Electric circuits: a new approach – part 1

David Shipstone and Peter C-H. Cheng

Many students experience difficulties in understanding the behaviour of electric circuits. Perhaps it is time to look at circuits from a new perspective.

In the summer term of the year 2000 one of us (DS) experimented with a novel way of teaching dc circuit theory to a group of 16 students in year 12, the first year of their GCE A-level physics course, in a comprehensive school.

The students were taught using box diagrams and AVOW diagrams, two closely related representations of the electric circuit. The teaching objectives, in employing the new approach, were:

- to resolve any problems of understanding the students might have and help them to develop clear working concepts of current and pd in circuits;
- to develop the students’ ability to break down complex circuits into their component parts without losing sight of their behaviour as complete circuits;
- to enhance the students’ problem-solving skills.

These objectives are not, of course, entirely independent of each other. Full details of the trial, including lesson plans and student exercises, are available elsewhere (Shipstone and Cheng, 2001).

ABSTRACT

Two new ways of representing electric circuits, box diagrams and AVOW diagrams, are described. The authors believe that use of these will help students to develop basic electrical concepts, improve their understanding of circuit processes and support them in problem solving. This article shows how they may be used to solve problems concerning networks of resistors which obey Ohm’s Law. Trials have been conducted with physics students in years 12 and 13. Some outcomes are described and feedback from students and teachers is included. The article concludes with suggestions as to how the techniques might be incorporated into teaching of basic circuit theory.

Box diagrams

In its simplest form the representation of a circuit that was employed is best referred to as a box diagram. In its more elaborate form (originally devised by PC) it is called an AVOW diagram (Cheng, 1999), for reasons which will be explained shortly. These diagrams can be employed to support the teaching of dc circuit theory at a variety of different levels. They work because they encapsulate Kirchhoff’s Laws.

The box diagram shown in Figure 1(b) may be used to represent what is happening in the circuit (a). Here the left-hand box represents the cell and the right-hand box the lamp. The heights of the boxes represent, respectively, the terminal pd of the cell and the pd across the lamp. The widths of the boxes, which are equal, represent the current, which is the same for both circuit elements. The direction of the current, in the conventional sense of a flow of positive charge from the positive terminal of the cell through the lamp to the negative terminal, is shown by the bold arrows. Current is always shown as downwards through the box representing the load in the circuit. This could be imagined as a sheet of current – in some ways like the sheet of water that comes over a waterfall, except that in this case the wider it is the more of it there is.

Connecting wires are not shown and appear as horizontal lines in these diagrams because, although there are currents through them, there is no pd across them. The current may be imagined as towards the lamp along the line at the top of the box diagram and from the lamp back to the battery along the line at the bottom. These bold arrows will be omitted later, when students have become familiar with the representation.

Figure 2 shows the box diagram for the load in a more complicated circuit. In this case the ‘sheet’ of current is broken up into a number of sections, just as
a waterfall is broken up by protruding rocks and ledges. A wider box represents a bigger current. The currents of 2 A and 1 A through resistors $R_1$ and $R_2$, which are connected in parallel, appear side by side and, when they leave the parallel combination, recombine to give a current of 3 A through $R_3$. The current through the battery is also 3 A.

Potential increases as we move upwards through the diagram. If we label the bottom line in the diagram as 0 V, i.e. set it at zero potential, then the top line will be at 6 V. Taller boxes represent bigger pd’s. The two resistors $R_1$ and $R_2$ connected in parallel have the same pd across them and so the boxes representing them are the same height.

Because the total current is the same all the way down through the network of resistors forming the load and, for that matter, the same all round the circuit, the width of the diagram is the same at the bottom as at the top. Also, because the pd’s along any current track always add up to the total applied pd, the sides of the diagram will be the same height. So all completed boxes must be rectangles, a representation which, we believe, should guide students when applying the basic principles on which such diagrams are based.

The box diagram for the whole circuit is like an open book – Figure 2(b) – with a ‘left-hand page’ for the battery and a ‘right-hand page’ for the load. The area of each box comprising the diagram is given by the product of the pd across and the current through each corresponding circuit element. The area of the left-hand page therefore shows the power delivered by the battery, while the areas of the boxes making up the right-hand page show what power is dissipated

Figure 1 Box diagram representation of a simple circuit.

Figure 2 Box diagram for a circuit with a network of resistors.
in each part of the load. For a box representing a resistor the ratio of its height to its width is the pd across the resistor divided by the current through it and so gives the resistance.

Trials of prototype materials during the spring term revealed that it was important to introduce this new representation with care, starting with revision of the circuit diagram and the distributions of current and pd within it, showing how each component is represented and explaining, in particular, what is happening to the current at each junction. Most A-level students have taken to the diagrams easily but a few weaker students have struggled at first. With these it is important to identify and address any problems that they have with the representation at an early stage.

The introduction of box diagrams to the experimental group concluded with the development of the diagram to represent the circuit shown in Figure 3(a). This built upon the experience gained with the circuit of Figure 2 by adding the series combination of resistors $R_3$ and $R_4$. Obviously, at some stage, if we are only concerned about what is happening in the network of resistors which forms the load, then there will be no need to include the left-hand part of the diagram, with the result shown in Figure 3(b). It is important to note that the outline of the box diagram is a rectangle again and also that there are no gaps left anywhere within it.

As in Figure 2, all those parts of the circuit where the electrical potential is constant appear as horizontal lines and all connectors, and any other components which have zero pd across them, also appear as horizontal lines. The vertical lines in the diagram mark the boundaries between the separate current streams through the load.

When combined with knowledge of Ohm’s Law these representations of circuits and networks will support students in the solution of a wide range of problems such as that in Figure 4. With problems of this type it is not a matter of first constructing the box diagram and then using it to solve the problem. The solution is usually reached, rather, at least in large
measure, in the process of constructing the diagram. In arriving at this point the various constraints already described provide valuable guidance towards the solution, particularly the need to arrive at an overall box diagram which is rectangular.

With practice in drawing these diagrams, together with the knowledge and understanding of basic electrical principles that goes along with this, students should be able to solve a wide range of resistance network problems. Some network problems could not be solved by this means, however. Examples are those in which only the resistance values and either the total current or total applied pd are given. For these, though, the procedure may be developed further by using AVOW diagrams.

**AVOW diagrams**

By taking one further step, that of adding diagonals to the boxes as shown in Figure 5, we arrive at the AVOW diagram. The gradient of the diagonal is the pd across the component divided by the current through it and so represents the resistance, which in Figure 5(a) is 3 Ω. The complete diagram, with general form as in (b), therefore represents the Amps, Volts, Ohms and Watts, whence the name AVOW. This would be an opportune moment at which to omit the current arrows introduced in Figure 1, or at least move them to positions above or below the boxes.

AVOW diagrams may be used to represent any component that has resistance, but not capacitance or inductance. Figure 6 shows how a range of resistors of different sizes would be represented in a diagram of a resistance network.

AVOW diagrams are more versatile than the box diagrams previously described and can be used analytically in many instances that are of practical importance. Figure 7(a) demonstrates, in a series of steps, what happens to the AVOW diagram of a resistor which obeys Ohm’s Law when the pd across it is gradually increased to twice its original value. Because it obeys Ohm’s Law the resistance, and therefore the slope of the diagonal in the diagram, remains constant. The current, of course, is eventually doubled too and the power delivered to the resistor is increased by a factor of four in accordance with the formulae $P = IV$, $P = FR$ and $P = V^2/R$.

It would be useful to introduce students to the different ways, such as those illustrated in Figure 7(b) and (c), in which the size of an AVOW box may be changed while preserving its proportions. One corner, here denoted by X, must be anchored in each case, while the diagonally opposite corner is moved outwards or inwards along the line of the diagonal. In addition to the diagonal representing the resistance, the other diagonal might be used as a construction line. Figure 7(c) shows how a box is expanded downwards along this diagonal.

**Combinations of resistors**

Figure 7 reminds us that a resistor which obeys Ohm’s Law may be represented by an infinite number of boxes of different sizes but which are all the same shape. We can therefore expand or contract AVOW boxes so that they fit together to form diagrams which accurately represent the pd’s, currents and power

![Figure 6 AVOW diagrams representing resistors of different sizes.](image)

![Figure 5 Representing resistors by AVOW diagrams.](image)
distributions in complex networks of resistors. Figure 8 shows what happens when two separate resistors of 2 Ω and 4 Ω are connected together, first in series and then in parallel. A 2 Ω resistor, for example, may be represented by any box which is 2 units high by 1 unit wide, and so the units in which these boxes have been drawn are arbitrary. We have found it useful to put the numbers representing the ratios inside the boxes, as shown here, to distinguish them from any actual values of current or pd, which we would place outside. In Figure 8 all the boxes have been drawn to the same horizontal and vertical scale. This will not generally be the case and, indeed, with resistance values running into megohms, would often be impractical.

In the series combination of resistors (b) the same current passes through both. The AVOW diagram for the combination therefore shows the two boxes as

Figure 7 Equivalent AVOW diagrams for one resistor.

Figure 8 Use of AVOW diagrams to represent series and parallel combinations of resistors.
equal in width and stacked one on top of the other. The constant width of the diagram serves to emphasise that the current in the circuit is continuous and does not decrease as it flows through the resistors. The total resistance of the combination is given by the slope of the bold diagonal. While current is the same for both resistors the pd’s across them will be proportional to their resistances. Also, for a series combination of resistors, it is the larger resistor that dissipates most power, as shown by the areas of the boxes.

Where resistors are connected in parallel as in (c), it is the pd that is the same for both while the current is divided between them. The AVOW diagram of the combination consists of two boxes equal in height and side by side. In creating the diagram the box representing the 2 Ω resistor has been expanded in such a way as to keep the slope of the diagonal constant. The slope of the bold diagonal again gives the total resistance of the combination, making the point, very strongly, that this is less than the resistance of either of the component resistors. The width of the expanded box shows that the current through the 2 Ω resistor will be twice that through the one of 4 Ω. The areas of the boxes demonstrate that when resistors are connected in parallel it is the smaller resistor that receives most power, in sharp contrast to what occurs in a series combination.

With the experimental group, the AVOW diagrams were produced alongside diagrams of the resistor combinations, following the procedure illustrated in Figure 8, and, for each combination in turn, the distributions of current and pd were discussed before the corresponding formula was deduced.

**Calculations for complete circuits**

The use of AVOW diagrams in solving more complex circuit problems may be best illustrated by means of an example and we shall consider the problem posed in Figure 9.

Construction of the AVOW diagram for the load begins with the diagram for the parallel combination which, following the procedure used in Figure 8(c), produces a box 6 units high and 3 units wide. The total current through the parallel combination also passes through the 2 Ω resistor. The AVOW box for the 2 Ω resistor must also be 3 units wide, therefore, and so will be 6 units high. Once the AVOW diagram has been drawn there are several different ways of solving the problem. Here is just one example:

The width of the AVOW diagram, 3 units, represents a current of 2 A, so each unit of width is 0.667 A. Immediately, therefore:

(a) current in the 6 Ω resistor = 0.667 A and
current in the 3 Ω resistor = 1.333 A.

From \( R = \frac{V}{I} \):

(b) pd across the 2 Ω resistor = \( 2 \text{ A} \times 2 \Omega = 4 \text{ V} \).

Since both the 2 Ω and 3 Ω boxes are 6 units high:

(c) pd across the 3 Ω resistor = 4 V also.

Since the pd is the same for both the 3 Ω and 6 Ω resistors:

(d) power delivered to the 6 Ω resistor

\( = 0.667 \text{ A} \times 4 \text{ V} = 2.67 \text{ W} \).

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**Figure 9** Using an AVOW diagram to support solution of a circuit problem.
In addition to the trial with year 12 physics students the approach has also been used by two teachers, in another school, with their year 12 groups. It has also been introduced as revision with both year 12 and year 13 students who had, in each case, completed all of their electrical modules. These experiences of teaching with the diagrams have led us to believe that students will benefit from their use. Many students, across the various trials, commented that the diagrams helped them to form clear pictures of circuits and of the relationships between the different electrical quantities with which they had to work. For example:

The AVOW box method helped a lot to clarify relationships between A, V, O, W – it was a good method of learning in that it made it easier to understand. (Y12)

It made calculating voltages and currents much easier as you can clearly visualise the whole circuit and the amounts/sizes of each calculation. (Y12)

Some found the diagrams valuable as memory aids since, as one year 12 student said, ‘it is possible to work back from a diagram to remember the facts’. Others found that the diagrams provided guidance on the progress of calculations and helped them to identify errors. A reasonably accurate sketch will indicate the approximate magnitudes of the quantities to be calculated in many instances. Most found the experience of working with the diagrams very useful.

For the students who had already studied circuit theory by traditional methods the diagrammatic approach showed circuits in a new light and it was clear that many found their encounter with something quite novel in a revision lesson very refreshing. Students vary enormously in their preferred learning styles and it is quite possible that some found the new approach more appealing than the algebraic methods. Most were constructing box and AVOW diagrams quite confidently after only one hour’s instruction.

Some students included negative comments in their evaluations, however. Most of these were closely related and pointed to the need to use the new approach judiciously in combination with traditional methods:

I felt that the method was very good for complex diagrams but conventional methods may be easier for more simple circuits. (Y13)

Sometimes it can be hard to tell when to use them and when not to. (Y12)

Having alternative methods available for attacking problems provides considerable benefits but does also, of course, entail selecting appropriately amongst them. Students therefore need plenty of practice and experience with the alternative techniques made available to them.

The teachers who used the approach reported that their novice year 12 students developed a working understanding of the technique much more quickly than they had expected. Both plan to use it again in the future. One commented:

I thought they would struggle with it. And they didn’t; they didn’t struggle with it at all. Even the weaker ones – the basic facts about the boxes they grasped very quickly.

Reflecting on the outcomes the same teacher reported:

What I did see was increased levels of confidence in dealing with circuits which previously … they wouldn’t have known where to start. At least when you gave them a complicated circuit then they could draw the boxes for this. And then when you put the extra feature in, where the box always has to be a rectangle, that was a great comfort to them … It was like an intermediate check to see whether they had analysed it correctly. If you do that, effectively just using equations, you never get that …

**Our evaluation of the approach**

Were our teaching objectives with the year 12 physics students achieved? The experimental group scored higher than the comparison group on every question in the test that we administered and we were confident that reasonable progress had been made on all three teaching objectives. One example from the students’ end-of-course test and for which the gains were particularly striking is provided in Figure 10, together with one student’s working.

The problem posed in Figure 10 concerns an unbalanced bridge circuit. The task, to find the values of the currents $I_1$ to $I_5$, was somewhat simplified by giving the current in the $2 \Omega$ resistor and showing the direction of the current $I_5$ in the $6 \Omega$ resistor. Nevertheless, we expected this to be a challenging question for any group of A-level students.
Splitting the current of 2 A into $I_1$ and $I_2$, and combining $I_3$ with $I_4$ to give $I_5$, embeds the box representing the 6 Ω resistor in the completed AVOW diagram as shown in the student’s working. For this student no calculations were involved other than those he used in constructing the diagram. These provided the current values required:

$$I_1 = 0.5 \text{ A}, \quad I_2 = 1.0 \text{ A}, \quad I_3 = 0.5 \text{ A} \quad \text{and} \quad I_4 = 1.5 \text{ A}.$$  

Balanced bridge circuits no longer formed part of the NEAB syllabus that these students followed and they had not met problems of this type during their course. In the event, however, 10 of the 16 students (62.5%) in the experimental group produced correct solutions. In a comparison group of 29 A-level physics students from year 13, all of whom had been taught by traditional methods, the success rate was much lower, at 12%. These students had also studied course units in electronics.

If students were to succeed in this question they needed to:

- understand that pd’s along any current track through a network add up to the total applied pd;
- understand that current in a circuit is continuous (which implies, amongst other things, that the total current flowing into a junction equals the total current flowing out of it);
- know the relationship $V = IR$, linking pd, current and resistance;
- be able to analyse the network into its component parts without losing sight of the whole (e.g. to ‘see it’ as a distribution of current and pd in something like the way it is portrayed in a box diagram).

We can be certain that ten of the students who had followed the experimental course had these abilities by the end of it, at least when confronted by a problem involving a network of resistors. It is worth noting that five of the ten students used AVOW diagrams in their solutions to the problem, whereas the other five who solved it did not, or at least not overtly. The proportion solving the problem without AVOW diagrams was still greater than for the comparison group, however, suggesting that these students’ learning had nevertheless been supported by the teaching approach employed. (There will be further discussion relating to the first two objectives in part 2 of this article.)

We have come to see box and AVOW diagrams as valuable aids in the teaching of dc circuit theory and in the solution of problems, not as a substitute for learning the basic equations of circuits and how to employ these. Evidence from the trials we have carried out has indicated that students benefit from experience with the diagrams, even if they make little or no use of them in problem solving thereafter. Their use as teaching aids is most powerful in circumstances where students are unlikely to see immediately how

In the circuit shown below the current through the 2 Ω resistor is 2 A. In whatever order you find most convenient, find the values of the currents $I_1$, $I_2$, $I_3$ and $I_4$.

![Image of circuit diagram](image1)

**Figure 10** An item from the end-of-course test together with one student’s working.
current, pd and power will be distributed in circuits. The additional lesson time required to include this technique, up to the point described in this article and including some paper-based exercises, is approximately 1.5 hours.

Students will gain best service from the techniques described if they first sketch the diagrams, either for the complete circuits or just the loads. Diagrams drawn very carelessly can prove misleading but a reasonably accurate sketch will indicate the relative proportions of the various electrical quantities. Once a sketch has been produced it should then be much clearer what methods to adopt to complete a calculation. We are certainly not advocating the solution of problems by accurate scale drawing or by the scaling up or down of AVOW diagrams which have anything other than simple scale factors. For calculations involving complex circuits we strongly encourage use of an eclectic approach employing a mixture of traditional and box or AVOW diagram methods, as in the example given earlier.

In this article we have described a variety of relatively simple ways in which box and AVOW diagrams may be employed in teaching dc circuit theory and in the solution of circuit problems. In part 2 we shall explain how AVOW diagrams may be used to explore more complex circuit behaviour and examine the impact of the approach on the alternative conceptions of electricity that students hold.

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References

Shipstone, D. M. and Cheng, P. C-H. (2001) Teaching electric circuit theory at A-level with AVOW diagrams. Technical Report No. 72. ESRC Centre for Research in Development, Instruction and Training, School of Psychology, University of Nottingham. [Copies available from Irene Jackson, CREDIT, School of Psychology, University of Nottingham, University Park, Nottingham, NG7 2RD (e-mail: Irene.Jackson@nottingham.ac.uk)].

David Shipstone taught physics to GCE A-level before joining the staff of Nottingham University as a Science Education Lecturer in the School of Education. He is now a research worker in the School of Psychology.

Peter Cheng is a Senior Research Fellow in the School of Psychology, University of Nottingham and Deputy Director of the ESRC Centre for Research in Development, Instruction and Training.
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