The teaching of elementary Nature of Science

1. Title

The teaching of elementary Nature of Science. The case of the Millikan oil drop experiment

2. Key words

Nature of science, history of science, scientific controversies, Millikan, Ehrenhaft, oil drop, fundamental electric charge, electron

3. Target population

Secondary school, students aged 15-16, Physics teachers.

4. Authors and Institutions

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5. Abstract

The specific case study deals with a lesson addressed to students aged 15-16 who are attending a Physics lesson within the framework of the traditional Physics curriculum. Used in this teaching is the history of sciences, and, more specifically, the controversy between Millikan and Ehrenhaft on the nature of the electric charge, with a view to an understanding by the students of elementary Nature of Science (NOS).

6. Description of case study

The purpose of the case study was that the basic ideas about the relation of the historical event of Millikan / Ehrenhaft controversy should be transformed by the bringing out of characteristics of NOS, in a didactical sequence of units which would make it possible for students aged 15-16 to approach basic characteristics of NoS in the context of a traditional Physics curriculum.

The basic guiding principles of a proposed didactical intervention are as follows:

- the explicit teaching of elementary NoS as a procedure incorporated into the framework of the scientific content. The features of NoS which it was judged possible to teach through the controversy between the two researchers were: (a) the provisional character of scientific knowledge, (b) the distinction between observation and conclusion, (c) the definitive role of empirical data in the shaping of concepts of the natural sciences, (d) the subjective character of natural sciences, and (e) the role of the imagination and the creativity of the scientist in the forming of a theory.
- the creation of short stories through which the specific controversy over the quantisation of the electric charge was presented. Four short stories were devised which had as their aim to highlight the specific scientific content and to help the students gain a better understanding of the characteristics of NOS which had been chosen to be taught.
- the adoption of a modified didactical model proposed by Monk & Osborn (1997) according to which the initial perceptions of the students of a subject are

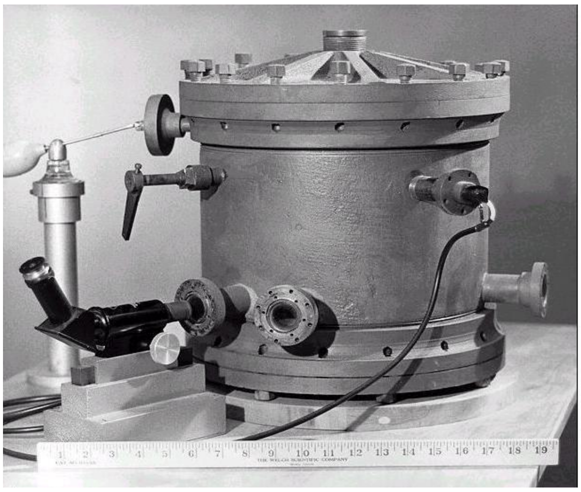
contrasted with the views which, historically, were formulated by scientists on it.

7. Historical and philosophical background including nature of science

The historical event which is used in the proposed didactical intervention is the Millikan-Ehrenhaft controversy over the existence of the elementary electric charge, often referred to as the 'battle of the electron'. The events took place around 1910 and led the two protagonists in diametrically opposed directions: one to success and a Nobel Prize, the other to failure and obscurity. These were the American Robert Millikan, at that time an unknown professor at a new university, the University of Chicago, a man of about 50, with few scientific publications to his credit, and the European Felix Ehrenhaft, a distinguished physicist and professor at a famous university, the University of Vienna; he was 11 years younger than Millikan.

Millikan believed in the hypothesis that there was a minimum electric charge, that of the electron. He put forward the atomic theory account of electricity: the approach, that is, that there was in nature an elementary electric charge of which all bodies consisted. Millikan worked in a research tradition which went back to the formulation of G. J. Stoney in 1881 about an atomic unit of electricity, which he later termed an 'electron'. J. J. Thomson made an important contribution to this tradition of research when, in 1897, he showed that cathode rays consisted of atomic units, which he called 'corpuscles', and then went on to determine the e/m ratio for these. Ehrenhaft, on the other hand, believed that there was no minimum charge, and that there were small particles whose charge was a fraction of the charge of the electron. He adopted the explanation of continuity for electricity. Ehrenhaft was influenced by the philosophical trend favouring the continuity of the structure of matter which flourished in continental Europe, and whose chief exponent was Mach. The supporters of this philosophical trend wished physics to be free of useless metaphysical hypotheses, such as those of atomic theory (Holton, 1978). More specifically, Mach rejected the existence of non-observable entities and maintained that science should concern itself only with entities which could be observed by empirical means (Matthews, 1994). Both scientists recognised that the object of their research, like the essence of their disagreement, touched upon the foundations of science.

Millikan, to begin with (1908), used the Wilson method, which was based on the study of a cloud of vapour droplets which moved under the influence of a gravity and electric field. Using this method, Millikan and his pupil Louis Begeman found a mean value for the elementary electric charge which was somewhat smaller than that expected, and with a wide range of values. This wide range could have led to the conclusion that the charge can take on any values, and that there are no integral multiples of the minimum electric charge. Millikan himself notes that: "Indeed the instability, distortion and indefiniteness of the top surface of the cloud were somewhat disappointing, and the results were not considered worth publishing." (Millikan, 1947, p. 55-57). This experimental result, instead of leading Millikan to the conclusion that his hypothesis as to the quantisation of the charge was mistaken, led him instead to the need to improve the experimental method he was using. After constant improvements to the experimental method, Millikan succeeded in calculating a value for the elementary electric charge very close to that expected, and in 1910 he embarked on the first important publication of his results. In this, Millikan explained the way in which he assessed his measurements. "The observations marked with a triple star are those which were marked 'best' in my notebook ... The double starred observations were marked in my notebook 'very good'. Those marked with single stars were marked 'good' and the others 'fair'." (Millikan, 1910. p.220). Also: " ... I have discarded three observations which I took on unbalanced drops." (in Holton, 1978, p.38)



The controversy started when in this article Millikan criticised the accuracy of the results which Ehrenhaft had published, in spite of the fact that the results and the method which he used resembled his own. Ehrenhaft answered Millikan's criticism in a subsequent article in which he calculated the charge of each droplet for each of Millikan's observations separately. The result was a very wide range of values for the droplet's charge, not all of them an integral multiple of the elementary one.

This result weakened the argument for the existence of the minimum electric charge. Ehrenhaft's view was that Millikan's conviction as to the existence of the elementary electric charge had led him to show a high level of error in the values. Millikan's view of the way in which Ehrenhaft handled the data was that it "Would force one to turn one's back on a basic fact of nature - the integral character of *e* [the charge of the electron]" (Holton, 1978, p. 69). The confrontation between the two sides was heated. Ehrenhaft wrote some 12 articles within four years, all of them aimed at disputing Millikan's measurements. Millikan through his own articles rebutted Ehrenhaft's arguments.

A new dimension was added to the Millikan-Ehrenhaft controversy when Holton discovered two of Millikan's laboratory notebooks in the archives of the California Institute of Technology. These notes (28 October 1911 to 16 April 1912, approximately 175 pages) provide a rare opportunity to see the work of a scientist in his laboratory. The notes had raw data, and from these some of the processes of selection of the data which were used in the article published in the Physical Review (Millikan, 1913) can be seen. On the other hand, Ehrenhaft's notes were lost in the Second World War, when he emigrated to the United States after the conquest of Austria by the Nazis. In Millikan's laboratory notes there were measurements for 140 droplets, whereas the published results in 1913 state emphatically that there were measurements for 58 droplets. What happened to the other 82? Millikan did not use the values of the electron charge which were contrary to his initial idea, and it seems that the reason that he did not take into account more than half the data was the guiding hypotheses which he held. As can be seen from the above, the historical event of the Millikan – Ehrenhaft controversy is capable of bringing to light different aspects of NoS, some of which were used as didactical aims in the specific case study.

8. Target group, curricular relevance and didactical benefit

This didactical sequence is addressed to students in the 2nd class of high school in the Greek educational system (aged 16-17) who are following a Physics course intended for students who have chosen literary studies as their future course. These students have not previously been taught elementary NOS incorporated into the scientific content before this didactical intervention. In the traditional curriculum it is simply stated that "the charge of the electron is the smallest quantity of negative electric charge to occur free in nature", while the students are called upon to solve some mathematical problems connected with the topic. The proposed teaching, on the one hand, reproduces the environment in which the specific scientific knowledge was generated, and, on the other, brings out features of NOS the absence of which creates in students a picture of science being objective, unchanging, a product of routine and of the application of specific rules or instructions. In this way, the objective is that the students should approach this specific piece of scientific knowledge in an interesting way, that they should acquire a positive attitude towards the natural sciences (particularly those students who will not follow a natural sciences course), and will also adopt a critical approach to the functioning of the natural sciences. Alternatively, the proposed teaching can be used in the in-service training of those teaching natural sciences at various levels of education, with the same objectives.

9. Activities, methods and media for learning

The structure and content of the teaching

The proposed didactical intervention (see **table**) consists of five teaching units. In the first of these, the historical and cultural background against which the issue of the quantisation or otherwise of the electric charge arose was explained to the students. For this purpose, a text entitled 'Historical Framework' was given to the students. An account was also given of the two guiding hypotheses of quantisation and the continuity of the electric charge formulated by Millikan and Ehrenhaft, respectively. In the second didactical unit, after the historic oil drop experiment carried out by Millikan had been explained to the students, they were given a worksheet with hypothetical data of the experiment and asked to answer questions intended to involve them in a discussion of the differing interpretations which can be given to the same data, and, consequently, of the role played by subjectivity, imagination, and creativity in the process of building up scientific knowledge. They are also given here the opportunity of noting that the data of themselves do not tell the scientist what he should think, but, on the contrary, he has to develop ideas on the interpretation of the data. In this way, the role of imagination and creativity in scientific knowledge is brought out.

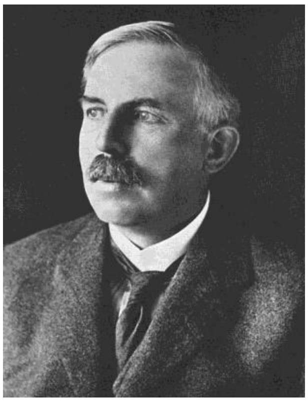
In the third, fourth, and fifth didactical unit, short stories concerning the

Millikan - Ehrenhaft controversy are introduced, each of which is accompanied by questions which focus the attention of the students on a different characteristic of NOS.

Table: *Didactical procedure model*
See at end

1. Historical Framework
In the late 19th and early 20th century…
The landscape in physics
Mechanics was fully developed. The battery was about a hundred years old. The uniting of electricity and magnetism had been achieved with the help of Faraday's experiments. The nature of light had been attributed to electro-magnetic waves, which were used for the reproduction of all the phenomena of Optics (reflection, refraction, etc.).
The theory of the behaviour of gases had reached its culmination.

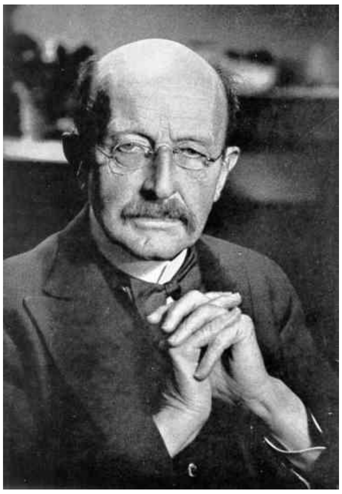
The concept of the atom had not been fully accepted. Plenty of scientists even in 1905 rejected the particle theory of matter. Some may have recognised it as useful for the explanation of certain phenomena, but they considered it far removed from reality.
Although chemists knew about atoms 100 years previously, and physicists, through the behaviour of gases, had also made extensive use of atomic hypotheses, **nothing was known about atomic composition and structure.**
Around 1895 and two or three years later, Physics took a decisive turn: certain experimental discoveries opened up the way to microscopic investigation of the atomic world. Progress made in the creation of a vacuum helped significantly in this direction.



At that period, we have the discovery of X rays by the German Röntgen and of radio-activity by the Frenchman Becquerel and the Curies. J. J. Thomson, Director of the Cavendish Laboratory at Cambridge, confirmed that cathode rays are microscopic particles in nature. The British Rutherford, together with Geiger (1908), after experimenting, arrived at the conclusion that the alpha radiation emitted by radio-active uranium is helium nuclei, and calculated Avogadro's number, the charge of the electron, and other constants which had already been measured by entirely different experiments, e.g., black body radiation (Planck). These experiments convinced even the most dubious (Mach, Ostwald) of the existence of atoms.

In 1911, Bohr introduced his own atomic model.

In 1905, Einstein completed his special theory of relativity, from which the famous equation E=mc2 stems. The same year, he published two further papers - a study of Brownian motion in which he forecast the existence of microscopic particles which must move at random in suspensions accessible to the microscope, and an explanation of the photo-electric phenomenon.



In the Western world, where the knowledge of atomic structure began to develop in the world of science, a foremost position was occupied by Britain, France, and Germany. At that period and up to 1930, in the field of physics America was represented more by experimental scientists than by theoreticians. One such experimental physicist was Michelson; he and Morley were the first American scientists to win Nobel Prizes (1907). In general, in the 19th and early 20th century, American scientists came to Europe, and particularly to Germany, to engage in their research activities.

In the early 20th century, the question of the existence of the elementary electric charge and the nature of electricity was of the greatest concern to the scientific community of physicists.

Some scientists maintained that there is one elementary unit of electric charge and that the charge cannot take on any value, and others that the electric charge,however small, can take on any value.The first hypothesis, that electricity is of a particle nature, had been put forward by the great American physicist Benjamin Franklin in 1750: "*The electrical matter consists of particles extremely subtle, since it can permeate common matter, even the densest, with such freedom and ease as not to receive any appreciable resistance.*

The socio-cultural landscape

The new physics emerged at a time when a new, radical way of thinking predominated, not only in the world of science, but in many other areas also. These were years of social and intellectual upheaval. In literature we have an exaltation of individualism, in art an uprising against academicism. Movements within society were organised everywhere, while anarchism reached its culmination in violence, in the assassination of members of royal families. In the late 19th century, there was ever-increasing competition between the countries of Europe at an economic level, in territorial claims, and in colonisation.

Vienna at that period was a cultural and scientific centre.

Germany was rapidly becoming more powerful, and under the rule of the military, the country had entered upon an imperialistic phase. Kaiser Wilhelm II led Germany into the First World War (1914-1918).

At that time, there were no aeroplanes, no telephones, and the use of electricity was very limited. Nor were there motor cars, and travel and transport were by carriages and carts.

In general, the late 19th century was a time of optimism and faith in science.

2. The short stories

The aim of the first story is to draw attention to the fact that Science seeks, produces, and is based upon empirical data. Thus this story deals with all the attempts to measure the elementary unit of the electric charge, from Townsend (1897) to the first results of Millikan's measurements in 1910. In this story it emerges that the main aim of all these efforts was as much accuracy as possible in the measurement, and that in 1908 the most appropriate value for the unit of the electric charge was regarded as that which Rutherford had calculated by a method entirely different from that of Millikan and the others. Using Rutherford's own words, we bring out the fact that the agreement of the results of the experimental measurements from two completely different fields of physics contributes to the firm establishment of the theory of the existence of the elementary electric charge.

The second short story has as its aim to highlight the distinction between 'observation' and 'conclusion'. This story includes an extract from Millikan's autobiography in which those items which are a product of observation during the experimental process are distinguished from those which are a product of the thought and conclusion of the scientist.

The purpose of the third story is to bring out the subjective character of scientific knowledge. More specifically, it deals with the differing interpretation given by Millikan and Ehrenhaft to similar experimental data which they had collected.

The fourth short story has as its objective to draw attention to the fact that although scientific knowledge is of a subjective nature when it is produced, in the end it is the scientific community which will accept or reject any scientific viewpoint. In this story, it is explained that the controversy between Millikan and Ehrenhaft on the quantisation of the electric charge evolved in an environment which was dominated by the controversy over the quantisation of matter, which, as can be seen from Rutherford's own words, tended to accept the theory of the atomic nature of matter and of electricity.

3. The worksheets

3.1

Worksheet 1

Measurement of the elementary electric charge - Millikan's oil drop experiment

Suppose that the following measurements for the value of the electric charge have resulted from the Millikan oil drop experiment:

TABLE OF MEASUREMENTS

1st measurement	2nd measurement	3rd measurement	4th measurement	5th measurement	6th measurement	7th measurement	8th measurement	9th measurement	10th measurement	11th measurement	12th measurement
4	8.1	12.1	15.9	1.9	24	44	1.2	5.6	36	27.9	39.9

1.

a. Suppose that you accept Millikan's guiding hypothesis: that there is a minimum quantity of electric charge and all the others are integral multiples of this. How would you interpret these measurements?

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b. In the light of this guiding hypothesis, what would be the minimum electric charge?

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c. Within this framework, how would you interpret the three red measurements?

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2. Suppose that you accept the guiding hypothesis of Ehrenhaft: that there is no minimum electric charge, and that this can take on any value. How could you answer Millikan's arguments?

3.2

Worksheet 2

1st short story

In the late 19th century, many scientists believed in the existence of an elementary unit of the electric charge and had engaged in the experimental measurement of it.

J. J. Thomson in 1897 had confirmed that cathode rays consisted of atomic units, which he called 'corpuscles', and he had calculated the ratio of the charge to their mass (e/m). The next step should have been the calculation of the charge and of the mass separately.

After that, scientists such as Townsend (1897), and then J. J. Thomson (1898), together with his student Charles Wilson, worked on the measurement of the value of the elementary electric charge and published their results. When, in February 1910, Millikan published his first experimental results, Ehrenhaft's results had already been published in 1909.

At the same period (1908), the bibliography gave the most appropriate value for the elementary electric charge as e=4,657·10-10esu, which had been calculated by Rutherford and Geiger. Rutherford and Geiger determined the charge of α particles as equal to 9,3·10-10esu, and hypothesised that it was equal to double the charge of the electron. Thus the charge of the electron should have been e= 4,65·10-10esu. In an article which Rutherford wrote with Geiger he cites the

work of Thomson, Townsend, and Millikan, praises the work of Ehrenhaft on the measurement of the charge of the electron by a method different from his own, and argues that this is further evidence that "*electricity, like matter, has an atomic structure*".
On the value calculated by Ehrenhaft (1909), which is very close to that which he calculated himself with Geiger, he says that "*the most recent measurements by very different methods which are far more reliable than the older estimates of Thomson, Townsend, Wilson*», and concludes that it would not be logical "To *believe that such concordance (in the experimental values of* e ..., *based on different theories) would show itself if the atoms and their charges had no real existence*", hence doubts concerning the atomic theory of matter are "*quite erroneous*".

<u>Question</u>: *What does the above extract suggest about the role of empirical data in the defence of a hypothesis in the natural sciences?*

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3.3
<u>Worksheet 3</u>
2nd short story

Millikan writes in his autobiography that: "*Moving upward [in the electric field, against the gravitational pull] with the smallest speed it could take on, I could be certain that just one isolated electron was sitting on its back. The whole apparatus then represented a device for catching and essentially seeing an individual electron riding on a drop of oil.*"
Furthermore, when the movement of the drop which he was observing suddenly changed, he noted:
"*I had seen a balanced drop suddenly catch an ion*" from the air around.

<u>Question:</u> *Which of the above words of Millikan could be described as 'observation' and which as 'conclusion'?*

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3.4
<u>Worksheet 4</u>
3rd short story

The theoretical basis was completely clear to Millikan: "*Being quite certain that the problem of the value of the electric charge* (Franklin's *fundamental atom of electricity - apparently invariant and indivisible - the assumed unit building block of the electric universe) was of fundamental importance, I started into it.*"

Millikan began the experiments in 1908, and in 1910 published the first experimental results which were considered reliable.

The experimental data (the fractional charges of 1/3e, 2/3e, 1/10e, etc.) which did not support his view he did not hesitate:

a) to attribute to experimental errors, such as:

· The battery's tension had fallen

· There was an error in the chronometer

· The distance should have been kept more stable

b) not to take into account. It was over this fact in particular that he was criticised by Ehrenhaft, to whom he replied that it was not possible to take into account all the data because a great many imponderable factors entered into their method, and these led to experimental errors.

On the other hand, Ehrenhaft, in applying a method similar to that of Millikan, collected the same experimental data (charges which were integral multiples of an elementary charge and fractional charges of 1/3e, 2/3e, 1/10e, etc.), from which he drew the conclusion that an elementary electric charge on the level which Millikan had calculated did not exist, and that his results could not be attributed to errors in his experimental method. Ehrenhaft used the fractional charges in order to deny the existence of the elementary electric charge. He also noted that his experiments provided a critical examination of the hypothesis of the atomic nature of electricity, and that his way of working would be to rely directly on the data of his experiments themselves.

__Question__: *How could this disagreement between the scientists as to the interpretation of the experimental data be explained? What does it show about the way in which Science operates?*

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3.5

__Worksheet 5__

4th story

In the battle over the electron, a role was played by the competition between two conflicting theoretical frameworks (guiding hypotheses) for the explanation of the same experimental findings. The one guiding hypothesis was that the electric charge is quantised, that is to say, there is one unit of electric charge and all the other charges are integral multiples of this, and the other guiding hypothesis is that the charge is continuous, and so there is no elementary electric charge, and this charge can take on any value. At the same period, two guiding hypotheses about the structure of matter co-existed. One was the atomic theory, and the other the continuity of matter. Experiments carried out in other areas of physics (black body radiation, study of radio-activity, nature of light) militated in favour of the existence of discontinuity both in matter and in electricity.

Rutherford maintained that "*Progress in physics strengthened the credibility of*

the atomic theories of matter and of electricity" and added that "*The negation of the atomic theory has not and does not help us to make discoveries*". In the end, the scientific community adopted Millikan's view, and in 1923 awarded him the Nobel Prize, chiefly for the measurement of the elementary electric charge.
Question: *In the light of this extract, what could be the reasons why the scientific community adopted Millikan's view on the nature of the electric charge?*
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10. Obstacles to teaching and learning

Research into the teaching of the natural sciences has shown that students have simplistic views about NoS, regardless of the research efforts which have been made to improve their ideas about its characteristics. Abd-El-Khalick & Lederman have argued that the failure of the research efforts, which they described as 'unspoken', was due to the hypothesis that students could build up the elements of NOS in an automatic way, as a result of the study of scientific issues or their involvement in research activities. Instead of this, they have maintained that an understanding of NOS should be the dominant didactical aim and have recommended an explicit reference to the characteristics of NOS and emphasis on informing the students of those of its characteristics which are brought out through rethinking on research activities in which they are involved. The majority of students believe that the content of the natural sciences is not subject to changes, that it is objective, and emerges directly from experimental data. This particular didactical intervention serves to rebut these ideas by specific teaching, incorporated into the scientific content, of elementary NOS, centring upon the Millikan - Ehrenhaft controversy over the existence of the elementary charge of the electron.

11. Pedagogical skills

Research has shown that a knowledge of elementary NOS does not result automatically from teaching of scientific content. In this specific didactical intervention the teaching of elementary NOS is a central didactical aim, which is achieved by the introduction of short stories. The questions to be found at the end of these stories help the students to focus their attention on a particular feature of NoS, which is explicitly referred to. The students engage in discussion, exchange views, formulate arguments, and rethink the structure and function of Science. They also play roles and are called upon through these to defend their views. They acquire the understanding that Science is a human undertaking, and that scientific concepts are human constructs which are thus subject to changes. This makes it possible for them to investigate and assess scientific assertions. They develop critical thought in order to recognise the subjective values and the weak sides of the argumentation put forward on an issue of scientific controversy.

12.Further user professional development

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Table: *Didactical procedure model*

	1st teaching hour		**2nd teaching hour**	**3rd, 4th, and 5th teaching hours**
Teacher's actions	Poses the question: "is the electric charge quantised or not? Is there an elementary electric charge and how great is it?" Sketches the socio-cultural-scientific background against which the question was posed through a text given to the students.	Makes a historical presentation of the guiding hypotheses which were formulated.	Makes a presentation to the students of the Millikan apparatus. Presents the oil drop experiment with ppt and video, gives hypothetical data.	Introduces short stories, which end with a question focusing the students' attention on an specific feature of NoS.
Students' actions	The students are asked to give an account of and to think about typical events of the period (early 20th century) which occurred in other areas of human activity (painting, music, politics) apart from the natural sciences and to link this with what was happening in these.		Discuss the possible conclusions which can be drawn from the data. Completion of worksheet 1	Read the short stories and discuss them, and answer in writing the questions to be found at the end of each short story.
Expected cognitive results	The students are expected to understand the significance of the particular question and to correlate it with the other socio-scientific issues of the period.		They are expected to understand that the empirical data derived from an experiment are interpreted on the basis of the theoretical approaches of the researcher.	They are expected to understand the definitive role of empirical data in the shaping of a view (Worksheet 2), the distinction between conclusion and observation (Worksheet 3), the subjective nature of scientific knowledge (Worksheet 4), and the reduction of its subjective character by public discussion and the judgement of the members of the scientific community, respectively (Worksheet 5).