

PAPER • OPEN ACCESS

Magnetic phenomena and living systems in the bio area degrees

To cite this article: O Caltun *et al* 2019 *J. Phys.: Conf. Ser.* **1286** 012023

View the [article online](#) for updates and enhancements.



IOP | ebooks™

Bringing you innovative digital publishing with leading voices to create your essential collection of books in STEM research.

Start exploring the [collection](#) - download the first chapter of every title for free.

Magnetic phenomena and living systems in the bio area degrees

O Caltun¹, M Michelini² and A Stefanel²

¹ T Alexandru Ioan Cuza University, Faculty of Physics, Bd. Carol I nr. 11, 700506 Iași, Romania;

² Research Unit in Physics Education, University of Udine, via delle Scienze 206, 33100 Udine, Italy

alberto.stefanel@uniud.it

Abstract. An educational path was designed aiming to improve the comprehension of basic concepts of magnetism of students of the Bio areas and developing a functional understanding of these concepts applied in the specific context of study and their work profession. A pilot study at the University of Udine involved students of agro-food degrees to analyse how they considered magnetic concepts and their use in their own area of study. In the final examination, they were requested to exemplify and to discuss in which contexts of their own area of study magnetic phenomena are involved. The students identified a wide spectrum of contexts in which magnetic concepts can be actualized at four different scales: astronomical/planetary, human/animal, cellular and atomic/nuclear. In the majority of cases, they showed competencies in using concepts like magnetic field and interaction to discuss in context examples in their own areas of study. Some difficulties in distinguishing magnetic effects from electrostatic effects emerged, as well as the need to be conscious of the strength, complexity and role of magnetic phenomena involving different scale levels at the same time.

Teaching physics in biology and related sciences, which in the following we will address as the Bio area, requires a great change in approaching of physics concepts and introducing their representations into contexts specific to the field of study [1]. The physics concepts and models have a transversal role in building concepts, models, processes and theories of the Bio area. Magnetic phenomena at first sight seem marginal in this area but have a far more pervasive role than one might think. For example, the role of magnetic cues for compass orientation has been confirmed in numerous species, as well as having a decisive role in the development of life on emerging lands [2–3]. The systems used by animals to perceive the Earth's magnetic field based on fundamental physical and biological processes involve important cellular structures [4–5]. Recent research has highlighted the role of magnetic fields in the growth of some plants [6]. An important application of magnetic phenomena is the NMR diagnostic method very used in different Bio areas [7]. Therefore, in introductory or general physics courses for the Bio area degrees, it is important to engage students in constructing a functional understanding of concepts of magnetism, considering different and interesting topics in their own subject of study.



This goal requires significant revision of the teaching of magnetism concepts involving issues at different levels. New educational learning-teaching pathways must be constructed, according to the Model of Educational Reconstruction [8], taking into account both the content analysis individuating the crucial concepts to be faced and typical students' reasoning patterns and learning problems. It is well known that most students use alternative models to explain magnetic phenomena such as the charge pole model [9], or wrong models of the sources of magnetic field and of the magnetic interactions [10–11]. All these learning problems can strongly affect the comprehension of the role of magnetic corpuscles in living cells for detecting the Earth's magnetic field, or the distinction between techniques based on magnetic or electric principles.

Our research started with the hypothesis that it is possible to construct a pathway for improving Bio areas students' comprehension of basic concepts of magnetism and developing a functional understanding of these concepts to be applied in the specific context of area of study and future profession. The pilot test discussed in the present work involved more than 150 students enrolled in General Physics courses for Agro-Natural-Food Science specialization at University of Udine.

1. Theoretical framework

Research in physics education has focused for many decades on innovation in teaching physics for degree courses in physics, identifying educational needs, developing tutorials based on inquiry approaches and instruments for students learning assessment and evaluation, strategies for active learning [12–13]. Due the increasing role of physics in the biosciences and therefore in Biosciences degrees [14–15], these researches addressed the development of new curricula for physics courses in Biological degrees [16], aiming to integrate Bio-Science and Physics contents [16–17], and to improve the teaching of physics in the bio-area degrees [1,16–19]. The teaching of physics for students of the Bio area is a multidimensional problem, mainly linked to what Lillian Mc Dermott defines as “functional understanding” of physical concepts [20], that is the ability to correctly and consistently use physical concepts in the specific thematic-disciplinary-applicative context of one's own field of study and work.

It requires tackling at least four problematic issues. First, re-designing how physics is presented, so that its role can be recognized in the specific context that characterizes the specific degrees, turning the approach to physics to characterize the role in specific areas, identifying specific applications in the professional field of study [21–22]. Second, offering the opportunity to use actively in different fields instruments and methods typical of physical science [21]. Third, identifying strategies able to produce an active role for students in the learning of physics, giving them the opportunity to appropriate the applied physical methodologies [21]. Fourth, supporting students' learning with multitasking methodologies and ICT tools, experimental laboratory activities, problem solving, evaluation and self-assessment of learning outcomes [1,13,17]. The challenge is to show how to use physics to explain and formalize significant biological processes [1]. It is not just a matter of contextualizing exercises and examples, but also considering biology issues with physics tools and problems that imply interdisciplinary skills [23].

The present work contributes to this problematic area. The suggestions of the Redish group are followed, especially regarding the need to modify deeply the approaches, rooting the treatment of physics contents in problematic contexts interesting for the Bio area students [1,22]. It is also important to foresee a high-level commitment of the students, rather than following simplified approaches that have the effect of reducing the educational level and the construction of learning obstacles, and to realize an active involvement of the students both in the face to face activities and web based projects [13,17].

2. Research questions

This work aims to answer the following research questions:

RQ1. In which contexts do students identify magnetic phenomena?

RQ2. What concepts do they use in the analysis of these contexts and what learning problems do they highlight?

RQ3. For which aspects does the proposed educational pathway activate effective learning of magnetic phenomena and functional understanding? Which difficulties remain?

RQ4. How to modify the educational pathway?

3. Instruments and methods

To answer the previous research questions we designed the following instruments, the first two of which are extensively described in the next sections. A) An educational pathway of learning magnetic phenomena designed to address the basic concept of magnetism useful for students of the Bio area to analyze important context for them as NMR imagery. B) A questionnaire consisting of multiple choice items based on a selection of questions from that developed in literature [9-11, 24-25], and available on the web as a self-evaluation instrument. C) The written final examination including two questions on magnetism. The first was a multiple choice item addressing the force acting on a wire in which a current flows in the presence of a uniform magnetic field, the same situation faced in the on-line questionnaire B) but with a different orientation of the wire with respect to the magnetic field lines. The second was an open response item requesting to “Discuss the role of magnetic phenomena in contexts and techniques of the Bio-area” (a preliminary discussion had been presented on the web forum on the same question). Suggestions for reference papers [6, 26-27] and for interesting topics [2-4, 7] supported the discussion.

3.1. The Educational Pathway on Magnetism for the Bio Area

Following the Model of Educational Reconstruction [8], to design the educational pathway on magnetic phenomena, a preliminary analysis was made to identify concepts that students need to know and to understand in order to explain magnetism in living systems. This pathway aims to construct the competence of students to manage the concepts of magnetic field, magnetic moment and magnetization without a large use of formalism in the analysis of interaction of magnets, current and fields and living things. It promotes skills in analyzing magnetic phenomena and processes in living systems, and applying these competencies to understand the physics concepts involved in the papers recommended for lecture [6, 26], in important applications like the NMR technique [7], or in the processes fundamental to the ability of some living things to perceive or map the magnetic field [4-5] and to use that in orientating themselves. As a preliminary study, we were interested in collecting information on how an approach to physics concepts produces competences for analyzing the Bio contexts [27].

First step in the learning pathway was to realize how the interaction of two magnets results in a tendency to rotate in order to minimize the energy and to reach the equilibrium of movement. This was followed by obtaining the representation of magnetic field and magnetic lines based on the use of a magnetic needle (compass) as a detector of the “orientation field” (then identified as the magnetic field), produced by a magnet or by the Earth itself. The magnetic field can be described drawing the line of orientation of the needle compass, recognizing its 3D structure, the symmetry of the source line dynamically connected to the magnet itself. Normalizing the number of lines represented per units of surface area, the field lines can represent quantitatively the intensity of magnetic field. The magnetic poles emerge as the parts of the magnet where the line density is greatest. An important step in the learning pathway is the impossibility to separate the poles indicating that the magnetic field lines are a continuous structure passing from outside to inside the magnet.

To connect in a phenomenological way magnetism to electricity, Oersted’s experiment was included in the path, helping students to discover that current flowing through an electric wire is a source of magnetic field. Exploring the magnetic field produced by the electric currents, it emerges that the magnetic field depends on the geometry of the wire itself and that a solenoid produces a magnetic field equivalent to that of a bar magnet. These steps reinforced the idea that magnetic field lines are always closed. The Ampère theorem represented the minimal tool used for formal description of the structure of the magnetic field.

The force acting on a wire immersed in a magnetic field and carrying an electric current (the Lorentz Force) was also introduced. The interaction of a current loop with a magnetic field is considered using the concept of a mechanical couple (torque) acting on the loop in order to satisfy the maximum magnetic

flux density rule. The concept of magnetic moment associated with a magnet or closed currents was also introduced. In quasi-static magnetic fields, the mechanical couple determines the alignment of the magnetic moment (also called the magnetic dipole) with the magnetic field line, in order to minimize the energy. In the dynamic situation when an alternating field is superimposed perpendicular to the orientating magnetic field, Larmor precession of the magnetic moment is activated.

The end of the learning pathway introduced the magnetic field inside the matter, individuating at the phenomenological level paramagnetic, diamagnetic, ferromagnetic materials characteristics and their magnetic properties, described through the magnetization vector and magnetic susceptibility. Finally, as an example the fundamentals of the NMR technique were discussed in detail without using formulas but including basic concepts of magnetic moment relaxation in an alternating field introduced by diagrams and schemes illustrating the geometry and role of DC and AC superposed fields.

3.2. The on-line questionnaire

As a self-evaluation tool for students, a web questionnaire was designed, based on items used in research on students learning [9-11, 24-25]. It included ten multiple choices items (Q1–Q10) regarding nine situations presented with the pictures shown in figure 1 and related to the following conceptual knots:

Q1 – an iron ball and a magnet, to identify the direction of the force of interaction; involving the distinction between trajectory and field line;

Q2-3 – the magnet and a coil on the table, to identify the extension and the reciprocity of that interaction;

Q4 – A charged polystyrene ball at rest close to a magnet, to identify the null force acting;

Q5 – Two magnets and a compass, to recognize the superposition principle of magnetic fields;

Q6 – The magnet approaching different objects, to discriminate objects strongly (ferromagnetic objects) and weakly (diamagnetic and paramagnetic) interacting with a magnet;

Q7 – The electric wire parallel to the magnetic field line produced by the poles of a magnet, to identify the null force;

Q8 – The magnetic dipole in the external magnetic field, to identify the torque acting and establishing mechanical equilibrium when the dipole aligned with the field lines;

Q9 – Cylinders of different materials (dia/para/ferro-magnetic and superconducting) inside a uniform field, to identify the direction of the induced magnetization in each cylinder.

Q10 - The rotating charged cylinder inside a magnetic field, to identify Larmor precession.

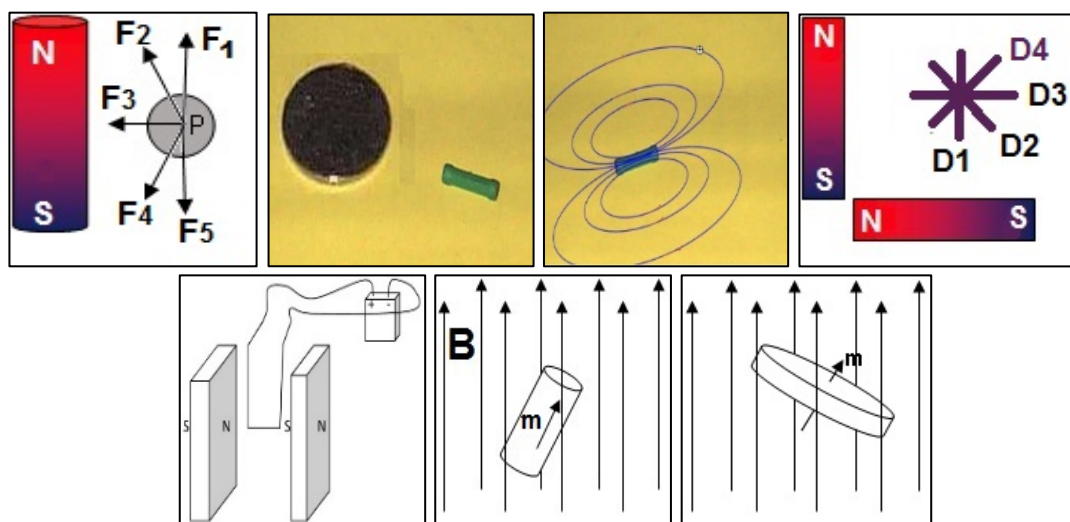


Figure 1. Pictures representing the situations of items: Q1, Q2-Q3, Q4, Q5, Q7, Q8, Q10. Each picture appears in an item, as figure.2 exemplifies.

Figure 2 shows examples of the format of the multi-choice items of the on-line questionnaire.

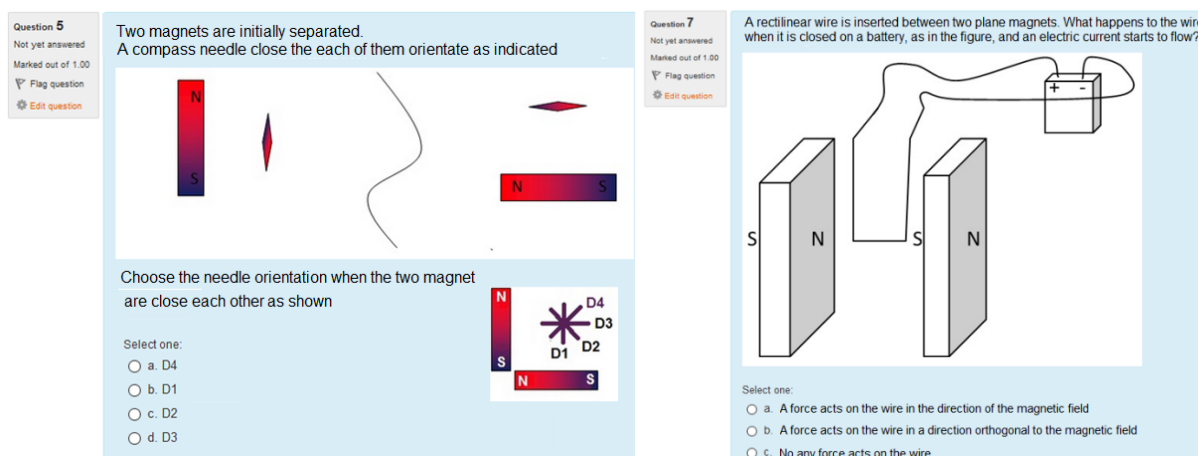


Figure 2. Item 6 and Item 7 of the on-line questionnaire.

3.3. The Context and the Analysis Methods

A pilot test involved two groups of first year students at Udine University: the first group studying Agronomy (AGR), Oenology (VEN), and Science of Environments (SAN); the second group the Science and Technology Food (STF hereafter) branches. Each group attended a lecture lasting 2 hours, that presented in an interactive way the learning path summarized above. After the lecture, students completed the web-questionnaire on magnetism and contributed to the discussion in the web forum (during 20 days), and at the end, they had the final examination. In pretests, the majority of students (85%) demonstrated the representation of magnetism as an attraction with limited range [9] acting on all metallic objects. The number of students that completed the on-line questionnaire was $N=118$, 76 of the SAN and 42 of STF branches. 188 students discussed in the final examination "the role of magnetism in the context of natural, bio, agro-food sciences, with adequate examples" (39 of AGR, 38 of SAN; 59 of VEN 54 of STF branches).

Each item of the questionnaire was analyzed by the frequency of options, evidencing the mode of the distribution and the main encountered difficulties. The open written sentences were categorized in topics, divided by the context quoted and the learning problem evidenced.

4. Questionnaire data analysis

This section synthetizes the analysis of the on-line questionnaire, completed by 118 students. Table 1 refers to all items, except items Q6 and Q9, which are summarized in tables 2 and 3. The majority of the full sample obtained positive results concerning the direction of the force acting on an iron ball placed close to a magnet, involving the distinction between trajectory and field line (Q1), the range of the magnetic field (Q2), and the magnetic dipole in a homogeneous field (Q8). The question related to the reciprocity of the interaction between magnet and iron coin (Q3), superposition (Q3) and the precession movement of a magnetic dipole in an external alternating field (Q10) were problematic for half of the sample, with lower performances for the STF students. Problematic contexts and not resolved knots for the majority of students (~70%) were when the magnetic field did not produce a force: a charge at rest close to a magnet (Q4), or an electric wire parallel to the field lines (Q7). The last situation was proposed also in the final examination, as explained before. It obtained little better results (35% of students gave the correct answer), remaining for the majority a problematic knot.

Table 1. Percentage of answers concerning questions Q1-Q6, Q7-Q8, Q10. In grey the frequencies corresponding to the attended answers (dark grey – frequencies lower than 40 %; NA=no answer)

Option	Q1				Q2				Q3.1				Q3.2				Q4				Q5				Q7				Q8				Q10			
	AOS	STF	TOT		AOS	STF	TOT		Option	AOS	STF	TOT	Option	AOS	STF	TOT	Option	AOS	STF	TOT	Option	AOS	STF	TOT	Option	AOS	STF	TOT	Option	AOS	STF	TOT				
F1	5	3			A	26	33	29	Y	97	76	90	Y	58	33	49	A	34	48	39	D1	3	5	3	A	24	19	22	A	68	62	66	A	39	43	41
F2	8	24	14		B	66	52	61	N	3	10	5	N	42	52	46	B	39	33	37	D2	53	33	46	B	58	48	54	B	24	33	27	B	42	19	34
F3	66	67	66		C	8	14	10								C	26	19	24	D3	3	14	7	C	18	33	24	C	8	5	7	C	18	38	25	
F4	13	10	12																	D4	42	43	42													
F5	8	5									14	5			14	5																				
NA																																				
	100	100	100		100	100	100		100	100	100		100	100	100		100	100	100		100	100	100		100	100	100		100	100	100		100	100	100	

Table 2. Item Q6, testing strong or weak interaction when approaching a magnet to different objects. Frequency for the full sample (any significant difference between the two groups). In grey, the expected answers.

	Cu wire	Wood piece	Scissor	Pen	Plastiline piece	Aluminum cube	Paper sheet	Magnet	20 eurocent coin	Hair	Paper clip
Yes	69	3	85	24	10	58	5	86	73	8	86
No	27	95	12	69	83	37	85	10	20	80	10
Only in particular situation	3		2	7	5	3	10	3	5	10	3
No Answer		2	2		2	2			2	2	

Table 3. Magnetization vector for para/dia/ferro magnetic and superconductor material. The external field direction is from the right to the left. Frequencies related to the full sample.





				
Diamagnetic	25	29	14	10
Paramagnetic	36	24	9	15
Ferromagnetic	14	15	36	15
Superconductors	5	14	20	41
No Answer	20	19	22	19
Total	100	100	100	100

Table 2 shows the results for item Q6 concerning which object strongly interacts with a magnet (ferromagnetic) and which do not interact (para or diamagnetic). As expected, the difficulty raised to the students was to identify para/dia magnetic metallic objects: Cu wire, Al cube, 20 eurocent coin.

Concerning item Q9 that referred the magnetization of a cylinder inserted in a uniform magnetic field, the main difficulties concerned the distinction between paramagnetic and ferromagnetic materials (see table 3).

The analysis of the web-questionnaire shows a learning process under construction, where some problematic knots remained. The next session gives a more completed image of the student competencies achieved at the end of the instructional pathway (course), analyzing the discussions about the role of the fundamental concept of magnetism in the contexts of natural, bio, agro-food sciences.

5. Data analysis of the open question in the final written examination of the course

This section synthesizes the analysis of the on-line questionnaire, completed by 118 students (see Table 1). Discussing the role of magnetism in the context of natural, bio, agro-food sciences, the 188 respondents suggested more than one hundred different topics covering the four scales synthesized in figure 3: atomic-nuclear; cellular; human/animal; astronomical/planetary. A first interesting outcome is the fact that a large majority of students identified contexts involving two of these four levels. They described these contexts using adequate physics concepts, but often adopting different conceptual references for different scale sizes. That means that students considered these as different phenomenologies, requiring different physics concepts, and for that evidencing difficulties in analyzing a phenomenon involving different scale sizes (e.g. the earth magnetic field affecting cellular/atomic processes).

Table 4 summarizes the most frequently cited topics. The most quoted topics were those suggested in the papers on magnetism affecting growing plants [2,6] and the perception of magnetic field by living things [7] the discussions proving the students' competencies in using magnetization and field concepts and their great interest for discussing physics concepts in these contexts. Students showed awareness in discussing physics concepts also in the following topics: earth magnetic field (8), bacteria, magnetosome, cryptochrome and magnetic sensing (15); compass and human orientation (51), terrestrial and magnetic maps (25), magnetic separation and food preparation (38), electricity production (8).

Some needs emerged from the collection of aspects indicated by students. Students tend to generalize a results related to a specific species of animals. For instance, students indicated just one mechanism of magnetic field detection that they generalized to all animals. They need to know there are three main ways to perceive magnetic field by living systems (magnetic nanoparticle acting as small compass, electromagnetic field induction, and chemical reaction influenced by magnetic field).

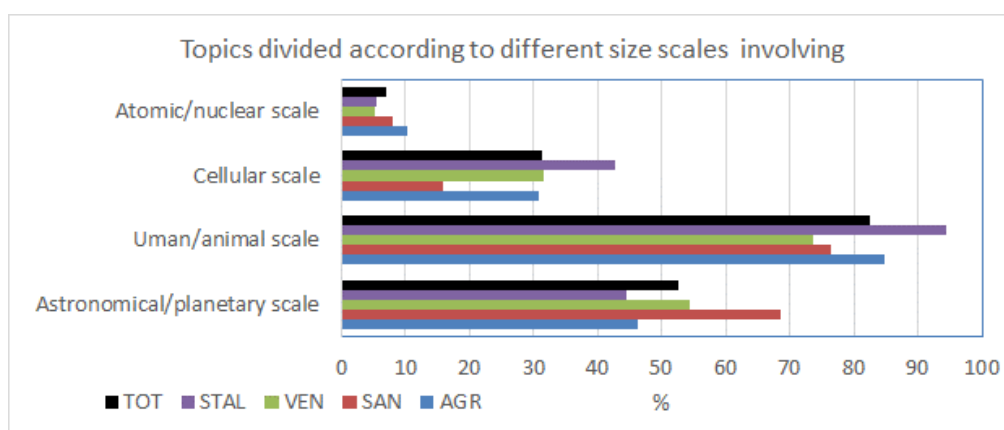


Figure 3. Frequencies of the topics cited by students, divided in four scale sizes.

Students showed little insight into the strength of the magnetic effects (in particular of the earth magnetic field). They need to be aware of the different strengths involved and that often the effects of magnetism are quite indirect. In many cases students did not distinguish phenomena due to electric fields from those produced by magnetic fields. The well-known tendency to identify magnetic and electrostatic

phenomena are also common in the case of bio phenomena find. In fact, magnetic and electrostatic phenomena are more often involved at the same time in living things (e.g., sharks perceive the magnetic field through electric field sensors based on electromagnetic induction). In the bio area many effect due to the Van der Waals forces could be confused with magnetic effect, without a microscopic model. This shows the importance to activate in the interactive pathway of learning connections between disciplines and do not leaving students alone in this connection.

Table 4. Main subjects quoted by students discussing the role of magnetism in the bio area

	Topic: Living Orientation in magnetic field (%)								Other Topics (%)	
	All livings	Migration	Bird	Bacteria	Fish Shellfish	Cetaceans	Terrestrial mammals	Insect	Growing plants	NMR
AGR	56	10	31	3	26	0	0	0	23	5
SAN	37	26	18	5	11	5	3	3	21	3
VEN	33	12	9	16	12	5	2	0	7	14
STF	44	20	22	31	2	2	0	2	22	19
Total	42	15	19	15	12	3	1	1	18	11

6. Conclusion

Teaching/learning a general physics course for Bio area degrees requires redesigning the approaches, changing the way of teaching by contextualizing content and problems relevant for students. A transdisciplinary approach seems useful: students became motivated, recognized physics as useful knowledge for their own area of study, learned how to apply physics to understand bio systems and analysis techniques in their field. The content knowledge can be addressed in a multidisciplinary context with examples from the Bio area with huge impact on learning outcomes. The specific context of magnetic phenomena in living things is particularly interesting for this goal. An educational pathway was designed to introduce the basic concepts of magnetism such as magnetic field, magnetic moment and magnetization for students of Bio area. A preliminary study was carried out with students of the degrees in Agronomy, Oenology, Science of Environments and Science and Technology of Food at University of Udine. From the analysis of a pre-test it emerged that initially students usually represented the magnetism as attraction, acting at limited range and have the idea that all metallic objects interact with a magnet.

The analysis of the web questionnaire, offered as self-evaluation instrument, highlighted competencies on: distinction between trajectory and field line, range of the magnetic field, behavior of a magnetic dipole in a homogenous field. Problematic areas remained, such as situations in which magnetic fields do not produce force on charged bodies (RQ3). Asked to contextualize magnetic phenomena in their area of interest, they identified in the final examination about 200 examples at four scale sizes: atomic/subatomic, cellular, human/animal; planetary/astronomical (RQ1). The majority of the students, discussing these examples, showed adequate competencies in using the physical concepts introduced in the educational path, but at the same time, the different scales invoked different phenomenologies in the perspectives of students. This is connected to another problematic issue that emerged in our study related to the fact that applied physics to natural and bio systems implies that different processes and phenomena intervene and cannot be separated as is usually done in physics. The students' tendency is to consider all the physical effects together as usual in the Bio area, without identifying each processes and the related affects (RQ2). To achieve this, the introduction of magnetic phenomena for students of the Bio area requires considering these different scales, discussing paradigmatic examples familiar for students showing that the same physics explains all the apparently

different situations involved. In particular, the human size scale was the most important for students of our sample (RQ4).

The results of the pilot study indicate for students of Bio areas as necessary (but not sufficient) the following competencies: A) knowledge of physical phenomena and where they can be observed, and which laws/principles govern these phenomena (for instance distinguish electrical and magnetic phenomena); B) recognize the different sources of electric and magnetic field; C) internalize and distinguish it in real situations as electrostatic processes in capillarity in plants or application of crop protection products and electromagnetic induction in the capability to perceive also magnetic of animals like sharks having only electric field detectors); D) a functional understanding of basic physics concepts (a qualitative but correct use of a concept in other contexts); E) an operative ownership of basic physics model to describe in a quantitative or semi-quantitative ways processes encountered in everyday life or natural phenomena. (RQ4).

References

- [1] Redish E F, Bauer C, Carleton K L, Cooke T J, Cooper M M, Crouch C H, Dreyfus B W, Geller B, Giannini J, Svoboda Gouvea J, Klymkowsky M W, Losert W, Moore K, Presson J, Sawtelle V, Thompson K V, Turpen C, Zia R K P 2014 NEXUS/Physics: An interdisciplinary repurposing of physics for biologists *Am. J. Phys.* **82**(5) 368–77. DOI: 10.1119/1.4870386
- [2] Doglioni C, Pignatti J and Coleman M 2016 Why did life develop on the surface of the Earth in the Cambrian? *Geoscience Frontiers* **7** (6) 865–73. DOI: 10.1016/j.gsf.2016.02.001
- [3] Holland R A, Kirschvink J L, Doak T G and Wikelski M 2008 Bats use magnetite to detect the earth's magnetic field *PLoS ONE* **3**(2) e1676. DOI: 10.1371/journal.pone.0001676
- [4] Lohmann K J and Johnsen S 2000 The neurobiology of magnetoreception in vertebrate animals. *Trends Neurosci.* **23**(4) 153–9. DOI: 10.1016/S0166-2236(99)01542-8
- [5] Wiltschko W and Wiltschko R 2005 Magnetic orientation and magnetoreception in birds and other animals *J. Comp. Physiol. A Neuroethol. Sens. Neural Behav. Physiol.* **191**(8) 675–93. DOI: 10.1007/s00359-005-0627-7
- [6] Maffei M E 2014 Magnetic field effects on plant growth, development, and evolution *Front. Plant Sci.* **5** 445. DOI: 10.3389/fpls.2014.00445
- [7] Marion D 2013 An introduction to biological NMR spectroscopy *Mol. Cell. Proteomics* **12**(11) 3006–25. DOI: 10.1074/mcp.O113.030239
- [8] Duit R, Gropengießer H, Kattmann U 2005 Toward science education research: The MER *Developing Standard in RSE*. In: Fisher H E (Ed) (London: Taylor) 1–9
- [9] Borges A T and Gilbert J K 1998 Mental models of electricity *Int. J. Sci. Educ.* **20**(3) 361–78
- [10] Guisasola J, Almudí J M and Zubimendi J L 2004 Difficulties in learning the introductory magnetic field theory in the first years of university *Sci. Educ.* **88**(3) 443–64. DOI: 10.1002/sce.10119
- [11] Maloney D P, O'Kuma T L, Hieggelke C J and Van Heuvelen A 2001 Surveying students' conceptual knowledge of electricity and magnetism *Am. J. Phys.* **69**(7) 12–23. DOI: 10.1119/1.1371296
- [12] Heron P R L, Shaffer P S and McDermott L C 2004 Research as a Guide to Improving Student Learning. In *Invention and Impact* (Washington: AAAS) 33–8
- [13] Laws P W 2004 Promoting the Diffusion of Undergraduate Science Curriculum Reform. In *Invention and Impact* (Washington: AAAS) 247–52
- [14] AAAS-American Academy for the Advancement of Science (2011). *Vision and Change in Undergraduate Biology Education* (Washington, DC: AAAS)
- [15] Brewé E, Pelaez N J and Cooke T J 2013 From vision to change: Educational initiatives and research at the intersection of physics and biology *Cell Biol. Educ.* **12** 117–9. DOI: 10.1187/cbe.13-03-0069
- [16] Donovan D A, Atkins L J, Salter L Y, Gallagher D J, Kratz R F, Rousseau J V and Nelson G D 2013 Advantages and challenges of using physics curricula as a model for reforming an

- undergraduate biology course *Cell Biol. Educ.* **12** 215–29. DOI: 10.1187/cbe.12-08-0134
- [17] Redish E F and Hammer D 2009 Reinventing College Physics for Biologists: Explicating an Epistemological Curriculum *Am. J. Phys.* **77** 629–42. DOI: 10.1119/1.3119150
- [18] Manthey S and Brewe E 2013 Toward University Modeling Instruction—Biology: Adapting Curricular Frameworks from Physics to Biology *Cell Biol. Educ.* **12** 206–14. DOI: 10.1187/cbe.12-08-0136
- [19] Thompson K V, Chmielewski J, Gaines M S, Hrycyna C A and LaCourse W R 2013 Competency-Based Reforms of the Undergraduate Biology Curriculum: Integrating the Physical and Biological Sciences *Cell Biol. Educ.* **12** 162–9. DOI: 10.1187/cbe.12-09-0143
- [20] McDermott L C, Heron P R L, Shaffer P S & Stetzer M R 2006 Improving the preparation of K-12 teachers through physics education *Am. J. Phys.* **74**(9) 763–7. DOI: 10.1119/1.2209244
- [21] Hoskinson A-M, Caballero M D & Knight J K 2013 How can we improve problem solving in biology? Lessons from 30 years of physics education research *Cell Biol. Educ.* **12** 162–9. DOI: 10.1187/cbe.12-09-0149
- [22] Meredith D C and Redish E F 2013 Reinventing physics for life science majors *Physics Today* **66** (7) 38–43. DOI: 10.1063/PT.3.2046
- [23] Svoboda Gouvea J, Sawtelle V, Geller B D and Turpen C 2013 A Framework for Analyzing Interdisciplinary Tasks: Implications for Student Learning and Curricular Design *Cell Biol. Educ.* **12** 187–206. DOI: 10.1187/cbe.12-08-0135
- [24] Ding L, Reay N W, Lee A and Bao L 2008 Effects of testing conditions on conceptual survey results *Phys. Rev. ST—Phys. Educ. Res.* **4** 10112. DOI: 10.1103/PhysRevSTPER.4.010112
- [25] Li J and Singh C 2017 Developing and validating a conceptual survey to assess introductory physics students’ understanding of magnetism *Eur. J. Phys.* **38** 025702. DOI: 10.1088/1361-6404/38/2/025702
- [26] Wu L-Q and Dickman J D 2012 Neural Correlates of a Magnetic Sense *Science* **336**(6084) 1054–7. DOI: 10.1126/science.1216567
- [27] Van Hook S J and Huziak-Clark T L 2007 Tip-to-tail: Developing a conceptual model of magnetism with kindergartners using inquiry-based instruction *J. Elem. Sci. Educ.* **19**(2) 45–58. DOI: 10.1007/BF03173662