AC 2012-4051: ELECTROMAGNETICS MISCONCEPTIONS: HOW COMMON ARE THESE AMONGST FIRST- AND SECOND-YEAR ELECTRICAL ENGINEERING STUDENTS?

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Electromagnetics: how well is it understood by first- and second-year electrical-engineering students?

Abstract

Over the last decade there has been a significant increase in the diversity of students enrolling in engineering courses. To support these students effectively, and to ensure the courses they take remain appropriate, the academic preparedness and conceptual understandings of these students should be known. However, while there is much research reported in the literature concerning student understanding in the area of forces, and some in the area of electricity, there is little in the area of electromagnetics. Yet most would expect student misconceptions to be just as prevalent, and therefore important, in electromagnetics as in mechanics or electricity. In order to investigate student academic preparedness, and address a comparative lack of research into student misconceptions in electricity and electromagnetics, short diagnostic tests were administered at the start of two electrical-engineering courses, one taken by first-year students, the other by second-year students. This paper categorizes, presents and discusses the main student misconceptions revealed by these pretests, and notes some corroboration from international research findings.

Introduction

Each year, the University of Auckland (UoA), a large research-led university of around 40 000 students, accepts about 600 students into the first year of its four-year Bachelor of Engineering (honours) degree. These students increasingly come from a diverse range of national and international backgrounds. Compounding this diversity, students schooled in New Zealand now have a choice of three distinct pathways to university. The modular nature of the most common of these, the National Certificate of Educational Achievement (NCEA), makes it possible for students to present for examination some aspects of the physics curriculum while not presenting others, such as the electrical-systems module, for example. In some high schools, students can even enroll in a high-school physics course that contains no electricity content. Given all the above, it is no longer possible to assume that first-year students have a shared base level of knowledge.

ELECTENG 101, Electrical and Digital Systems, is part of the common program compulsory for all first-year engineering students at UoA. Of the 600 students enrolled in this course each year, only about one quarter subsequently pursue a degree in Electrical and Computer Engineering. Many students enrolled in ELECTENG 101 have no particular interest in matters of an electrical nature, and may not have studied this aspect of physics in depth at high school. Faced with this academic diversity, and deeming it important to have some insight into the skills and understanding of the incoming students, in 2007 the lecturers in ELECTENG 101 introduced a short pretest. The aim was to determine the incoming students' levels of conceptual understanding of electricity and electromagnetics, and consequently to modify where necessary the course content, delivery, and remedial interventions in order to provide the best learning opportunities for all students. The initial development of this test was informed by prior research, in particular physics-education research (such as that conducted by Maloney et al[1], Engelhardt and Beichner[2], Ding et al[3], and Saglam and Millar[4]). This prior research had identified widespread misconceptions students have about the behaviour of DC and AC circuits, and electromagnetics. Even so, from its first implementation in 2007 the ELECTENG 101 pretest astonished lecturers with the extent of the student misconceptions it revealed amongst a student body deemed by their entry scores to be academically very capable. The test, with modifications, has been used each year since, with the results reinforcing those of 2007. Follow-up interviews have provided further insights into student thought processes. Some questions have been revisited in final examinations to determine the extent to which the course has addressed certain student misconceptions.

ELECTENG 204, Engineering Electromagnetics, is part of a compulsory common program for all year-two electrical-and-electronic and computer-systems engineering students at UoA. Each year around 150 students enrol in this course, with about three quarters going on in electrical-and-electronic engineering, one quarter in computer-systems engineering. In 2011, a pretest was introduced at the start of this course, partly to follow up some areas of concern that had been highlighted by the year-one pretest 12 months earlier, and partly to explore student understanding in some new areas, such as electric fields, that had not been tested by the earlier test, nor taught in ELECTENG 101.

The construction of the year-one pretest, the overall results it produced, and an analysis of the electric-circuits misconceptions it revealed, have all been previously presented[5]. This paper presents an analysis of the misconceptions in the electromagnetics area that were revealed by the year-one and year-two pretests.

Year-two pretest, initial analysis

The year-two pretest consists of 22 multiple-choice questions. The first 10 probe understanding of electric fields (including electric forces and electric potential); the remaining 12, magnetic fields (including magnetic forces, magnetic flux and induced voltages). The topic of electric fields is covered in year-12 physics in New Zealand high schools, but not in year-13 physics (year-13 is the final year of high-school education in New Zealand), nor in the first year of the Bachelor of Engineering (honours) degree program. Electric potential is covered in each of the three years of education mentioned above but, with the exception of year 12, only in the context of voltage in circuits. Concepts like equipotential lines are not covered at all. The topic of magnetic fields fares rather better, being covered in all three years. In year 12 the students are taught about magnetic fields, forces and induced voltages, though the concept of flux is not mentioned. These concepts are revisited in year 13, with magnetic flux and Faraday's law also being covered. All these topics reappear in ELECTENG 101.

As for the year-one pretest, the initial development of the year-two pretest was also informed by the results of previous research, in particular physics-education research. A number of questions were taken from, or are similar to, questions constructed by Maloney et al[1], Saglam and Millar[4], and Ding et al[3]. Some of the questions are well-known to teachers and lecturers and have appeared regularly in a range of assessments for decades, including national high-school physics examinations in New Zealand.

The pretest was administered (without prior warning) on the first day of the course. Invigilators reported that the 25 minutes allocated for the test appeared ample: most students finished with adequate time to spare. The students also appeared to take the test seriously: they spent most of the allocated time working on their answers. After marking, the test marks were released to the students but, in order to preserve the integrity of the test for future years, test scripts were not released. A mark histogram is provided in Fig.1.

The mean mark for the test was 9.1 out of 22 (41%), and the pass rate was 32% (UoA regards a mark of 50% or more as a pass). Nine percent of students scored a mark of 4 or lower, a mark attainable by simply guessing all 22 multiple-choice questions. Although the students' prior educational experiences had given them far less exposure to the topic of electric fields, the electric-fields part of the test did not disadvantage them significantly: the average score was 4.0 out of 10 (40%) for the electric-fields questions, and 5.1 out of 12 (43%) for the magnetic-fields questions.

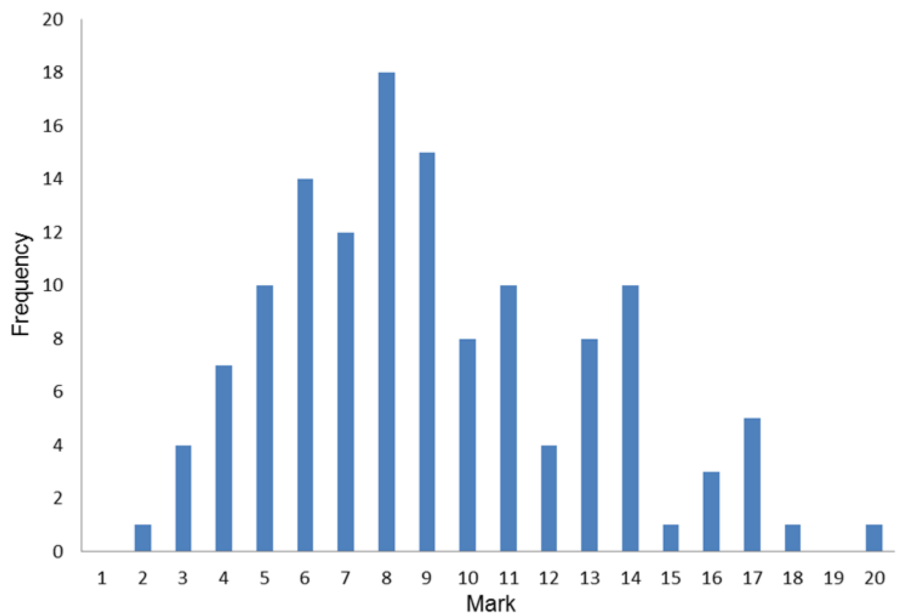


Fig. 1. Mark histogram for 2011 year-two pretest.

The pretest results were clearly disappointing. They indicated students had either forgotten or not properly understood much basic physics. For most students, most of this basic physics would have been covered at high school, with a significant portion of it being subsequently revisited in year-one engineering courses. However, not all of the conceptual problems revealed were in electromagnetics: the question that returned the lowest score of all in the test (Question 16) did so as a direct result of students' failure to correctly apply Newton's third law to the situation where unequal parallel currents exert forces on each other. This misconception, and several others, is discussed in more detail in the following section.

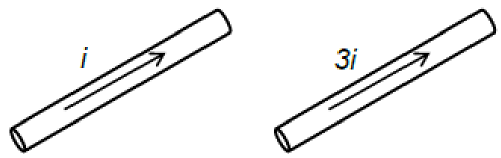
Misconceptions revealed by diagnostic testing.

A. Newton’s Third Law in an electromagnetics context

Student lack of understanding of Newtons’ third law is well known in mechanics. For example, Redish et al[6] noted that, when confronted with situations involving a large truck colliding with a small car, or one student pushing another, only a minority of university physics students could correctly apply Newtons’ third law: 30% and 43% respectively. This lack of understanding also impacts on the realm of electromagnetics.

Two questions in the year-two pretest required students to apply Newton’s third law in an electromagnetics context. Question 16 (see Fig. 2) asked students to compare the forces unequal parallel currents exerted on each other.

Two parallel wires I and II that are near each other carry currents *i* and 3*i* in the same direction as shown below. Compare the forces that the two wires exert on each other.



(a) Wire I exerts a stronger force on wire II than II exerts on I.
(b) Wire II exerts a stronger force on wire I than I exerts on II.
(c) The wires exert equal magnitude attractive forces on each other.
(d) The wires exert equal magnitude repulsive forces on each other.
(e) The wires exert no forces on each other.

Fig. 2. Year-two pretest, Question 16.

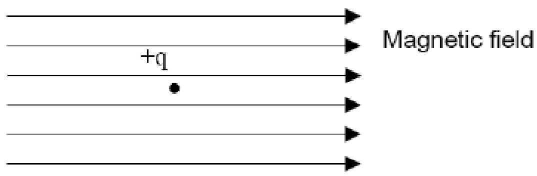
Only 16% of students gave the correct answer, (c). A greater percentage (20%) gave (d), correctly applying Newtons’ third law but thinking that like currents repel, following the pattern of like charges, perhaps. This propensity to liken forces between currents to forces between charges has also been noted elsewhere[7]. Adding the two percentages above, it may be concluded that 36% of students showed an awareness of Newton’s third law. By contrast, 53% of students chose answer (b), believing that the larger current would exert a stronger force. Similar results were obtained by Maloney et al[1] in testing students enrolled in general-physics courses: about 45% of both algebra-based and calculus-based students answered (b) in both the pretest and the posttest. Encouragingly, Maloney et al did find an improvement from the pretest to the posttest for option (c), 7% versus 22% for the calculus-based students.

Another year-two pretest question asked students to compare the forces that unlike, unequal point charges exerted on each other. Students were not offered the distractor choice of unlike charges repelling. Only 27% of the students said the charges would attract each other with equal-magnitude forces, while 35% said the larger charge would exert a correspondingly larger force. Maloney et al’s corresponding figures for calculus-based students were 25% and 48% for the pretest, and 44% and 38% for the posttest. Galili[8] tested a group of above-average Israeli high-school students with a similar question and obtained similar results: 33% and 33% respectively.

B. The force experienced by a stationary charge in a magnetic field

It is a popular misconception that a charge in a magnetic field always experiences a force, even when stationary. Question 11 (see Fig. 3) was used in both the year-one and year-two pretests. In the year-one pretest, only 25% of the students correctly answered (e), while 31% chose (b). Twelve months later in the year-two pretest, 33% correctly answered (e), while 24% chose (b).

A positive charge q is held at rest in a uniform magnetic field, and then released. You can ignore the effect of gravity on the charge.



How does the charge move after it is released?
(a) The charge moves to the right with constant velocity
(b) The charge moves to the right with constant acceleration
(c) The charge moves in a circle with constant speed
(d) The charge moves in a circle with increasing speed
(e) The charge stays at rest

Fig. 3. Year-two pretest, Question 11.

Those choosing (b) exhibit two misunderstandings: (1) a magnetic field exerts a force on a stationary charge, and (2) the force is in the direction of the magnetic field lines. Elsewhere, similar questions, albeit with answers that included both reasons and outcomes (e.g. "the charge remains at rest since the initial velocity and the force are zero"), have returned similarly-disappointing results. Such a question given to groups of upper-secondary-school students in Turkey and England was correctly answered by 16% of the Turkish students and 38% of the English students[4], while a significant number of the students chose an option indicating they believed a stationary charge would accelerate in the direction of the magnetic field. Here it should be noted that these groups of high-school students were judged to be above-average, they received advance warning of the test (which was a posttest), and were given a sheet listing formulae and other useful information about electromagnetism. University general-physics students in the United States, when confronted with a similar question (again with answers that included both reasons and outcomes) fared poorly too, with only 26% of calculus-based students correctly answering the pretest question (posttest, 28%)[1]. The corresponding figures for algebra-based students were better at 31% and 44% respectively. An incorrect option stating the charge would move with constant acceleration (no direction given) was chosen in the pretest by 31% of the calculus-based physics students (posttest, 28%). Again, the corresponding figures for algebra-based students were better at 19% and 8% respectively.

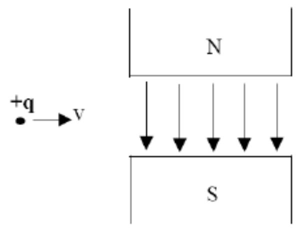
C. The direction of the force experienced by a moving charge in a magnetic field

It is a popular misconception that the force on a charge in a magnetic field is in the direction of the field. Students who answered (b) in Question 11 displayed this misconception, and 31% of year-one students and 24% of year-two students did just that. Question 12 (see Fig. 4) was used in both the year-one and year-two pretests to directly target this misconception.

In the year-one test, 29% of students answered (a), showing the belief that field direction matches force direction. The correct option (d) was chosen by 42% of students. A further 25% chose (e), showing they did at least know force was perpendicular to field. One year later, the year-two diagnostic test returned 18% for (a), 60% for correct option (d), and 20% for (e).

The following information is for questions 12 and 13:

The diagram below shows a positive charge q moving with constant speed v towards a region of uniform magnetic field.



Question 12

How does the charge move when it enters the field?
(a) It is deflected downwards ↓
(b) It continues moving at the same speed in the same direction
(c) It slows down and stops
(d) It is deflected into the paper
(e) It is deflected out of the paper

Question 13

What is the path of the charge?
(a) A parabola (or part of a parabola)
(b) A circle (or part of a circle)
(c) A straight line
(d) Other

Fig. 4. Year-two pretest, Questions 12 and 13.

A very similar question given to the groups of upper-secondary-school students in Turkey and England was correctly answered by 25% of Turkish students and 43% of English students[4]. Almost half (48%) the Turkish students indicated they thought the force on the charge was in the same direction as the field. Maloney et al[1] tested the same concept in a different way, showing an electron's curved path and seeking the magnetic field's direction. In the pretest, 35% of the calculus-based physics students incorrectly equated field direction with force direction. Another 17% saw the field opposite in direction to the force, perhaps because the charge was negative. The correct answer was selected by 16% of students. In the posttest 39% of the students correctly determined field direction, while another 30% had the field direction the reverse of the correct direction, perhaps not taking into account that the charge was negative.

A question used by Singh[7] asked calculus-based, introductory-physics students to predict what would happen when a positive charge moved with its velocity vector opposite to the magnetic field direction. The most popular answer was that the charge would slow down. In the pretest, only 17% answered correctly that the particle's velocity would not change (posttest, 64%).

D. The trajectory followed by a moving charge in a magnetic field

It is a popular misconception that a charge moving in a magnetic field follows a parabolic trajectory. Question 13 (see Fig. 4) was used in both the year-one and year-two pretests to directly examine this misconception. In the year-one test, 71% of students incorrectly answered (a), believing the charge followed a parabolic path in the magnetic field. Only 17% of students correctly answered (c). One year later, the year-two pretest returned 59% for (a), the parabolic-trajectory option, and 32% for correct option (c). Even of the 80% of students who did realise force is perpendicular to field direction (and therefore recognised they were not dealing with an electric field) only 31% correctly divined the trajectory, with 59% still choosing the parabolic-path option. A very similar question given to the groups of upper-secondary-school students in Turkey and England was correctly answered by 29% of Turkish students and 25% of English students[4].

E. Equating electric fields with magnetic fields

As noted in *B.* above, a significant percentage of students believe that a stationary charge in a magnetic field experiences a force. This belief may be a result of treating the magnetic field as an electric field. There is also evidence that students sometimes treat electric fields as magnetic fields. For example, when answering Question 5 (see Fig. 5) in their pretest, 15% of the year-two students chose option (e), believing that the charge would remain at rest in the electric field. When essentially the same question was given in a pretest to calculus-based, general-physics students in the United States[1], 36% of students chose option (e). The same percentage (36%) of the algebra-based, general-physics students also chose option (e).

A positive charge is released from rest in a uniform electric field. Describe its subsequent motion.

(a) it will move with constant speed.
(b) it will move with constant velocity.
(c) it will move with constant acceleration.
(d) it will move with a linearly-changing acceleration.
(e) it will remain at rest.

Fig. 5. Year-two pretest, Question 5.

For these three groups, the percentages of students selecting the correct answer, (c), were 44%, 24% and 16% respectively. Incidentally, in each of the three student groups, about 25% chose either (a) or (b), indicating that they possessed an Aristotelian rather than Newtonian view of motion, equating constant force with constant speed or velocity rather than constant acceleration.

F. Equating direction of cause with direction of effect.

It was noted above (in *B.* and *C.*) that significant percentages of students believe field direction equals force direction. A more general misconception is that direction of cause equals direction of effect. This misconception is illustrated well by student responses to Question 19 (see Fig. 6).

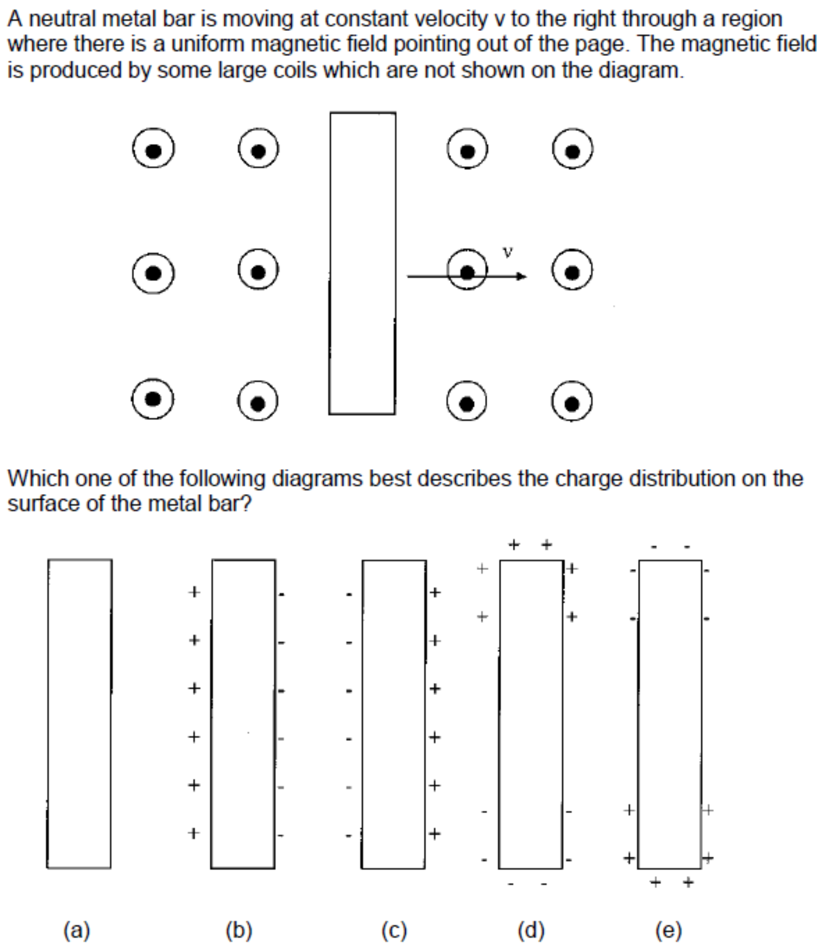


Fig. 6. Year-two pretest, Question 19.

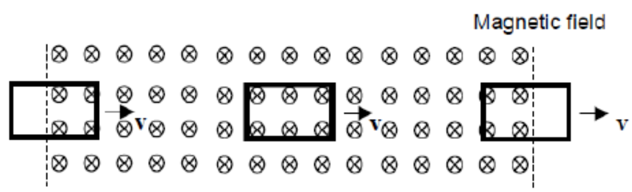
In the year-one pretest, only 28% of students correctly answered (e). A further 29% reversed the direction of induced EMF and chose (d). Options (b) and (c) together captured 40% of student responses. When the same question was given in a pretest to the calculus-based general-physics students in the United States, only 6% of students correctly chose option (e). Options (b) and (c) together captured 62% of student responses. For algebra-based students, the corresponding figures were 4% and 68%. A very similar question given to the groups of upper-secondary-school students in Turkey and England was correctly answered by about 22% of the students, with options (b) and (c) together capturing 31% of Turkish student responses. When these students were interviewed, they all repeated the answers they had previously given but none could give an explanation[4]. It is probable that the students answering (b) or (c) were relying on some intuitive notion that the movement of charges in the bar should be parallel to the direction of the bar's motion.

Encouragingly, in the year-two pretest, 47% of students correctly answered (e), with only 14% captured by options (b) and (c). When used as a posttest question with the calculus-based students mentioned earlier, the corresponding figures were 14% and 49% respectively. The algebra-based students did better, with corresponding figures of 26% and 40%.

G. Relating induced voltage to magnetic flux rather than change in flux.

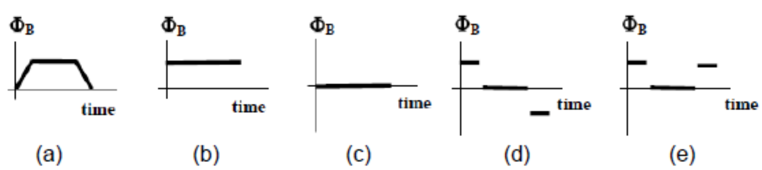
Student responses to Questions 21 and 22 (see Fig. 7) indicate that this misconception is common. In the year-two pretest, 47% of students of students correctly answered (a) for Question 21 but only 25% correctly answered (d) for Question 22. A significant percentage (29%) of students answered (a) for Question 22, equating flux with induced voltage. The same two questions were given to the groups of upper-secondary-school students in Turkey and England. Of the Turkish group 53% answered the first question correctly, 13% the second. For the English group, the figures were 80% and 28% respectively. Clearly there is a large fraction of students who, given flux, cannot correctly determine induced voltage. In the year-two pretest, of the students who correctly answered (a) in Question 21, only 29% correctly answered (d) in Question 22. More (30%) equated voltage to flux and answered (a).

The diagram below shows a flat coil moving at constant speed in a uniform magnetic field. The magnetic field is confined to the region indicated by the dashed lines.



Question 21

Which of the graphs below shows how the magnetic flux Φ_B through the coil changes from the moment it enters the field until the moment it leaves the field?



Question 22

Which of the graphs below shows how the induced voltage $\mathcal{E}$ in the coil changes from the moment it enters the field until the moment it leaves the field?

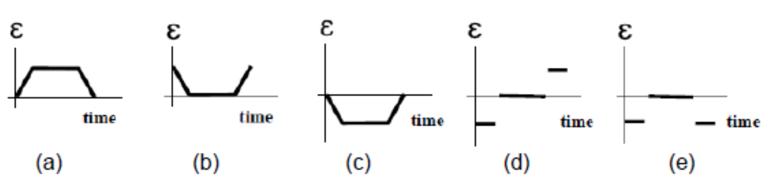


Fig. 7. Year-two pretest, Question 20 and 21.

Discussion

In order for instructors to maximise the learning of their students, it is critical that the instructors have a good grasp of the knowledge and understanding that the students bring with them initially. While there have been many studies focussing on students' understanding in mechanics[9, 10] in particular, and in electric circuits too, there have been comparatively few focussing on electromagnetics, as others have also noted[4, 11]. The present study reinforces the notion that student misconceptions are just as significant in electromagnetics as they are in mechanics and electric circuits, even though they are less well known. The misconceptions are widespread: in every country where testing for these misconceptions is conducted, significant percentages of students are found to hold them, and the percentages are often similar from one country to the next. It is important that instructors are aware of the specific student misconceptions. It is not enough for instructors simply to believe that their students don't know much; the evidence is that misconceptions are often deeply-rooted and are hard to dislodge unless targeted explicitly[12-14]. Such targeting is impossible if the instructors are unaware of the actual misconceptions. Unfortunately, it is likely that many instructors are unaware of their students' actual misconceptions, for they frequently occur at very elementary levels, more elementary than might be expected. For example, only 25% of year-one students correctly stated that a stationary charge in a magnetic field experienced zero force. This theme that student misconceptions occur at surprisingly-elementary levels extends beyond electromagnetics. In electric circuit theory, for example, many students have difficulty in identifying which components are in series and which are in parallel: a question in the ELECTENG 101 pretest which asked students to identify the resistances in series in a simple circuit consisting of four resistances and one voltage source was correctly answered by only 37% of students. Similarly, in mechanics, students have difficulty accepting a Newtonian model of force: Halloun and Hestenes in their ground-breaking research found that only 15% of college students studying physics believed that a particle acted on by a constant force has constant acceleration[14]. Unfortunately, if such misconceptions are not identified and corrected, it is very likely that students possessing them will have significant difficulty grasping more advanced topics. The reality is that having misconceptions is actually worse than having no concepts at all: elementary misconceptions skew the way more advanced concepts are added to a students' conceptual framework.

Once pretesting had revealed the full extent of these misconceptions, the instructors took pains to target misconceptions directly, spending some time revising the concepts that students should have grasped but often didn't. By sharing and discussing the pretest results with the students, the instructors were able to justify and motivate the time spent on 'revision' and the students were receptive to this approach. In the year-one course, tutorial questions were set that targeted the misconceptions. These questions were often the subject of peer-marking exercises, a method chosen to promote student discussion of the questions and answers. The introduction of these peer-marking exercises was an encouraging intervention and has been reported on elsewhere[15]. Peer-marking exercises were also introduced into the year-two course. Additionally, in the year-two course, prior results were used to identify academically at-risk students and special weekly tutorials were run for these students. While these tutorials did lift the performance of the students who attended them regularly[16], it was disappointing that many students did not attend regularly and therefore gained little or no benefit. More work is still required, particularly at the year-two level, in order to successfully address the issue of student misconceptions.

Conclusions

In order to better inform instructors about the conceptual understandings of their students, pretests were conducted with year-one engineering students and year-two electrical-engineering students. The results have been consistent across the duration of the testing (since 2007 for the year-one students). Both tests acted as “wake-up calls” and led to behavioural changes in students and to some modification of course content by instructors. Question-by-question analysis of the diagnostic tests has proven valuable, with the most striking feature to emerge from the analysis being the basic (pre-tertiary) level of the misunderstandings. Several common misunderstandings were identified in the area of electromagnetics. A number of these occur around the concept of force and there is some overlap here with misconceptions in the area of mechanics. For example, Newton’s third law is poorly applied in both electromagnetics and mechanics. All too many students do not appreciate that the force experienced by a stationary charge in a magnetic field is zero and, for a moving charge in a magnetic field, cannot correctly state the direction of the force on the charge, or describe its trajectory. Other misconceptions centre on confusing one entity with another, possibly related, entity. For example, students at times treat electric fields as magnetic fields, and vice versa. Some students also confuse direction of cause with direction of effect. Another prevalent mistake is the calculation of induced voltage from flux itself rather than change in flux.

These misconceptions have also been noted by other researchers. When questions similar to those in the present study were used in other countries, the statistics produced have been remarkably similar: a number of critical misconceptions are certainly widespread. Given courses and instruction styles do vary considerably from country to country while the misconceptions remain similar, it is clear that they are not easy to eradicate. Still, the first step in the eradication of misconceptions is instructor awareness of them. It is hoped this paper has assisted in that regard. In the future it is hoped to report on some successes in directly tackling these misconceptions, particularly at the year-two level.

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