions 2, 3 and 4 reveal misconceptions that a battery always supplies a fixed amount of current. Both of these misconceptions are well documented and widely held.

PCK element 6: Allow opportunities for students to debate alternative conceptions

After students complete Predictions 2 and discuss them with their partners, the teacher asks for volunteers to explain their predictions to the class. Students who hold different alternative conceptions are encouraged to argue for their view and against other views. The level of excitement can get very high, until students are dying to know what will happen. This has two benefits—it helps students let go of the tendency to only worry about the “right” answer and it raises the level of student interest. The teacher then sets up the circuits in the front of the room and shows the students what happens. Often the two light bulbs are not exactly the same brightness, which can lend support to the view that one of the two bulbs in series will be brighter than the other. In this case the teacher can swop the position of the two bulbs in order to show that the brighter bulb remains brighter regardless of where it is in the circuit.

The teacher tells the class that from now on they will assume that the brightness of a bulb indicates how much current is flowing through it. Using this assumption, and after seeing that the two bulbs in series are the same brightness (more or less), students should be able to reason out that current cannot be used up in one bulb before it reaches the second one. However, they may not believe it.

PCK element 7: Help students distinguish between related concepts

For many students, the idea that current is not used up in a circuit is counter-intuitive. After all, everyone knows that batteries go flat eventually. In some cases students’ misconceptions may be due to “cluster concepts” (Niederrer, 1987), groups of related concepts that are undifferentiated in the student’s mind. Electricity is an example of a cluster concept. For a student, electricity may have elements of current, voltage, energy and power all mixed together. One way of helping students distinguish among related concepts is to introduce a new concept that they can associate with their correct intuitions. This strategy is called concept substitution (Grayson, 2004).

In the example we are discussing, the teacher tells students that they are right that something gets used up. However, that “something” is not current, it is energy. Strictly speaking, energy from the battery is not used up—it is transformed into other forms of energy, such as heat and light. Current, on the other hand, just flows round and round the circuit; it is not used up. Now students can make sense of the fact that the two bulbs can have the same brightness and yet the battery will go flat eventually.

The teacher next sets up a circuit with three bulbs in series next to the circuits with one and two bulbs, respectively. Students are able to see that the brightness of the bulbs decreases as the number of bulbs in the circuit increases. Although this demonstration should be proof that the current passing through the batteries in the three circuits must be different, some students will argue that the diminishing brightness is because more bulbs have to “share” what they think is a fixed amount of current from the battery.

Students then complete Predictions 3. In question 1 they are asked to compare the brightnesses of two bulbs connected in parallel across a battery. In question 2 they are asked to compare the brightnesses of each of the bulbs in parallel with the brightness of a single bulb in series with a battery. In question 3 they are asked to compare the current through the batteries in the two circuits. Common alternative conceptions are:

1. The two bulbs in parallel will be dimmer than the single bulb because they have to share the current from the battery whereas the single bulb gets all of it;
2. The bulb closer to the battery will be brighter than the one further away from it.

3. The current through the two batteries is the same.

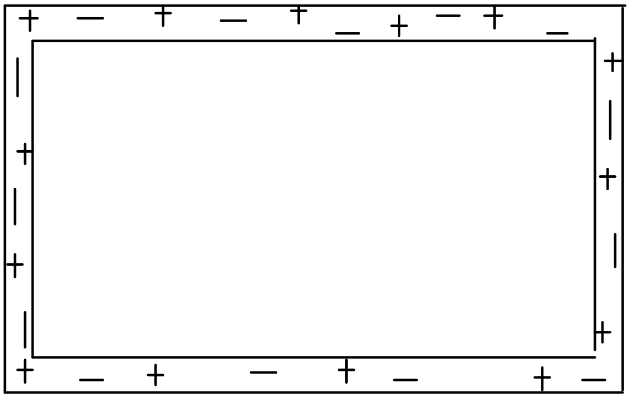
Alternative conceptions 1 and 3 again relate to the misconception that the battery supplies a fixed amount of current. As before, students are asked to debate their predictions as a class. The teacher then sets up the circuits and the students see that all three bulbs glow equally brightly. For many students this result makes no sense at all. How can identical batteries produce different amount of current?

At this point concept substitution is used again. The teacher holds up two batteries and reads the labels on them—1.5 V. She tells the students that the thing that is the same about the batteries is not current but voltage. So the voltage across the batteries is the same but the amount of current passing through a battery depends on what it is connected to and how. She also clarifies the notion of “sharing” current. Bulbs in parallel *do* share the current from the battery (some current goes through one bulb, the rest goes through the other bulb), while in a series circuit all the current goes through each bulb. If bulb brightness is related to current, then the bulbs in parallel must have more current flowing through them than the bulbs in series. Furthermore, the current through the battery attached to the two bulbs in parallel must be twice as much as through a battery connected to only one bulb.

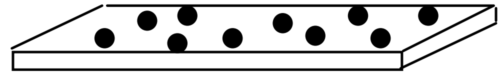
Students carry out several experiments and exercises involving circuits with two or more light bulbs in different configurations in order to reinforce the scientific concept that the amount of current that passes through a battery varies according to the load connected to it. In order to reinforce the concept of conservation of current students predict what the current will be on either side of various circuit elements in a closed circuit and then measure the current at these points using an ammeter. The distinctions between the three related concepts of current, voltage and energy are emphasised once more.

PCK element 8: Use analogies where appropriate

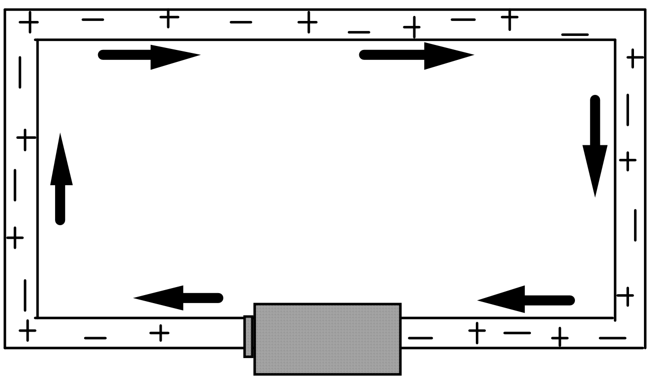
After working with the concept of current for some time and learning to distinguish it from energy, students are now formally introduced to voltage. Students have already learnt that voltage is the quantity that is the same for identical batteries. Now voltage is defined as the difference in electrical potential energy per unit charge between two points. Students are presented with a series of diagrams representing charges in a circuit and balls on a plank and are asked to make an analogy between the two situations (Figure 2). They need to indicate which aspects correspond in the two situations, which aspects are similar and which ones are different. The teacher emphasises the need to show not only where the analogy is useful but also where it breaks down. In this case, the analogy breaks down because the charges are in a closed circuit and keep circulating, while the balls fall off the end of the plank. (The analogy does not show which type of charge moves.)



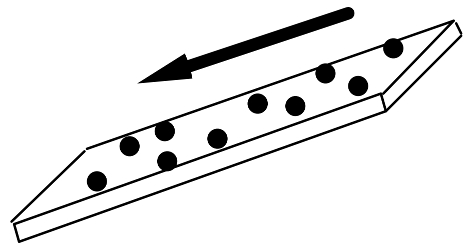
No electrical potential difference



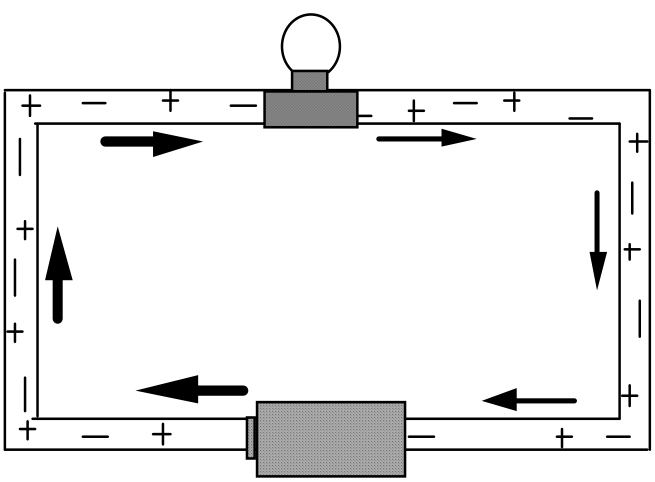
No gravitational potential difference



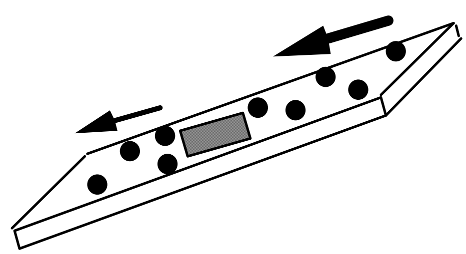
Inserting a battery creates an electrical potential difference



Tipping the board creates a gravitational potential difference



Bulb presents an obstacle to the flow of charge



Block presents an obstacle to the

movement of balls

Figure 2: Analogy between charges moving in a circuit and balls rolling down a plank

One advantage to this particular analogy is that is helps students realise that the battery is not the source of charges in a circuit. Its role is just to cause the charges that are already in the circuit elements to move. After going through the analogy students do several experiments and exercises to develop a feel for voltage.

PCK element 9: Provide opportunities for synthesis

Students then do experiments and exercises in which they need to determine both current and voltage, identify the relationship between them and be able to distinguish between them. They also relate the rate at which energy is transformed (power) to current and voltage, both qualitatively and quantitatively. For example, students reason that less current flows through a battery connected to two bulbs in series compared to one connected to two bulbs in parallel. As a result, the battery connected to the bulbs in parallel must supply more energy and therefore goes flat faster than the one connected to the bulbs in series.

In summary, the pedagogical content knowledge used in this teaching sequence included:

1. Using predictions to elicit known student alternative conceptions.
2. Using experiments to challenge common misconceptions.
3. Relating counter-intuitive experimental results to students' everyday experience.
4. Explicitly teaching the difference between pictures and circuit diagrams.
5. Giving students practice in translating in both directions between pictures and circuit diagrams.
6. Allowing students to debate their alternative conceptions.
7. Helping students distinguish between the related concepts of current, energy and voltage.
8. Using a gravitational analogy to introduce the concept of voltage.
9. Providing opportunities for synthesis.

OTHER EXAMPLES OF PCK RELATED TO ELECTRIC CIRCUITS

There are many other examples of PCK related to electric circuits, but I will only present three other types of PCK that have been shown to be effective, by way of illustration.

Johsua and Dupin (1987) presented school children in France with a *modelling analogy*, which they define as, "an abstract analogy operating as a thought experiment, never leading to practical manipulations." In their modelling analogy,

> A train circulates on a closed track-loop (Figure 3). It is made up of cars only (no locomotive), rigidly linked together, and evenly spaced. In a station, workers permanently push on the cars going past in front of them and influence the train speed. Obstacles exist on the track that also influence the train speed.

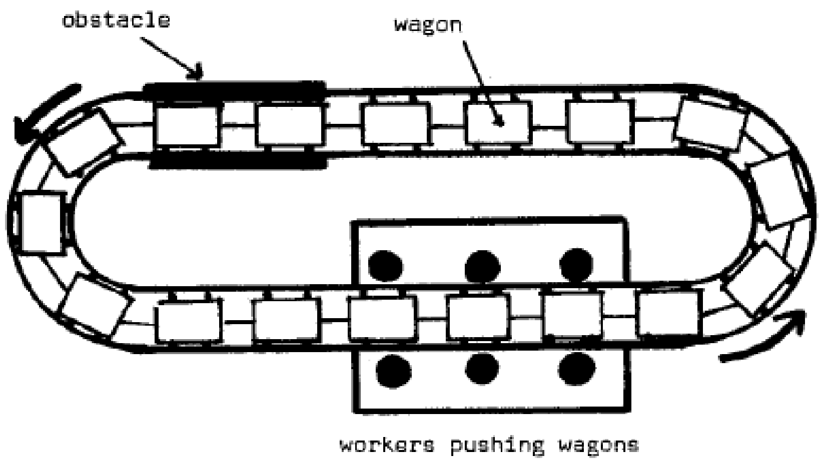


Figure 3: The train analogy (taken from Johsua and Dupin, 1987).

Table 1 elaborates the analogy. According to Johsua and Dupin, this analogy has both structural similarities and a metaphorical aspect.

> At constant pushing force and constant obstacle (electric resistance), the car flow-rate (current intensity) will be the same at each point on the track ("no losses"). The workers (the battery) maintain the movement by tiring their muscles (energy exhaustion of the battery).

Table 1: Correspondences between the train analogy and a simple electric circuit (from Johsua and Dupin, 1987).

Train analogy	Electric circuit
Cars	Electrons
Movement of cars	Movement of electrons
Rate at which cars pass a certain point along the track	Current intensity (rate at which electrons pass a given point in the circuit)
Mechanical friction (obstacle in the track)	Electrical resistance (atomic nuclei)
Men pushing train	Battery
Muscular fatigue of men	Wearing out of the battery
Vibrations of the cars, noise and heat produced by collisions with obstacles in the track	Heat in the wires and battery, heat and light in the bulb produced by the interactions of the electrons and atomic nuclei

Moodie (1995) devised a *physical model, or analogue,* for an electric circuit, which he used with school children in South Africa. The model was devised to be usable in rural schools that do not have equipment or even laboratories. It was also devised to give students a physical feel for the analogue in order to engage them actively and help them develop some intuition about the target electrical situation. In order to represent a circuit with a battery and a resistor, four chairs were laid out in a square and a rope was stretched around the legs of the chairs (Figure 4). The ends of the rope were tied together and the rope was marked off with dots of paint every 15 cm to represent charges. One student played the role of the battery; it was her job to keep the rope moving through her hands at a constant speed. Another child held an empty tin around which the rope was wrapped once to represent the resistor. A third child represented an ammeter by tapping a book with a ruler each time a dot on the rope passed him.

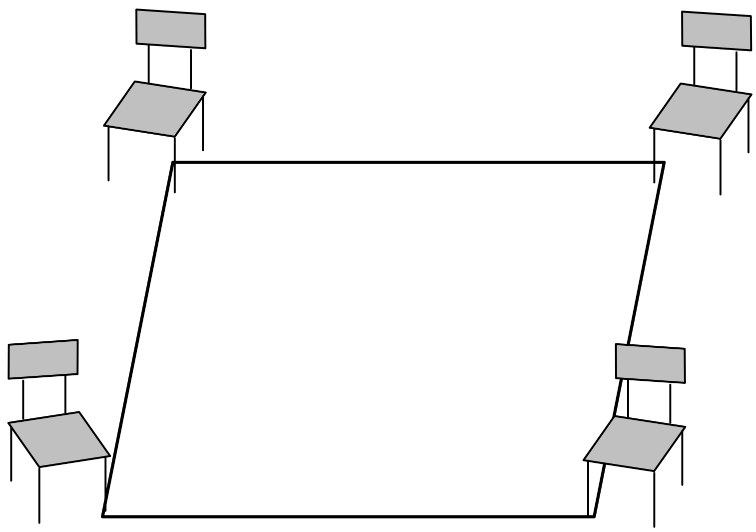


Figure 4: A physical model of an electric circuit.

Table 2 compares the features of the analogue with the features of the target situation, the electric circuit.

Table 2: Comparison between the rope and chairs analogue and an electric circuit

Analogue	Electric circuit
Rope with marks on it	Electric charges
Person moving the rope	Battery
Tin can	Resistor
Smooth chair legs	Good conductors
Frequency of ruler taps	Current (rate of flow of charge)
Increase in temperature of the tin can	Transfer of energy to the resistor
Increasing tiredness of the person moving the rope	Battery going flat

This model can be extended to two resistors in series by using two tins, each with one turn of rope wrapped around it. The student playing the battery is able to feel that it is much harder to pull the rope than before. The class can hear that the rope is moving more slowly because the person tapping the ruler taps more slowly. Similarly, the model can be extended to two resistors in parallel by using two ropes side by side and wrapping one turn of one rope around one tin and one turn of the other rope around the other tin. The person tapping has to tap each time he sees a dot go by on either rope, so students will hear the frequency of taps increase.

Both the modelling analogy and the physical model described above help students to distinguish between current and energy by helping them distinguish between what is moving and what is making it move. Both approaches also help students visualise the moving charges and thus “see” that in a circuit charges are neither supplied by the battery nor “used up”.

A very different type of PCK involves helping students make links between microscopic and macroscopic descriptions of physical phenomena. In Volume II of their book, *Matter and Interactions*, Chabay and Sherwood (2002) devote a whole chapter to making this link for electric circuits. As an example of their approach, they address the misconception that current is used up in a bulb connected to a battery by taking the student through the following chain of reasoning:

- current in a metal wire is the flow of electrons past a point;
- electrons cannot be destroyed (except by combining with positrons, but that is rare in everyday life);
- electrons cannot accumulate on the bulb because if they did the bulb would become negatively charged and then repel incoming electrons and stop the current;
- therefore current cannot get used up in a bulb and must be the same at all points in the circuit.

CONCLUSION

In this chapter I have given examples of a special kind of knowledge that teachers need if they want their students to acquire a sound and lasting understanding of physics, if they want to produce students for whom physics make sense, and if they want students to be able to apply their knowledge to different situations. Even though the discussion was limited to only one topic, electric circuits, there is still a lot of specialised knowledge needed to teach it effectively.

The detailed pedagogical content knowledge described in this chapter cannot be obtained by taking either a traditional physics course or a general teaching methods course, or even by taking both courses. A sound understanding of the relevant physics and competence in managing a classroom are essential, to be sure. But PCK is neither the intersection nor the union of content and general pedagogical knowledge; it is a different form of knowledge altogether. PCK is acquired by reading physics education literature, by watching and listening to experienced and reflective master teachers, and by actually teaching, reflecting on one’s own practice, and sharing ideas and experiences with one’s peers.

If teachers are to be most effective, PCK should be an explicit part of their preservice curriculum. Ideally, it should be taught by physics education researchers. But it is impossible for teachers to learn all the PCK they will ever need during their initial training, just as it is impossible for them to learn all the physics they will ever need for their whole teaching career in three or four years. For this reason, teachers need to participate in continuing professional development programs, professional associations, and to engage in regular reading in the field. Physics educators should also be encouraged to compile the PCK that is currently scattered across the literature and the continents into books and manuals that can be used by teachers and teacher educators.

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