High school students' understanding of magnetism

M. Snelder
Faculty of Behavioral Science, University of Twente,
7500 AE Enschede, The Netherlands and
Faculty of Science and Technology and MESA+ Institute for Nanotechnology,
University of Twente, 7500 AE Enschede, The Netherlands

J. T. van der Veen
Faculty of Behavioral Science, University of Twente,
7500 AE Enschede, The Netherlands

(Dated: August 11, 2014)

Abstract

We report on the development of a test on magnetism and the results of its first administration. The test is based on the three topics that are discussed in Dutch high school textbooks: the origin and direction of magnetic fields, Lorentz force and Faraday's law. The test was administered to 145 high school students and an analysis of its quality was done based on those data. We asked the students for their reasoning and compared their responses for the different questions on the same topic, from which we observe that the interpretation of the students' understanding is not self-evident. An important tendency observed in student reasoning is the use of formulas without physical insight into their meaning.

I. INTRODUCTION

Students' misconceptions and difficulties with physics have been the topic of a great number of studies[1–5] and are still very relevant. The understanding of magnetism by students ranging from secondary school to university level has also been studied extensively.[6–11] A common misconception revealed by these studies is the students' use of an electrical analogue in their reasoning, that is, north and south poles and current-carrying wires are thought to be equivalent or similar to a static electrical charge. In a current-carrying wire, the direction of the current seems to determine the sign of the "charge". Other misconceptions that have been noted include the presence of a Lorentz force on a static charge in a magnetic field and difficulties in indentifying a change in flux for different motions of a magnet near a metal loop.

In this work we build further on this previous research on students' concepts of magnetism. The central question is therefore "what are the (mis)conceptions of high school students regarding magnetism?". In order to answer this question we first developed a test on different magnetism concepts that are discussed in high school lessons and textbooks in the Netherlands. The development of this test and its quality are discussed in the first part of this paper. The test is meant to give more insight into the misconceptions that have already been identified and the reasoning behind the misconceptions encountered. The test was administered to 145 high school students (79 male, 66 female) between 16 and 19 years of age in four exam and three pre-exam classes of pre-university level education. In the Netherlands magnetism is taught in the pre-exam year of high school. We discuss the results of the test and compare them with the findings of previous studies. We end this paper with a summary and suggestions for instruction of magnetism in high school.

II. DEVELOPMENT OF THE TEST

Magnetism is presented in Dutch high school textbooks under roughly three topics: the origin and direction of magnetic fields, Lorentz force and Faraday's law. We have developed a test to cover these three topics. In Table I we indicate which questions on the test address each of the three topics. Questions 3, 6, 10, 12, 18 are based on questions 23, 28, 24, 25 and 29 respectively of Ref. 8. The complete test can be found in the Appendix.

TABLE I. Test questions addressing the three magnetism topics

Origin and direction of magnetic fields	1–4, 6, 7
Lorentz force	5, 8–10, 14
Faraday's law	11–13, 15–19

The test, its answers and the motivation behind the questions were discussed with a PhD student in physics in the field of magnetism, a high school teacher with over 17 years experience in teaching physics to high school students and a physics professor in the solid state physics track at the University in Twente. Their comments were taken into account in developing the test. Then, we piloted the test in a class of 21 students in their high school exam year. In the pilot test, attention was paid to the time needed to complete the test . After 30 minutes every student had finished the test and then the questions were discussed together with the answers. The students were individually asked for their comments on the clarity of the questions in connection with the expected right answer.

The test consists of 14 multiple choice questions and 5 open questions. The 5 open questions (questions 1, 4, 9, 14 and 19) are scored by means of a two-number code, where the first number indicates whether the answer is right or wrong and the second number indicates what type of right or wrong answer is given. For this second number, we made use of categories that satisfied the criteria explained by Marton and Booth[12]; each category has a clear relation to the phenomenon, there must be a hierarchy in the categories (an ordered difference in complexity) and the number of categories must be as small as possible. To check the inter-rater reliability of the scoring of correctness and assignment of categories for the open questions , the 21 completed pilot-tests were independently scored by an additional rater. Then the scores were compared to each other. The correlation between the scores was .82, which is a good value according to the literature.[13]

III. QUALITY OF THE TEST

In this section we first discuss the difficulty and discrimination of the items. Secondly, there are two overall evaluations of the quality of the entire test, namely its reliability and validity. The reliability of a test concerns the consistent reproducibility of the score. The validity concerns the degree to which scores on the test actually measure what you want to measure. We will discuss these two types of evaluation of quality separately.

A. Difficulty and discrimination of the test items

Fig. 1 (a) shows the difficulty of the test per item. The difficulty ranges from 0 to 1, where 0 means that all students could answer the question correctly and 1 means no student could answer the question correctly. A spread in difficulty would imply that the concepts have been tested at different levels of difficulty, as is the case here for the three topics addressed on our test. Fig. 1 (b) shows the discrimination per item. The discrimination is typically defined as the number of students in the top 27% for overall score who answered the item correctly (N_T) minus the number of students in the bottom 27% for overall score who answered the item correctly (N_B), divided by the average of N_T and N_B, i.e.,

$$D = \frac{N_T - N_B}{\left(N_T + N_B\right)/2},$$

where D is the discrimination of the item. The discrimination has a range from -1.0 to 1.0, with 0.2 taken as a typical lower limit. 21 out of the 24 questions satisfy this criterion. Question 5a and question 19 are below this value, which can be explained by the difficulty of these two items. Question 15 is the third question that falls below a discrimination of 0.2 and its discrimination is also negative. This means that the students who scored the fewest points answered this question better than the students who scored the most points on the overall test. Question 15 has only two options. and therefore the chance of guessing the right answer is relatively high. For this reason, we do not include this question in the remaining analysis of the results.

B. Reliability

Test scores among the three pre-exam classes are very similar to each other, as are the scores of the four exam classes. Together with the fact that the classes are from five different schools and the test was taken at different times, the reproducibility of the scores is established. The earlier mentioned correlation of .82 for scoring of the open items by an independent scorer indicates that the scoring of the open items should not influence the outcome significantly.

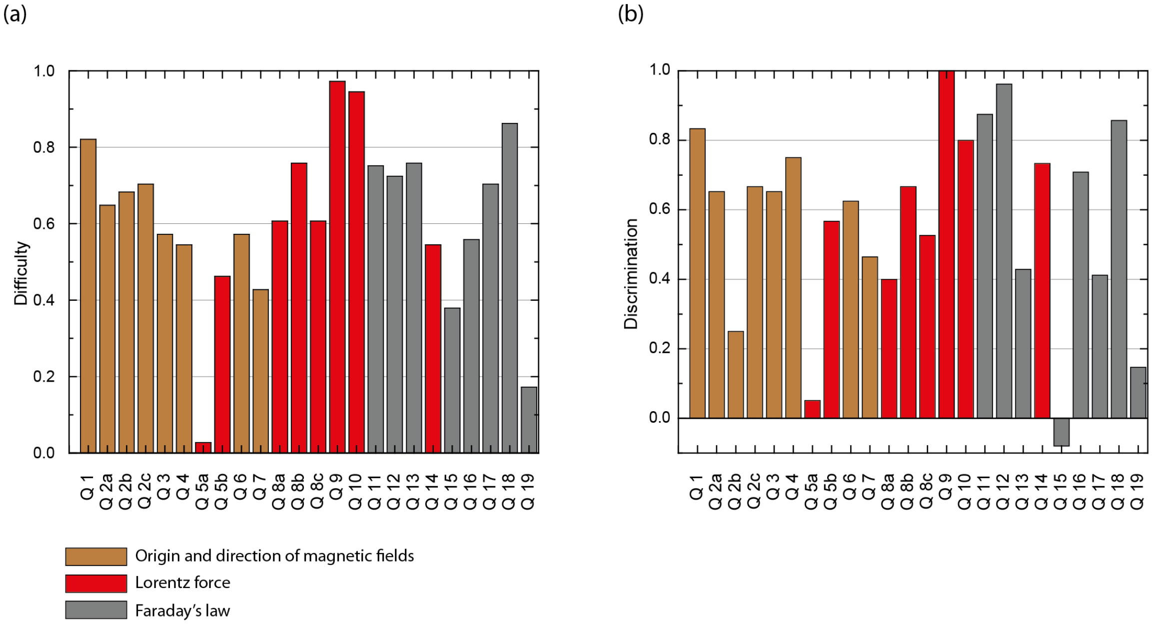

FIG. 1. (a) The difficulty of the test per item. A higher number indicates greater item difficulty. (b) The discrimination of the test per item.

C. Validity

To insure the validity of the test we incorporated multiple questions related to each topic. In the process of developing the test, the validity of the test was partly ensured by taking into account the comments of the three independent experts mentioned in section II and the comments of the students who participated in the pilot test. The spread in difficulty as seen in Fig. 1(a) shows that the three magnetism topics tested are each covered by items with a range of different degrees of difficulty. Moreover, the test was based on the topics students see in their high school career in using different school books, which also contributes to its validity. Finally, in most classes in which the test was administered we had an additional 20 minutes over the 30 minutes needed to complete the test. We asked the students to write as much as possible about their thoughts and reasoning next to the multiple choice questions during this time. In this way, we collected additional information on students' understanding of the concepts of magnetism, which also contributes to the validity of the test .

TABLE II. Response distribution for the multiple choice questions. The correct answers are bold. n/a means that the question was not answered.

Q2a	24.1% (1)	26.2% (2)	13.8% (3)	**35.2% (4)**	0.7% (n/a)	-	-	-
Q2b	41.4% (1)	11.7% (2)	14.5% (3)	**31.7 % (4)**	0.7% (n/a)	-	-	-
Q2c	26.9 % (1)	**29.7% (2)**	27.6% (3)	13.1% (4)	2.7% (n/a)	-	-	-
Q3	16.5% (1)	**42.8% (2)**	20.7% (3)	17.9% (4)	2.1% (n/a)	-	-	-
Q5a	**97.2% (1)**	1.4% (2)	1.4% (3)	-	-	-	-	-
Q5b	**53.8% (1)**	23.4% (2)	22.8% (3)	-	-	-	-	-
Q6	7.6% (a)	2.8% (b)	**42.7% (c)**	20.7% (d)	22.1% (e)	4.1% (n/a)	-	-
Q7	36.5% (a)	**57.2% (b)**	2.8% (c)	2.8% (d)	0.7% (n/a)	-	-	-
Q8a	14.5% (1)	**39.3% (2)**	7.6% (3)	37.9% (4)	0.7% (n/a)	-	-	-
Q8b	36.6% (1)	**24.1% (2)**	6.2% (3)	32.4% (4)	0.7% (n/a)	-	-	-
Q8c	**39.3% (1)**	31.7% (2)	13.1% (3)	14.5% (4)	1.4% (n/a)	-	-	-
Q10	51.7% (a)	9.0% (b)	24.8% (c)	7.6% (d)	**5.5% (e)**	1.4% (n/a)	-	-
Q11	37.3% (a)	18.6% (b)	18.6% (c)	**24.8% (d)**	0.7% (n/a)	-	-	-
Q12	33.1% (a)	11.7% (b)	11.7% (c)	5.5 % (d)	**27.6% (e)**	0.7 % (f)	6.9% (g)	2.8% (n/a)
Q13	27.6% (a)	**24.1% (b)**	28.3% (c)	18.6% (d)	1.4% (n/a)	-	-	-
Q15	35.9% (a)	**62.1% (b)**	2.0% (n/a)	-	-	-	-	-
Q16[a]	**44.1%**	20.7% (1,3	26.2% (1 or 3	9.0%	-	-	-	-
	(1,3)	+2and/or4)	+2and/or4)	(2 and/or 4)	-	-	-	-
Q17	20.6% (a)	**29.7% (b)**	15.9% (c)	9.0% (d)	22.7% (e)	2.1% (n/a)	-	-
Q18	**13.8% (a)**	22.8% (b)	6.2% (c)	15.8% (d)	2.0% (e)	36.6% (f)	2.8% (n/a)	-

[a] The students had to indicate with which statement(s) they agreed. Statement 1 and 3 are correct (first column). The other columns indicate the other combinations the students have chosen. The second column shows for example the percentage of students who had chosen the right statements but also chose statement 2 or 4 or both.

IV. RESULTS

Table II shows the response distributions for the answer choices for the multiple choice test questions. In this section we discuss the three topics separately by means of these statistics and the motivation of the students to choose a specific answer.

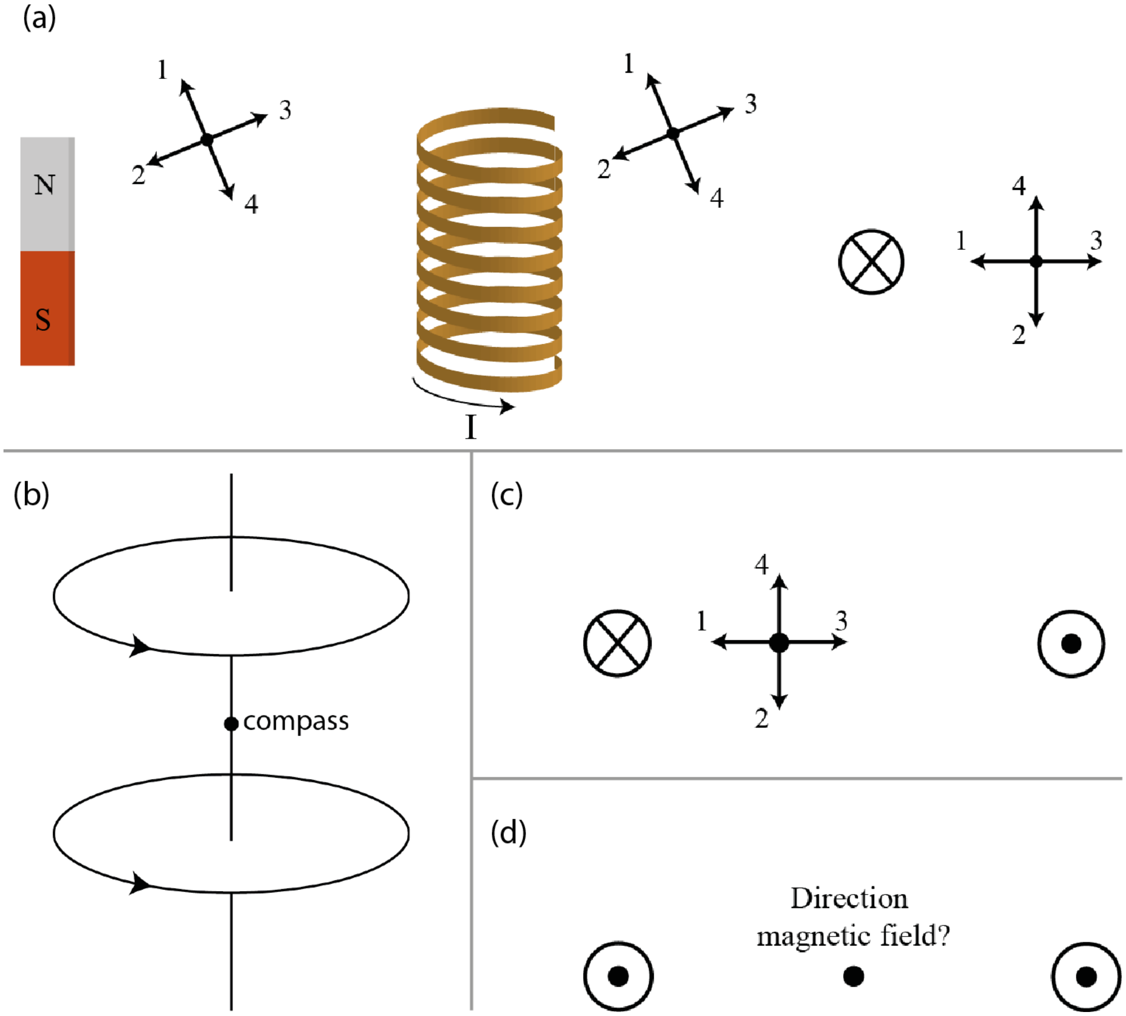

FIG. 2. (a) The students are asked what the direction of a compass needle is when placed at the point where the arrows are drawn. (b-c) Question 6, 3 and 4 of the test respectively. All three are superposition questions. In (c) and (d) the magnetic field direction at the indicated point is asked. (b) is a more complex situation with two current loops. The direction of the compass needle is asked at the point between the loops.

A. Origin and direction of magnetic fields

In Dutch text books the origin of the magnetic field in a bar magnet is described in terms of elementary magnetic particles that align in the presence of a magnetic field or are aligned permanently in the case of a permanent magnet. Around 18% of the students gave an answer in line with this. More than 50% believe that a form of charge is responsible for the magnetic field. Further we encountered here also the misconceptions that magnetism is due to the matter the magnetic material is made of or due to the magnetic field lines. Those misconceptions are similar, as found in Ref.6–9.

Question 2 (Fig.2(a)) is designed to test the application of the right-hand rule to determine magnetic field direction. The bar magnet, coil and wire are all three discussed in the school textbooks with the same symbols used on the test. Around 41% of the students chose the right answer for the coil and around 32% chose the direction exactly opposite to the magnetic field direction. Although the bar magnet has the same magnetic field, the students here were significantly more likely to choose the direction pointing directly towards the magnet or away from it, as would be the case in an electric field. Probably the bar magnet is seen by more students as a source of charge, as question 1 shows, and hence for the bar magnet the direction of the magnetic field and of the electric field are associated. Thirty percent of the students indicated correctly the field direction of the wire in Fig.2(a). Fifty-four percent chose the direction directly towards the wire or away from the wire, as if the wire were a static charge; this has also been noted in previous studies.

Questions 3 and 4 are superposition questions (Fig. 2(c,d)). Superposition is not discussed in the textbooks, but is usually assumed to be understandable for the students. For question 3, 42% of the students gave the correct answer. Just as in Ref. 8 the magnetic field direction towards the right wire is a strong distracter. The correct answer for question 3 can also be obtained by considering the field of only one of the wires , so question 4 was designed to be sure about the reasoning behind the student's answer. For question 4, around 39% of the students gave the correct answer by making a drawing of the magnetic fields of the wires along with the additional argument that the fields cancel each other. The percentages of correct responses on questions 3 and 4 are quite close, making it likely that roughly 40% of the students understand the superposition principle well. Another 14% drew the fields correctly for question 4 but did not note that the fields cancel each other. Around

29% drew an arrow in the direction of one of the wires, again indicating the field direction towards the wires as if the wires were charges. This percentage is almost half as large as the percentage that chose the direction of the wire's magnetic field as going directly towards the wire or away from it in question 2c. Not every student drew the wires' magnetic fields in their response to question 4 and in principle the correct answer is also obtained when the electrical analogue is used. This can explain the discrepancy between the incorrect responses for questions 2c and 4.

Question 6 (Fig. 2(b)) is another superposition question in a more complex configuration and is based on question 28 of Ref. 8. The answer distribution we obtained for this question matches very well what was reported in Ref. 8. In some classes we explicitly asked students to write down their reasoning for this answer. A total of 30 students wrote their reasoning next to the question. Answer e which says that the compass indicates no direction was an important alternative, as in Ref. 8. Maloney *et al.*[8] argued that this could be another electrical analog. Against this suggestion, as in Ref. 8, the students who gave answer e provided common reasons such as: "the loops are not connected with each other so there is no magnetic field" and "the two magnetic fields of the coils cancel each other", which do not indicate an electrical analogue but rather other misconceptions. In the second case, the students even drew the magnetic fields as one would expect for a wire loop but for one of them drew the opposite field. Furthermore, some students argued that a compass is pointing to the nearest north so the compass is pointing towards the upper loop or that a compass is pointing to the nearest south pole so the compass is pointing towards the lower loop. In this way the correct answer or the opposite direction was chosen, respectively. In those cases the students' drawings suggest that they used the magnetic field of only one of the loops to come to the right answer. Hence by this reasoning, the question can also be answered correctly without using the superposition principle of magnetic fields, which was not noted by Ref. 8 as an alternative way of reasoning that yields the right answer.

B. Lorentz force

Question 8 (Fig.3(a)) is designed to get more insight into students' understanding of the direction of the magnetic force on an object in relation to the magnetic fields. In the textbooks nothing is said explicitly about the magnetic force on an object such as a nail

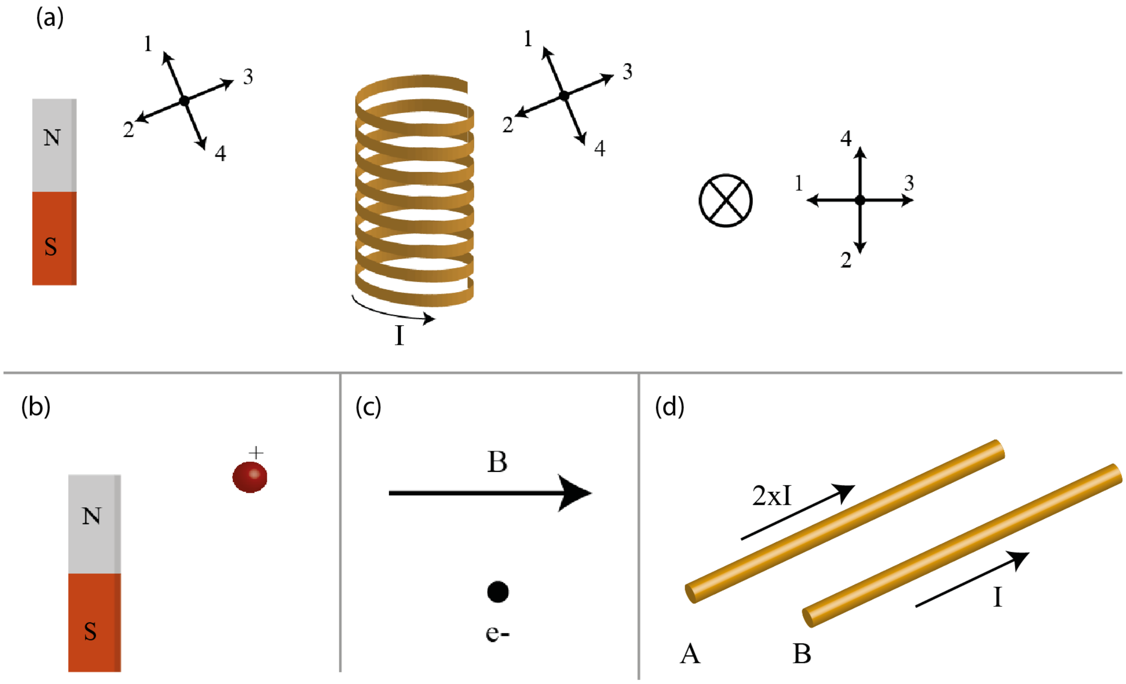

FIG. 3. (a) Question 8 of the test. The students are asked in which direction a nail move if it is placed parallel to the magnetic field lines at the point where the arrows are drawn. (b) Question 9 of the test. What is the magnetic force the magnetic bar is exerting on the positively charged static ball? A magnitude is asked for or a direction if they don't know the magnitude. (c) In line with question 9, question 14 asks the students specifically for the Lorentz force on the static electron in a magnetic field. (d) Question 10 presents two magnetic wires with different magnitudes of current running through the wires. What is the force they exert on each other?

when placed near a magnetic object. For the bar magnet, 37% chose the correct direction of force towards the bar magnet. The direction parallel to the magnetic field was a significant alternative. Although the coil has the same magnetic field as the bar magnet, only 24% chose the correct direction towards the coil. This could be due to the fact that bar magnets are seen more often in daily life than coils and therefore they know from experience that a nail moves towards the bar magnet. Thirty-seven percent chose the direction exactly opposite to the magnetic field direction and 32% chose the magnetic field direction that would be the case in an electric field. With the wire, 39% chose the right answer, and again the direction of the magnetic field was a strong distracter. To get more insight into the reasoning behind their choices we compared the responses to this question to the answers for question 2 (Fig. 2(a)) on the direction of the magnetic field. For the bar magnet, 50% of the students chose for question 8 the same direction or the exact opposite direction for the nail's movement as the direction of the magnetic field in question 2. For the coil and wire this percentage increases to 66%. So more than half of the students think that the force and magnetic field lines are parallel to each other.

This last result can be interpreted as students associating magnetic phenomena with electric phenomena. Question 12 reveals further nuances in this interpretation, at least for our test group. In question 12 three situations for an electron moving in a magnetic field are sketched. In situation 1 the velocity makes an angle between 0 and 90 degrees with the magnetic field, in situation 2 the velocity is perpendicular and in situation 3 the velocity is parallel to the field. The students are asked to list the Lorentz forces from the largest to the smallest. Twenty-eight percent correctly indicated the order of different magnitudes of the Lorentz forces relative to each other in the three situations. One-third of the students actually thought that the Lorentz force is the same in the three cases (answer a). This is different from Ref. 8, where option g is actually a strong distracter. Option g says that in situation 1 the Lorentz force is the largest followed by situation 2, with the smallest Lorentz force in situation 3. This answer was rarely chosen by the students who participated in this research. Nevertheless, the students who answered a were also the students who wrote down an additional argument. They answered that the speed of the electrons is the same in all cases so according to $F = BIL = qvB$ the Lorentz force is the same. It is therefore not necessarily true that the students interpret the situation as if the electron were a charge in an electric field. They filled in the formula of the Lorentz force, but they forgot about the direction in the product. This "thinking in formulas" is a well-known problem in high school. Students fill in formulas rather than having a clear concept of the meaning of the equation. Actually, considering how the Lorentz force is introduced to high school students, this thinking in formulas should not come as a surprise. In the textbooks the formula is directly presented and no attention is drawn to the concept. It is also briefly noted that only moving charges experience a Lorentz force and static charges do not, which is learned by heart. Building a conceptual model is not supported.

Question 9 (Fig. 3(b)) where the force of a magnetic bar on a static charge is asked for, was only answered correctly by 3% of the students. Seventy-nine percent thought that a magnetic field has influence on a static charge and 18% said that they had no clue or they needed their book to find the formula. This last group seems to think in formulas rather than in concepts. However, when the Lorentz force on the static charge in a magnetic field was asked for explicitly in question 14 (Fig. 3(c)), 50% gave the right answer, while 22% still answered that there is a force on the charge. The huge difference in responses between questions 9 and 14 can be explained if we assume that students expect that there are more magnetic forces than just the Lorentz force. This is highly probable considering the common answer they gave to this question: "the plus charge of the bar magnet bar and plus charge of the ball repel each other" or equivalent reasoning. In Ref. 8, it is concluded that students need to check the velocity when the magnetic force is requested. But it seems here that the majority understand that no Lorentz force is acting on a charge, but do not recognize that this is the only magnetic force present. This last point is also not made clear in the school textbooks and together with their additional misconception of charged magnetic poles, the difference in results for these two questions is not surprising.

Question 10 (Fig. 3(d)) shows another difficulty. It shows two parallel wires where one wire carries a current twice as large as the other wire. The students must indicate the relative magnitude of the forces the wires exert on each other. Fifty-two percent chose that wire A exerts a stronger force on B than B exerts on A (answer a). The option that the wires do not exert a force on each other is also a strong distracter, with 25% of the responses (answer c). Forty-two students wrote down their arguments for their chosen answer. When a was chosen, most of them wrote $F = BIL$ and I is two times as large in wire A so the force is two times as large. The extra step that the magnetic field acting on wire A is two times as small was not done by the students. However, the dependence of the magnitude of the magnetic field on current is discussed in the textbooks. For option c the most common argument was that "the fields cancel each other so nothing happens". Those students noted that the fields are opposite to each other but did not recognize that the field of a wire is not acting on itself.

C. Faraday's law

In question 16 the students are asked which actions cause a larger induction current when a bar magnet is moved into a coil. Around half of the students recognized that only the use of a stronger magnet (1) and a faster movement (3) give the desired effect. The other options that one must use a coil with a smaller diameter (2) or a coil made of a material with a larger

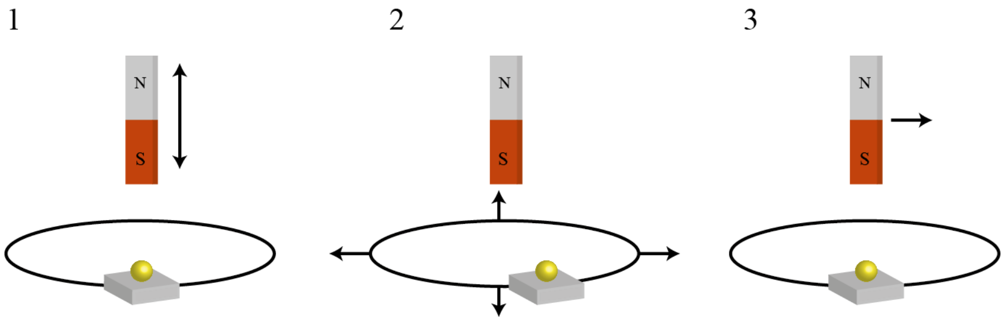

FIG. 4. Question 17. The students are asked in which situation the light bulb is glowing.

resistance (4) cause a smaller induction current. Only a few students (9%) did not recognize 1, 3 or both as the right answer. For this question, some students also wrote directly next to the question that they needed a formula or did not remember the corresponding formula. However, Faraday's law is discussed in the textbooks by means of an experiment where the measurement of a voltage meter is explained according to the movement of a bar magnet inside a metallic coil, before introducing a formula. However, the experiment is not always performed live in the class. Despite this extensive discussion, many students still rely on the formulas. This thinking in formulas is not noted in the other research literature where concepts in magnetism are studied.

For question 17 (Fig. 4) 37% answered that the direct movement of the magnetic bar in the loop (situation 1) is the only option where the light bulb is going to glow. Fourteen percent answered correctly that in the cases where the area of the loop is made larger (situation 2) and the bar magnet is moved horizontally (situation 3), the light bulb is also glowing. Twenty-three percent did not recognize that the horizontal movement of the bar magnet causes a change in flux. The answers chosen generally include situation 1 (89%). Situation 1 is the only situation that is seen in the high school textbooks when discussing flux, which might explain why students chose only this situation as the right answer. Around 55% of the answers given did not include situation 2 where the area of the loop changes. In Ref 8 as well, the majority (72%) did not include the collapsing loop, which is similar to situation 2.

Finally, question 19 asks the students whether a magnet or a wooden piece of the same mass will exit a vertical copper tube first when they are dropped into the tube at the same time. This question is included to get detailed information on the students' reasoning when it comes to Faraday's law. Twenty-eight percent answered correctly that the wooden piece will come out first as the magnet is delayed by the magnetic field of the induction current. Forty-two percent answered only that the wooden piece will be first without further explanation. The phenomenon seems not to be very clear to them. Sixteen percent said the magnet is delayed because the copper is magnetized or the magnet sticks to the copper which delays it. This experiment is also shown during instruction, which could explain the high rate of good answers, but clearly most of the students do not have a clear understanding of the concept.

V. DISCUSSION

A. Students' thinking on magnetism

The test together with the students' explanations of their motivation for choosing their answers probed the 145 students' thinking about magnetism. The insignificant differences between the three pre-exam classes and four exam classes drawn separately from different high schools show that the results are reproducible. However, we note that the pre-exam classes scored significantly better on the questions about magnetic field direction and Faraday's law. In the rationale for the answers on Faraday's law, we found that students did not remember the right formula or that they could remember the outcome of an experiment but did not remember the exact mechanism behind it. This together with the fact that this topic is taught in the pre-exam year could explain the difference between the exam and pre-exam classes. However, more research needs to be done to demonstrate whether this explanation is true.

This thinking in formulas was not noted in previous work and seems an important justification the students give for their answers. For the questions on the Lorentz force, the substitution of variables or numbers into the formula is also the foundation for their answer.

Along with this, we also saw misconceptions that have been reported elsewhere, such as the electrically charged north and south poles of a magnet. Therefore, the students also seem to expect that a magnet exerts a force on a static charge. Five questions are based on the work in Ref. 8. For most of the questions, we found the same distribution of answers as in Ref. 8. However, the extra justification provided by the students for their answers gives more insight into their reasoning and shows that the answers to the multiple choice question have to be interpreted carefully. On a question about superposition, for example, we observe that in a more complex configuration correct answers are also obtained based on different reasoning where superposition does not come into the picture. Similarly, in the case of the Lorentz force we must compare different questions and the additional reasoning to form a picture of the students' actual concepts.

B. Presentation of magnetism in school textbooks

We compared the students' answers to the presentation of the topic in Dutch textbooks. Performance on the questions and the students' reasoning are more or less in line with how the topic is presented. There is little to no attention to concepts in the textbooks. Magnetic field directions are presented as facts and should be learned by heart without considering the concept students have of north and south poles. In fact, most textbooks also introduce the concept of magnetic poles with a note that it is a model and that nothing like a magnetic charge exist in reality. Previous work shows that the mere mention of a common mistake (in this case the creation of a magnetic field by charge) is not effective at all.[11,17] The students make a mental note that they should not make this mistake in the test or corresponding situation. However, the underlying misconception remains and can still be used in other settings.[11,17] To convince the students that indeed a static charge cannot create a magnetic field, they should be confronted with their misconceptions. We will come back to this in the next subsection.

The Lorentz force is also directly presented in the textbooks by means of a formula and rules to determine the right direction, without an attempt to form a concept of the Lorentz force. In the discussion of Faraday's law more attention is drawn to an experiment where the effect can be observed, but despite this discussion the students mainly used the formulas in their argumentation or tried to remember the demonstration experiments they had seen.

C. Implications for instruction

Our observations show the need for more attention to building a conceptual model during instruction. Currently, a new program is slowly being introduced in Dutch high schools which intends to deal with physics in a more conceptual way. We would therefore like to discuss the implications for instruction involving teaching the concepts of magnetism to high school students based on our observations.

First of all, we observed that the students show little or no conceptual knowledge of the Lorentz force. The experiment described in the work of Onorato (2013) *et al.*[16] can help the students to obtain more insight and feeling for the Lorentz force. In this study, the students performed an experiment on the Lorentz force in which they studied the dependence of the force as a function of current, length of the wire and the dependence of the angle between the variables. Before the experiment 47% were able to indicate the direction of the Lorentz force, which increased to 84% afterwards. In Ref. 17 it is also noted that only a demonstration is not as useful as one might think. Students who experience for themselves the Lorentz force and the direction for the first time are still surprised, although they have seen it or solved problems about it several times. The same holds for Faraday's law.

Along with these experiments, we would like to suggest an experiment in order to deal with the rather rigid misconception of the presence of static electric charges in a magnet. In the work of Smolleck[14] and Åkerlind[15], it is argued that to successfully replace a misconception, the students should be confronted with their misconception and should experience that their model fails to predict or explain the phenomena. Ampère himself also had to convince the scientific community that the phenomenon he was describing was really a different phenomenon than electricity. He was aware of the fact that three parallel wires with current running in the same direction attract each other. This is impossible to explain if all of the wires have the same static charges.[17,18] The students can then start to think what actually is the mechanism behind magnetism. Hence, an opportunity is created to replace the misconception of static electric charges in a bar magnet and that magnets therefore have influence on static charges. Future research should provide an answer as to whether this experiment is indeed effective in dealing with the misconception of magnetic charges.

Tanel *et al.*[11] also suggested that cooperative learning is more effective when it comes to remembering and understanding of the subject. Students discuss and reflect more on their concepts and work. Certainly in the case of magnetism, which is a relatively abstract subject for the students, the students could thereby benefit from cooperative learning. Tanel also noted that the students work even harder compared to a conventional teaching method.

In this article, we discussed the development of and results from a conceptual test of magnetism inspired by previous research. We observed that besides the known confusion between magnetism and electric charges, a strong focus on equations rather than concepts also leads to misunderstandings. We hope that the results and the discussion of instructional methods will stimulate further research on teaching magnetism in high school.

ACKNOWLEDGMENTS

We would like to thank all of the teachers at the schools where the test was administered and their students for participating in this research. We acknowledge Benno Berendsen, Thomas J. Huisman and Alexander Brinkman for support and discussions about the development of the test.

---

[1] J. Clement,*Students' preconceptions in introductory mechanics*, Am. J. Phys. **50**, 66–71 (1982).

[2] D. P. Maloney, *Charged poles?*, Phys. Educ. **20**, 310–316 (1985).

[3] I. A. Halloun, D. Hestenes, *The initial knowledge state of college physics students*, Am. J. Phys. **53**, 1043–1055 (1985).

[4] F. M. Goldberg, L. C. McDermott, *An investigation of student understanding of the real image formed by a converging lens or concave mirror*, Am. J. Phys. **55**, 108–119 (1987).

[5] W. M. Christensen, D. E. Meltzer, N.-L. Nguyen, *Student understanding of calorimetry in introductory calculus-based physics*, Am. J. Phys. **79**, 11 (2011).

[6] A. T. Borges, J. Gilbert, *Models of magnetism*, Int. J. Sci. Educ. **20**, 361–378 (1998).

[7] B. Akarsu, *A qualitative study on high school students' conceptual understandings of electricity and magnetism*, Sosyal Bilimler Enstitüsü Dergisi Sayi, 117–125 (2010).

[8] D. P. Maloney, T. L. O'Kuma, C. J. Hieggelke, A. van Heuvelen, *Surveying students' conceptual knowledge of electriciy and magnetism*, Am. J. Phys **69**, S12–S23 (2001).

[9] J. Guisasola, J. M. Almudi, J. L. Zubimendi, *Difficulties in learning the introductory magnetic field theory in the first years of university*, Sci. Ed. **88**, 443–464 (2004).

[10] D. Sederberg, L. A. Bryan, *Tracing a prospective learning progression for magnetism with implications at the nanoscale*, Learning progression in science (LeaPS) conference (2009).

[11] Z. Tanel, M. Erol, *Effects of cooperative learning on instructing magnetism: analysis of an experimental teaching sequence*, Lat. Am. J. Phys. Educ. **2**(2)(2008).

[12] F. Marton, S. Booth, *Learning and Awareness*, Lawrence Erlbaum Associates, Mahwah (NJ) (1997).

[13] D. F. McCaffrey, J. R. Lockwood, D. Koretz, T. A. Louis, L. Hamilton, *Models for value-added modeling of teacher effects*, J. Educ. Behav. Stat. **29**, 67–101 (2004).

[14] L. Smolleck, V. Hershberger, *Playing with science: an investigation of young children's science conceptions and misconceptions*, Current Issues in Education, **14**, 1 (2011).

[15] G. S. Åkerlind, *A phenomenographic approach to developing academics understanding of the nature of teaching and learning*, Teaching in Higher Education **13**, 6 (2008).

[16] P. Onorato, A. De Ambrosis, *How can magnetic forces do work? Investigating the problem with students*, Phys. Educ. **48**, 766–775 (2013).

[17] A. B. Arons, *Teaching introductory physics*, John Wiley and Sons, Inc. (1997).

[18] T. K. Simpson, *Figures of thought - a literary appreciation of Maxwell's treatise on electricity and magnetism*, Green Lion Press (2006).

[19] L. C. McDermott, *Millikan Lecture 1990: What we teach and what is learned-Closing the gap*, Am. J. Phys, **59**(4), 301–315 (1991).

Appendix: Questionnaire

Question 1

In a coil and a current-carrying wire, the current is the source of the magnetic field. What is the source of the magnetic field of a bar magnet? Explain in one or two sentences. You don't have to explain why it causes a magnetic field.

Question 2

Ben has a bar magnet, a coil and a straight wire. They are shown in Fig. 1. The wire's current goes into the paper. Ben takes a compass and places it at the point where the arrows are drawn.

What is the direction of the compass needle in the case of

a) the bar magnet? Choose 1, 2, 3 or 4.

b) the coil?

c) the wire?

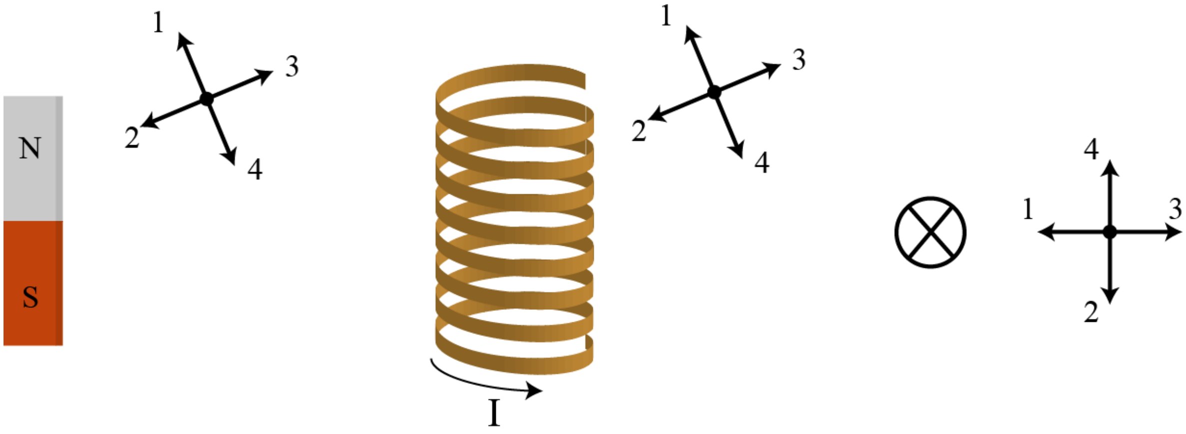

Fig 1.

Question 3

Next, Ben takes two wires. The current carried by one of the wires comes out of the paper (circle with the dot in the middle) and the current carried by the other goes into the paper (circle with the cross in the middle) (see Fig. 2). What is the direction of the magnetic field at the point where the arrows are drawn? Choose 1, 2, 3 or 4.

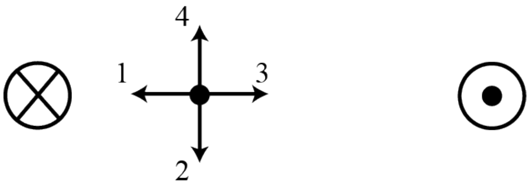

Fig 2.

Question 4

Ben changes the sign of the current of the left wire (see Fig. 3). What is now the direction of the magnetic field exactly in-between the wires? Explain your answer briefly.

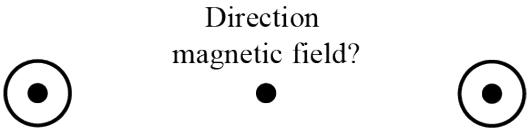

Fig 3.

Question 5

Ben places two bar magnets across from each other as shown in Fig. 4a. On another table he places two coils across from each other (Fig. 4b).

a) What effect do the bar magnets have on each other?

1 They repel each other

2 They attract each other

3 Nothing happens. They stay in the same position

b) What effect do the two coils have on each other?

1 They repel each other

2 They attract each other

3 Nothing happens. They stay in the same position

Question 6

Consider Fig. 5. Ben has two identical loops of wire across from each other, each carrying

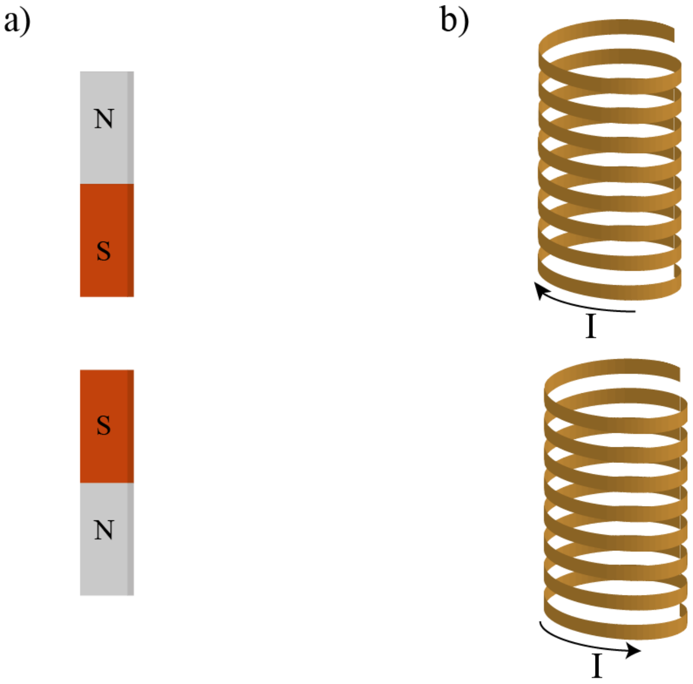

Fig 4.

a current I. He places a compass between the loops. What direction does the compass indicate, and explain your answer briefly?

a) The compass points to the right

b) The compass points to the left

c) The compass points up towards the upper loop

d) The compass points down towards the lower loop

e) The compass doesn't indicate a direction

Question 7

Consider Fig. 6. Ben takes a coil and wants to have a magnetic field such that the compass indicates the direction shown in Fig. 6. The location of the coil is also shown in Fig. 6. How should Ben position the coil and with which current direction? Choose a, b, c or d in Fig. 7.

Question 8

Ben again takes a coil, a current-carrying wire and a bar magnet, together with a nail (Fig. 8). The iron nail is placed at the point where the arrows are drawn. You may assume that

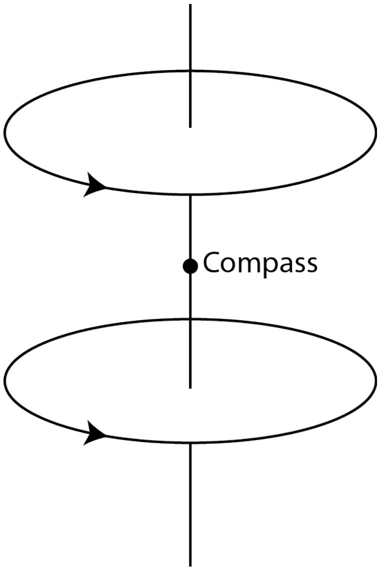

Fig 5.

Fig 6.

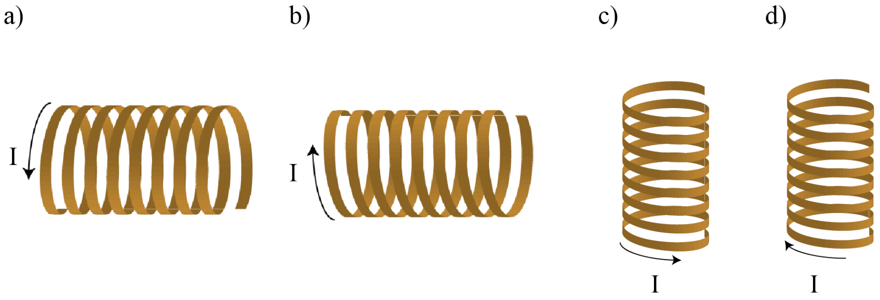

Fig 7.

the nail lies parallel to the magnetic field. What direction does the nail move in the case of

a) the bar magnet? Choose 1, 2, 3 or 4.

b) the coil?

c) the wire?

Question 9

Ben places a small positively charged ball near a bar magnet at the location indicated in Fig. 9. What can you say about the force the magnet is exerting on the ball? (give a magnitude or a direction)

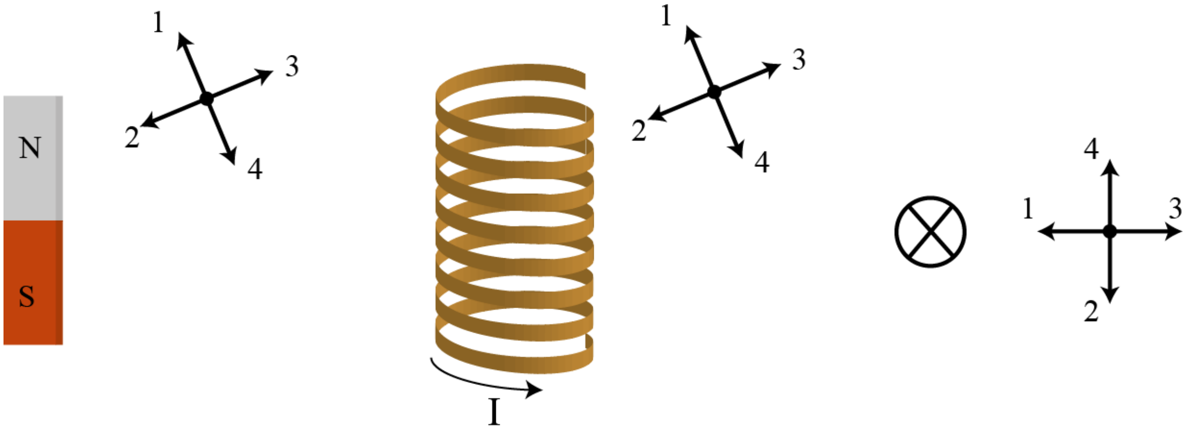

Fig 8.

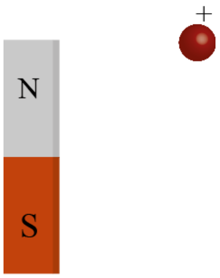

Fig 9.

Question 10

Consider Fig. 10. During an experiment Ben places two wires parallel to each other. Wire A has a current twice as large as carried by wire B. How do the forces that the two wires exert on each other compare?

a) Wire A exerts a stronger force on wire B than B exerts on A

b) Wire B exerts a stronger force on wire A than A exerts on B

c) The wires exert no forces on each other

d) They exert repulsive forces of equal magnitude on each other

e) They exert attractive forces of equal magnitude on each other

Question 11

The screen of a cathode ray tube television is built up by the collision of electrons inside the screen. The electrons are deflected in the right direction by the presence of a magnetic field in the television. The magnetic field changes continuously in direction and magnitude

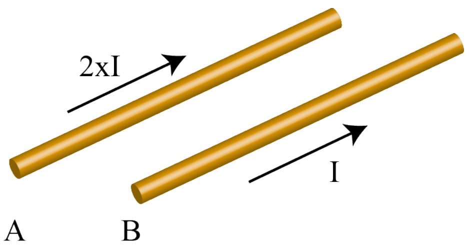

Fig 10.

to get the electrons in the right position. At a certain moment we have the situation shown in Fig. 11.

In which direction are the electrons deflected?

a) Towards the north pole of the magnet

b) Towards the south pole

c) Into the paper

d) Out of the paper

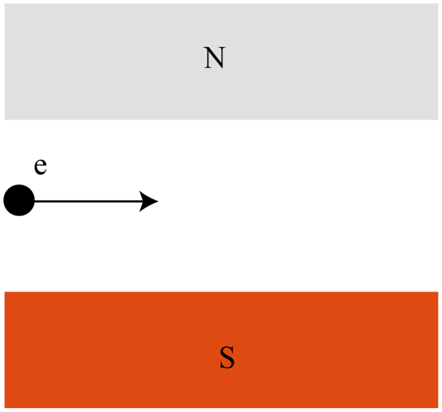

Fig 11.

Question 12

To understand the deflection of the electrons better, a student, Bob, uses the electron beam of the television in a self-generated magnetic field. At a certain moment he has the situation shown in Fig. 12. The electrons all have the same speed but not the same direction. The direction is indicated by the arrows.

Which statement is true?

a) The Lorentz force on electron 1 (F1) = the Lorentz force on electron 2 (F2) = the Lorentz force on electron 3 (F3)

b) F3>F1> F2

c) F3> F2> F1

d) F2> F3> F1

e) F2> F1> F3

f) F1> F3> F2

g) F1> F2> F3

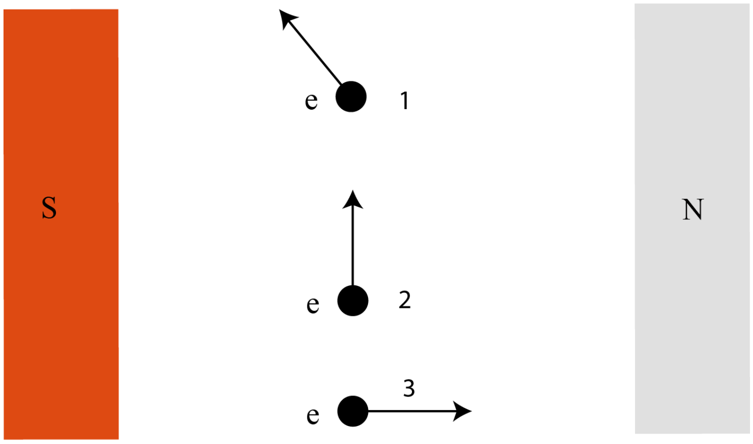

Fig 12.

Question 13

Question 13

At a certain moment later electron 3 is deflected upwards (Fig. 13). In which direction did Bob set the magnetic field?

a) The magnetic field points into the paper

b) The magnetic field points out of the paper

c) The magnetic field points upwards

d) The magnetic field points downwards

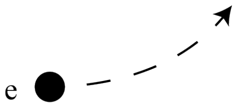

Fig 13.

Question 14

In a constant magnetic field we have a static electron (e-) (Fig. 14). What is the Lorentz force on the electron? Explain your answer.

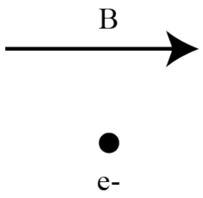

Fig 14.

Question 15

The same student, Bob, holds a bar magnet bar above a coil as shown in Fig. 15. The ends of the coil are connected to each other through a wire. Bob wants to induce a current in the direction as shown in Fig. 15. What should he do?

a) Move the bar magnet bar upwards

b) Move the bar magnet downwards

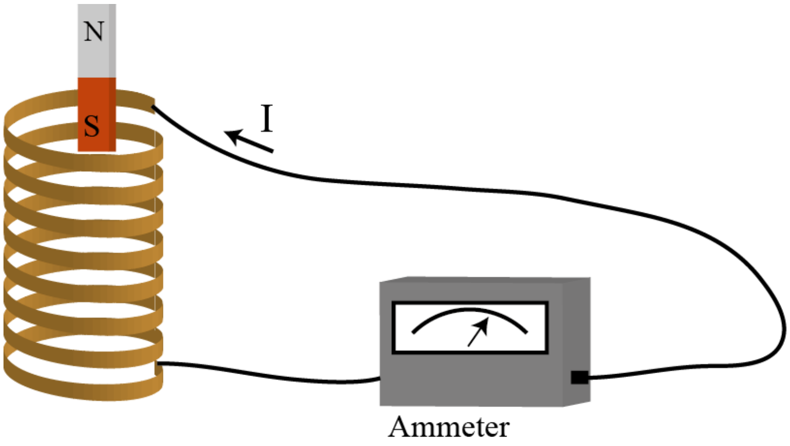

Fig 15.

Question 16

Next Bob wants to induce a larger current. He states that he can do that in four ways.

1) I can use a stronger magnet

2) I can attach a coil with a smaller diameter

3) I can move the bar magnet faster

4) I can attach a coil made of a material with greater resistance.

With which statement(s) do you agree?

Question 17

The teacher is curious whether after all his experiments Bob has an idea how induction works. The teacher gives him a few problems. The first set-up is sketched in Fig. 16. You see a short coil and a rectangular loop of copper. The loop is moved in three ways.

1 The loop is circled around the coil, with the distance to the coil remaining the same

2 The loop is hold parallel to the axis of the coil and moved upwards. The loop then moves above the coil

3 The loop is moved away from the coil

The teacher asks Bob in which situation there will be an induced current. What do you think?

a) In situation 1 and 2

b) In situation 2 and 3

c) In situation 1 and 3

d) In situation 1, 2 and 3

e) In none of the situations

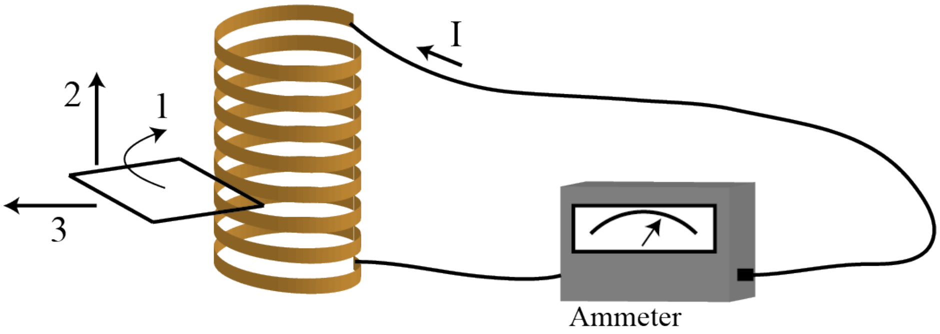

Fig 16.

Question 18

The other experiment that the teacher shows to Bob is three short experiments. These are sketched in Fig. 17. In number 1, a magnet is moved up and down near the copper loop with a light bulb. In number 2, the loop area becomes larger and in number 3 the magnet is moved horizontally. In which set-up is the light bulb going to glow?

a) In all three cases

b) In situations 1 and 2

c) Situations 2 and 3

d) Situations 1 and 3

e) In all three cases it is not going to glow

f) In one of the three cases, namely:......

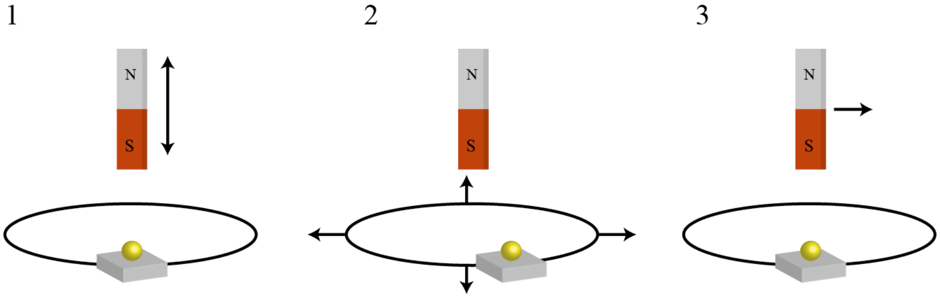

Fig 17.

Question 19

Meanwhile, Ben has joined Bob and the teacher. The teacher gives Bob and Ben each an identical copper tube. Ben gets a small magnet and Bob a small wooden piece of the same mass. Bob and Ben drop the magnet and the wooden piece into their tubes at the same time. Which one comes out first? You can neglect air resistance. Explain your answer briefly.