Developing scientific competencies: a collaboration between High School teachers and Physics researchers to create experiment-based learning activities

Filippo PALLOTTA¹, Alberto PAROLA¹, Maria BONDANI²

¹DiSAT  Department of Science and High Technology, University of Insubria, Como, Italy
²CNR – Institute for Photonics and Nanotechnologies, Como, Italy

Abstract. The last EU recommendations on key competences for lifelong learning encourage educational institutions to strengthen the collaboration between Physics researchers and Secondary School teachers to implement competence-oriented education, training and learning. Our group has carried out a collaboration project with a group of high school physics teachers engaged in a PLS (Progetto Lauree Scientifiche) professional development course promoted by the Department of Science and High Technology (DiSAT – Dipartimento Scienze e Alta Tecnologia) of Insubria University in Como, Italy. The aim of the course was to enable teachers to create balanced and effective learning activities to be used in class to reinforce the scientific competencies and skills required in the Final Exam of the Italian Secondary School (Esame di Stato) and in the entire physics curriculum. This paper presents the result of this collaboration to understand how to better support the collaboration between Physics researchers and High School teachers in order to design teaching and learning materials that can be effectively integrated in the daily classroom activities, focusing the attention on problem solving and data interpretation skills, as requested by the last education reform for Italian Secondary School Final Exam.

1. Introduction
The PLS (Progetto Lauree Scientifiche - Scientific Degrees Project) promotes teachers training programmes for the educational staff in Como and Verese school district: faculty members and physics researchers in different fields of theoretical and experimental physics have been actively involved in the professional development programme. One of the aims of the PLS project is to support teachers in improving the way physics is taught in Secondary School. The last education reform in Italy, in accordance with the recent European Council Recommendation on Key Competences for Lifelong Learning Goals [1], is promoting new curriculum design practices that should help teachers change their role in student’s learning process: from operating as mere reviewers of knowledge acquisition to becoming facilitators of scientific competencies development processes.

This change of perspective has raised many concerns among teachers, mostly related to the gap between how the Physics curriculum is developed in classroom and the framework of the Final Exam Paper (Seconda Prova dell’Esame di Stato per il Liceo Scientifico). The “exam simulation papers” published in the last three years focused the attention on scientific competencies and skills such as hypothesizing,
interpretation of experimental data and making conclusions more than on content knowledge. In addition to that, in 2018 a new school legislation introduced the possibility of having an exam paper with problems integrating Mathematics and Physics topics. To support teachers in this transition between knowledge oriented and competencies oriented educational practices, at the beginning of 2018/19 school year the PLS project at DiSAT promoted a collaboration with a group of about 40 Mathematics and Physics teachers of the Como school district in order to support them in defining appropriate teaching activities to prepare students for the Final Exam Paper.

This PLS project focused its attention to the scientific competencies related to the analysis and interpretation of experimental data. The purpose of this paper is to present the results of this collaborative project and to give suggestions on how to help teachers fostering scientific competencies in classroom learning activities.

2. Teacher training project

Long terms experiences and recent researches in Physics education in Italy show how high school teachers can be productively engaged in renewing instructional methods if they feel the need of enlarging their own view and understanding of the topic [2]. An analysis of the past collaboration between DiSAT and local schools also shows that teachers has not used the teaching materials they received during professional development workshops at University and so past collaborations have not resulted in the implementation of new teaching strategies. Another relevant element that has been pointed out by physics researchers at DiSAT, during internal evaluation meetings about their long experience in teacher training in the Como area, is that teachers are often simply delegating researchers the role of explaining complex topics or running experimental activities in extra-curricular workshops. On the other hand teachers are often concerned about a feasible educational transposition at schools of what they learn in the training courses especially regarding the intrinsic difficulty of the topic, generally labeled as “too difficult for the students”, or the lack of time and resources to perform the presented laboratory activities. The PLS project intends to create opportunities to promote the collaboration between physics researchers and high school teachers to design together good quality classroom activities that could be easily introduced in physics lesson plans and seen as a part of daily teaching activity. From this perspective the training courses promoted by physics researchers have an active-learning didactic approach [3] with the goal of improving conceptual understanding and promoting a meta-reflection about the role of problem solving skills. In order to renew instructional methods, the training course also includes “hands-on/minds-on” workshops: in this way teachers can immediately have the perception of the didactic application of what they have experienced in the workshop.

2.1. Project actions

Between December 2018 and February 2019, we organized a series of 5 meetings for a group of 40 high school teachers. On average, 20 teachers attended each meeting. In the first three meetings physics researchers and teachers solved together the problems of the exam paper simulations that were published in December 2018. This activity allowed the participants to define which parts of the test were particularly challenging for the students, pointing out the main skills and competencies (problem solving, data analysis and interpretation) needed to tackle the problems. Teachers also shared their teaching experiences and materials they used to prepare last year students for the final exam paper. Following the teachers’ request, all the teaching resources produced in the meetings were shared among the participants and will be made available on an online platform. In this first three meetings, teachers had the opportunity to discuss and share their view about the problems solving skills needed to solve the exam questions. In the last two sessions, teachers took part in two different physics workshops performing two experiments using simple materials and smartphone sensors. The first activity was about the measurement of the magnetic field of a little magnet. The second activity was about the measurement of the duration of the collision of a ping pong ball with a table. Both experiments were selected because the topics are part of the physics curriculum (mechanics and electromagnetism) and give the possibility to easily gather real data that can be analysed with students.
3. Data analysis and interpretation in Exam Paper Problems

The first part of the teacher training was dedicated to the analysis of the three exam papers published by the Ministero dell’Istruzione dell’Università e della Ricerca (Italian Ministry of Public Education and Scientific Research) to help teachers understand the characteristics of the new exam format. The problems were relative to two specific topics of the high school final year Physics curriculum: Problem 1 was about electromagnetism and Problem 2 was about special relativity. The exam papers are available online at LSOSA website [4]. Here we present the elements arisen from the analysis and discussion about the Physics exam paper.

In the discussion with teachers the reflection about the assessment criteria indicators attached to the exam paper (table 1) was relevant.

Table 1. Assessment Criteria for the Physics Exam Paper

| Criteria                           | Description                                                                 |
|------------------------------------|-----------------------------------------------------------------------------|
| Analyse                            | Examine the problem identifying the significant aspects of the phenomenon and formulating the explanatory hypotheses through models, analogies or laws. |
| Resolution process application     | Problem formalization and application of the concepts, mathematical methods and appropriate disciplinary problem solving strategies, performing the calculations needed. |
| Interpret, represent and elaborate data | Process the data, proposed or derived from experiments, checking the relevance to a chosen model. Represent and connect the data using the necessary graphic-symbolic codes. |
| Argue                              | Describe the resolution process adopted, the solution strategy and the fundamental steps. Communicate the achieved results evaluating the consistency with the problems and using disciplinary specific languages |

The criteria are not only related to the ability to solve the problem numerically, but also to the skills and competencies needed to analyse the problem, model and interpret the data. In particular the Question n.4 of Problem 1 was about the use of a data set (see figure 1). The students should be able to show that the Hall voltage $\Delta V_H$ is directly proportional to the magnetic field $B$ and to determine the value of the constant of proportionality $k$ with an estimation of its error.

Figure 1. Paper question about data analysis and interpretation. “Show that the data set could be fitted using a linear model for $\Delta V_H$ as a function of $B$”.

This question is mainly related to the third assessment criteria (data interpretation) and raised the concerns of the teachers because in their opinion it had a very weak connection with the skills students acquire during their high school physics programme and that kind of task is not commonly part of Physics worksheets in textbooks. As reported by the teachers, this is because experimental activities that
involve data analysis and interpretation are not part of the usual curricular activities. Although the laboratory activities are a useful tool for the development of scientific competences, such as problem solving skills [5], the teachers reported the lack of materials and resources in school to adequately incorporate performing experiments into planning. In addition to that, most of the teachers admitted that they had never been properly trained to run experiments and do not feel competent enough to perform experiments with students. As a result, the basic techniques of data analysis, such as the linear regression, are not fully covered during the instruction programme.

3.1. Discussion about the quality of a fit
During the meeting, the discussion between teachers and researchers was focused on how to fulfil the assessment criteria related to that question and consequently how to support students in the process of acquiring the specific skills related to data analysis and interpretation. To be able to answer the exam paper question (figure 1) it is important to reflect about the connection between experimental data and the theoretical model used to fit the data. This is worth doing in a didactical context to foster the reflection on how science researchers’ work contributes to the development of interpretative models of physical phenomena.

The data shown in the table do not fall exactly on a straight line, as required by the model. The physical causes can be various: imprecision in the measurements or effects induced by other phenomena we have not considered in the schematic model used. The data graph is shown in the figure 4 together with the best linear fit. The best fit has been evaluated using the least-squares method. Given a data set \( (B_i, \Delta V_i) \) and a theoretical relationship which connects them \( \Delta V = kB \), the quadratic error associated with the fit can be defined as the sum of the squares of the difference between the measured value \( \Delta V_i \) and the expected value \( k_B B_i \):

\[
\varepsilon(k) = \sum (\Delta V_i - kB_i)^2
\]

The value of \( k \) which minimizes this error \( \varepsilon(k) \) can be obtained by setting the derivative equal to zero, that leads to the following formula

\[
k = \frac{\sum \Delta V_i B_i}{\sum B_i^2}
\]

Figure 2. Graph using the data in the table
Inserting the data, the value \( k = 8.3 \times 10^{-7} \) V/T is obtained, which represents the slope of the straight line shown in the figure. This specific answer implies that the students need to know the least-squares method and so they need specific instruction about that. Nevertheless an estimation of the uncertainty about the value of the coefficient of proportionality \( k \) could be done by simply comparing the slope of two lines passing through the origin and the first and last point in the data set, respectively, so that all the remaining points lies in between those two lines. Even though the problem does not report the error on the measurements of the input data (\( B_i, \Delta V_i \)), the slope of these two lines (dashed in figure) could provide an underestimation and an overestimation of the value of \( k \).

The two values found are \( k = 7 \times 10^{-7} \) V/T and \( k = 8.6 \times 10^{-7} \) V/T. Using the average of the two values an estimate of the value of the constant \( k \) is given by the expression \( k = (7.8 \pm 0.8) \times 10^{-7} \) V/T. To calculate the uncertainty we used the “maximum error” formula that is often presented in the Italian Physics textbook as an estimate of the measurement error: \( \Delta x = (x_{\text{max}} - x_{\text{min}}) / 2 \).

Following the result of the discussion, the group of teachers took part in two workshops about low cost physics experiments that could be used to recreate the condition presented in the exam paper question: how is it possible to fit a set of data using a specific theoretical model?

4. Learning experiences

Two workshops were organized. In this paper we report the results of the workshop on the measure of the magnetic field [6] because of its connection with the result of the previous teachers work groups. This activity was also part of the LSOSA project [7], a database of experimental activities for Italian High Schools.

Teachers follow the same learning activity path designed for Secondary School students, but they are guided to reflect not only on the content but also on the difficulties that can arise in performing the activity in the class with the students. A specific attention has been paid to the data acquisition process using s smartphone app and to the data analysis techniques.

The aim of the learning activity is to support students’ reflection on the relation between the theoretical model of a physical phenomenon and the experiments related to it.

The goal of the activity is to determine the dependence on the distance of the \( x \) – component of the magnetic field produced by a small cylindrical magnet. The measurements are taken using the magnetic sensor of a smartphone and an app for the data acquisition: we used Phyxox [8] and Physics Toolbox [9]. The activity also requires a pencil, a sheet of paper and a ruler. The activity took two hours and involved about 15 teachers.

The activity structure is intended to mimic the sequence of an experimental scientific inquiry: starting from the elaboration of a theoretical model, moving to the preparation and calibration of experimental set-up and data collection and finally to data analysis and interpretation. In this way teachers can have a full experience of the experimental procedure and can more easily evaluate how it could be implemented in classroom activities

4.1. Theoretical model

Following teachers’ request of being properly introduced to the physics of the magnetic fields of small cylindrical magnets, the experimental activity has been preceded by a short lecture by a faculty member of DiSAT. This part of the activity made it possible to analyse in detail the theoretical model underneath the relation between the physics variables used to describe the phenomena. As reported by the teachers during the discussion, this introduction is considered a useful and essential tool to engage the student in the laboratory activity: in their experience, students seem to prefer to infer the interpretation of a single phenomenon from a general model instead of inductively building a scientific model from observations. Students are familiar with simple models of magnetic field generate by electric current (like solenoids) built using Ampere’s circuital law [9], [10]. The permanent magnet is schematized as a collection of circular loops crossed by a current of intensity \( I \) that can be identified with the superficial magnetization currents. This model activity could be used in classroom activities as an application of vector field model.
The field generated by a permanent magnet of cylindrical shape is calculated in $x$-direction that corresponds to the axis of symmetry of the magnet at distance much larger than its radius $a$ (but not necessarily larger than its length $l$). Under this condition the magnetic field in the $x$-direction is given by

$$B_x(x) = \frac{\mu_0 m}{2\pi} \frac{x}{x^2 - \frac{l^2}{4}}$$

(3)

where $m$ is the magnetic moment of the magnet and $\mu_0$ is the magnetic permeability of free space. If then $l \ll x$, the $x$-component of the magnetic field becomes

$$B_x(x) = \frac{\mu_0 m}{2\pi} \frac{1}{x^2}$$

(4)

Teachers were given a guided activity sheet to introduce the mathematical model of this specific magnetic field to the students. Teachers were asked to adapt that specific material and use it in classroom before presenting the experimental activity to the students. The modelling of the magnetic field gives also some elements about the type of magnets that could be used.

4.2. Become familiar with experimental devices
An important part of the experience was about learning how to properly use the data acquisition device. Teachers spent time to learn how to use the smartphone app, focusing the attention on how the device collects data. The first problem is to determine the position of the sensor inside the device. Secondly, the smartphone sensors need to be properly calibrated, taking into account that the measurements are strongly dependent on the device orientation and distance between the smartphone and the magnet. The possibility to verify the consistency of a theoretical model is bounded by the possibilities given by the characteristics of the experimental devices: this is something students need to understand to properly evaluate the results of their experimental activities.

Teachers reported that they could not collect data when the smartphone was too close (less than 5 cm) to the magnet, due to the sensor saturation (when $x < 5$ cm the value of $B$ did not change): that implies that the model could be verified only in a specific interval of distances from the device.

For the same reason the evaluation of the experimental uncertainty is part of the data acquisition process: every device, even digital ones, collect data with a specific uncertainty. This aspect was reported by the teachers during the practice. The value of the magnetic field measured by the smartphone fluctuates rapidly and this required an adjustment of the acquisition procedure: the values of the field for each measurement could be only obtained by averaging the values recorded in a specific period of time. In this way, an error corresponding to the uncertainty of the mean was associated with each value of $B_x$.

4.3. Data elaboration
The discussion generated around the problem of data elaboration was about how to fit the function that corresponds to the theoretical model (equation (4)). The spreadsheet used in schools (i.e. MS Excel, LibreOfficeCalc, GSpreadSheet) give the opportunity to fit power functions, but some teachers noticed that it would be useful to have the possibility to fit the data using a function using multiple parameters like the following

$$B(x) = \frac{k}{x^b} \quad \text{or} \quad B(x) = \frac{k}{x^b} + c$$

(5)

where the parameter could be related to specific physics constant ($k$) or instrumental offset error ($c$). As suggested by some teachers during the group discussion, a possible way to tackle this problem is to use a “logarithmic version” of the first function in equation (5): in this way the fit function becomes linear and data could be analysed using familiar the least-squares method.
\[ \ln(B) = \ln(k) - b \cdot \ln(x) \]  

In this case the gradient of the line represents the specific power dependence of the field intensity on distance. As suggested by physics researchers who participated in the meetings, a parametric function fit could be easily done using Matlab or Mathematica. Unfortunately the licences for those software are out of the public school budget. A more affordable alternative could be the use of Python and its data analysis libraries like NumPy and SciPy or the Python module Pandas. As suggested by teachers, the Python programming language could be also an opportunity to interact with computer science teachers and ICT experts in school. In figure 3 there is an example of data elaboration made by the teachers with the data collected during the laboratory activities.

\[ f(x) = -3.20742305320869 x + 4.1112168717606 
R^2 = 0.985215021789033 \]

Figure 3. Graph from the data using \(\ln(B)\) vs \(\ln(x)\)

4.4 Teaching – learning sequence

The modeling (part 1) and laboratory activities (part 2) are the two core activities of a teaching – learning sequence (TLS) that can be proposed to students. Starting from the process of creating a theoretical model that explain the relationship between two physical variables (magnetic field and distance), students can then test it as part of an experiment they can built from scratch. This could help students experiment one application of a scientific method of inquiry. The teachers suggested that part 1 could be used as a guided mathematical exploration about the relationship between Mathematics and Physics. To build the magnetic field model students should indeed be able to apply different knowledge and skills (e.g. use of vectors, derivatives) that are part of their mathematics curriculum. On the other hand the laboratory activity (part 2) is an opportunity for students to design an experiment and reflect on different aspects of experimental process, such as data acquisition procedures and error sources evaluation.

5. Conclusion

The collaboration between researchers and teachers is crucial to promote the development of science competencies. The activities presented in this paper have shown how school teachers are determined to improve the level of their teaching through collaboration. The meetings have been good opportunities to share teaching experiences and materials. Some teachers reported that have adapted the materials about the mathematical model of the magnetic field in a guided activity in classroom as an example of exam preparation exercise. They also underlined how pairing mathematical modeling and laboratory activities helped them to promote a better understanding of that specific topic among students. All the teachers agreed that high quality, scientifically-based learning activities need to be implemented into the curricular classroom activities and then become part of daily teachers’ practices in order to be effective: in this sense teachers need to be more committed to the design of their curricular instructional laboratory activities and processes. On the other hand physics researchers need to foster that design
process, promoting collaboration activities with teachers and helping the creation of an active educational ecosystem

6. References

[1] Bonjean D Council Recommendation on Key Competences for Lifelong Learning [Internet]. Education and Training - European Commission. 2018. Available from: https://ec.europa.eu/education/education-in-the-eu/council-recommendation-on-key-competences-for-lifelong-learning_en

[2] Besson U, Borghi L, De Ambrosis A, Mascheretti P 2010 Int. J. Sci. Educ. 32 1289.

[3] Fraser JM, Timan AL, Miller K, Dowd JE, Tucker L, Mazur E 2014 Rep. Prog. Phys. 77 032401.

[4] Available from: https://www.miur.gov.it/lsosa-lab

[5] Leite L, Dourado L 2013 Procedia – Soc. Behav. Sci. 106 1677.

[6] Arribas E, Escobar I, Suarez CP, Najera A, Beléndez A 2015 Eur. J. Phys. 36 065002.

[7] LS-OSA Project. Available from: https://ls-osa.uniroma3.it/pages/posts/1

[8] Phyphox. Available from: https://phyphox.org

[9] Vieyra Software. Available from: https://www.vieyrasoftware.net/

[10] Walker J.S. 2016 Fisica – Modelli teorici e problem solving (Onde Elettricità e Magnetismo vol 2) ed Linx Pearson (Milan) chapter 16 pp 330–332

[11] Amaldi U 2016 L’Amaldi per i licei scientifici.blu Seconda Edizione (Onde, campo elettrico e magnetico, vol 2) ed Zanichelli (Bologna) chapter 25 pp 940–942