# THE APPROACH OF TEACHING AND LEARNING SCANNING ELECTRON MICROSCOPE IN HIGH SCHOOL USING VIRTUAL EXPERIMENTS[*]

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*Abstract*. The simulations and virtual experiments can be used as an alternative to the real experiment to encourage scientific discovery learning and inquiry-based learning. The study of the electron microscope, introduced in the 12th grade curriculum, can successfully be done through these methods since the laboratory equipment is not accessible. In this paper we present a method to approach Scanning Electron Microscope, by combining on-line instruction, which has also meant using an e-learning platform, simulations and virtual experiments, with face-to-face instruction. We consider that the deep approach of this topic is of a great importance as it can stimulate students' interest and motivation for studying Physics by establishing a connection between classroom and the real word.

Key words: Scanning Electron Microscope, simulations, virtual experiments, scientific discovery learning, inquiry-based learning.

## 1. INTRODUCTION

The fulminatory development of IT and communication has opened great possibilities for the teachers to integrate technology in the teaching-learning process in order to improve students' achievements [1]. More than that, the fast progress in science and technology requires establishing new objectives for the science classes. Students learn about complex physical phenomena and sophisticated gadgets through the Internet. In this context, the students need critical abilities and a better technique to evaluate the complex information they are dealing with. Therefore it becomes obligatory that the science courses be periodically adapted and focused on independent investigation and discovery learning. The new learning technologies, including the information and

communication one, together with the resources offered by the Internet allow the alignment of the courses to the evolution of science [2].

It is recommended an adequate integration of the technologies into the teaching-learning sciences – especially Physics – process, in order to favour an efficient teaching-learning process in which the computer plays an important role [3-4]. This integration reflected in the instruction plan and the use of technologies must follow these 5 principles: technology should be introduced in the context of science content, technology should address worthwhile science with appropriate pedagogy, technology instruction in science should take advantage of the unique features of technology, technology should make scientific views more accessible, technology instruction should develop students' understanding of the relationship between technology and science [5].

The second principle suggests the fact that the use of technologies should allow students to move from "to know" towards "to do". This approach is in accordance with the constructivist theory in which the student is seen as an active agent in the learning process. Furthermore, computer learning environments help to advance developments [6].

Osborne considers that the main forms of ICT, relevant in the teaching-learning sciences process are: tools for data capture, processing and interpretation; multimedia software for simulation of processes and carrying out 'virtual experiments'; information systems, internet, intranet; publishing and presentation tools; computer projection technology [7].

An important role in Physics is played by the simulations or virtual experiments. Experimenting is the distinctive feature of sciences, which fundaments knowledge and scientific understanding [8].

Related to the principle of constructivism, the real or virtual experiments match the type of learning promoted by these since they encourage the discovery learning or inquiry-based learning [9-12]. Virtual experiments or simulations can substitute a real experiment when the phenomena cannot be investigated or observed in reality, the laboratory equipment is complicated, expensive and inaccessible or there is a danger for the real laboratory environment [13]. In addition, the virtual experiments compared to the real ones have the advantage of having erased the space and time limits, offering the students a repeated and endless use [14–15].

The contents studied at Physics in the 12th grade do not allow conducting real experiments, mainly because the laboratory equipment is expensive and therefore inaccessible. Yet, the curriculum stipulates specific competences such as: experimental investigation inside the laboratory/virtual laboratory of the law of external photoelectric effect or the description of the electron microscope construction and function. When there is no laboratory equipment the only alternative to achieve these competences remains the virtual experimentation.

In this paper we present a method for teaching-learning the Scanning Electron Microscope, by using an e-learning platform, simulations, virtual experiments and multimedia tools for presenting information. We consider that this topic deserves special attention; it must and can be deeply studied due to several reasons. Firstly, through the comparison optical microscope – electron microscope, it gives the opportunity to resume the study of the optical microscope which is pretty superficially dealt with in the 9th grade. Secondly, the Physical processes that appear can be fathomed, overcoming the theoretical level by presenting their impact in practical applications: the movement of the charged particles in electric and magnetic fields, de Broglie hypothesis, cathodoluminescence, X-ray and the interaction of charged particles with atoms. Thirdly, the electron microscopy is recognized as having endless applications in many domains such as: nanotechnology, biology and medicine, thus offering the students the opportunity to make interdisciplinary connections.

## 2. TEACHING AND LEARNING SCANNING ELECTRON MICROSCOPE IN HIGH SCHOOL

### 2.1. THEORETICAL BACKGROUND

The popularity of SEM comes from its capacity to obtain tridimensional images of the surfaces of a wide range of materials. These images are used in a variety of mass-media, from the scientific magazines to popular magazines and movies. But one of the most surprising aspects of the scanning electron microscopy is the apparent easiness with which the SEM images of the tridimensional objects can be interpreted by any observer, even by children, who have no previous knowledge about SEM or the electron-solid interaction [16].

Scanning Electron Microscopy (SEM) is a special technique which allows observing and characterizing the solid inorganic or organic materials at the micro and nano scale, offering information on their surface topography, composition, crystallography etc. [16]. In order to interpret the obtained images it is absolutely necessary that the possible interactions between electrons and the atoms be understood.

When interacting with the solid, the electrons are affected both by elastic scattering, due to the electrostatic interaction with the atomic nuclei, and also by inelastic scattering, due to the interaction with the atomic electrons.

Elastic scattering is an interaction process which results in the fact that the direction of the basic electrons change without any obvious energy loss. Since the electron beam leaves the sample (process called "backscattering"), the elastic scattering can give important information for the SEM image. As the ratio between the number of backscattered electrons (BSE) and the number of basic electrons

depends on the atomic number (linear for a small Z), the image obtained by using the BSE signal offers information mainly about the composition of the sample, but it can also offer information about its topography [17].

Inelastic scattering is an interaction process which results in the fact that the basic electrons lose energy, transferring it to the sample atoms differently. A small part of the kinetic energy may escape as secondary electrons, useful for creating the image, X-rays for analyzing the composition of the sample [18].

According to the law of conservation of energy applied to this process, the basic electrons transfer their energy to the electrons from the atoms in the sample. If these are weakly tied to the nucleus, they leave the atom and move into the solid as secondary electrons (SE). In their movement, they interact with other atoms, gradually losing their kinetic energy. Most of them stop within the interaction volume. The ones which were generated at a small depth near the surface may escape into vacuum [17]. That is why the image obtained by using the SE signal offers information about the structure (topography) of the surface of the sample.

If an electron leaves the atom, this enters an excited state. The de-excitation of the atom can be done in three ways. If the electron is from an outer-shell, the de-excitation results in the emission of a photon that can be in the visible range. This effect is called cathodoluminescence [18]. If the electron is from an inner-shell, the de-excitation can result whether with characteristic X-rays emission, or an Auger electron emission. The analysis of these signals can give quantitative and quality information on the composition of the sample.

If the sample is a semiconductor and a voltage is applied, the electrons and the holes can be separated before the recombination and a current will be generated in the circuit. This signal, electron beam induced current (EBIC) is used to form the image that can give information about the conductivity of the sample, the life-span of electrons and holes, their mobility and also about impurities and weak ties.

The magnetic domain structure can be determined using as a signal specimen current the current flowing to ground from the specimen [18].

All these signals are suggestively shown in Fig. 1, while in Fig. 2 there are represented the interaction volume and the regions from which these signals can be detected [18].

As for the imaging capabilities, there are a few strong points of the scanning electron microscope. Firstly, a higher resolution can be obtained, values of 1-5 nm becoming usual for contemporary instruments [16]. Another important advantage compared to the optic microscopy is the greater depth of field, this being one of the grounds for the apparent tridimensionality of the SEM images. Furthermore, not only can SEM obtain a higher magnification, but it can also examine objects at very low magnification. This feature is useful in various domains, among which we mention medicine, since the SEM image can complete the information obtained with the optic microscope [16].
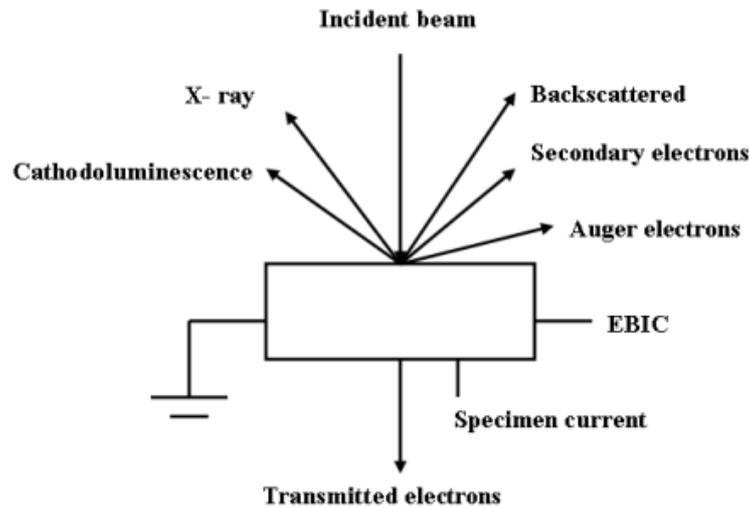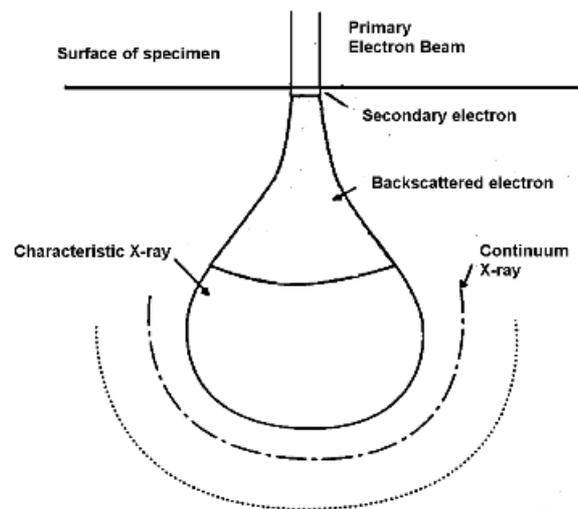
Fig.1 – Signals used in SEM.



Fig. 2 – The interaction volume.

## 2.2. THE USE OF SIMULATIONS AND VIRTUAL EXPERIMENTS IN THE STUDY OF SCANNING ELECTRON MICROSCOPE

Although the study of electron microscope is stipulated in the Physics curriculum for the 12th grade, it is hard to fathom this topic because of the small number of Physics classes assigned. The approach of this topic was possible only

for the classes having the specialization Mathematics-Informatics, which besides the 3 usual hours per week benefit from one more optional hour.

In order to make the teaching-learning process more efficient, an e-learning platform was created (Fig. 3), accessible on www.dinescu.info. Students can find here documents containing theoretical syntheses, but also several links to access the simulations and virtual experiments.
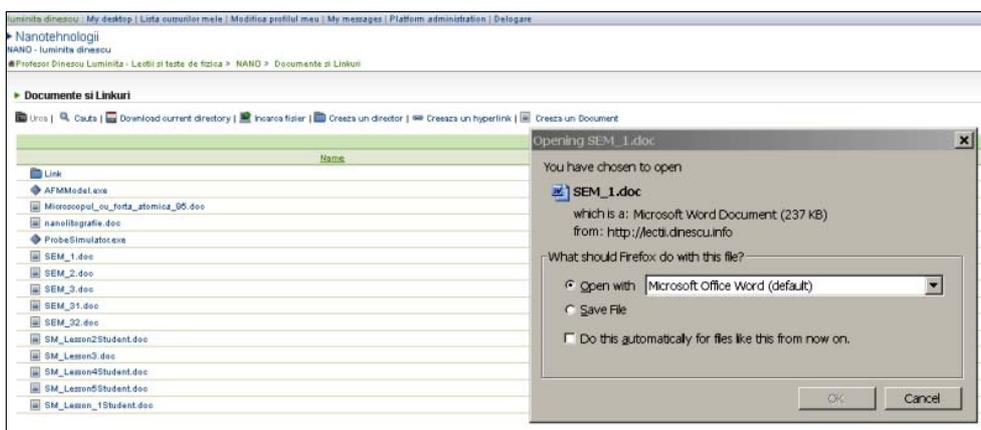


Fig. 3 – E-learning platform. The colored versions could be accessed at http://www.infim.ro/rrp/.

Thus, the students were able to access and study the theory before the class. All the problems or misunderstandings they had were clarified face-to-face, through discussions and exemplifications, with the help of simulations and virtual experiments. By combining these methods the instruction face-to-face time was reduced. Consequently, the approach of SEM could be fathomed.

The documents that contain the theoretical aspects were structured as follows: History, constructive details; Electron-solid Interaction; Formation and interpretation of images; SEM applications in nanotechnology. The simulations and virtual experiments regarded three aspects: the description of the constructive components of SEM and the simulation of the image formation process; familiarization with the basic operations that need to be made in order to obtain the image; acquiring and interpreting the image of a given sample through the manipulation of the parameters that its quality depends on.

UVA Virtual Lab: Scanning Electron Microscope [19] contains the description of the scanning electron microscope and simulation of the phenomena produced inside SEM, from the emission of the electron beam to the image formation (Fig. 4).
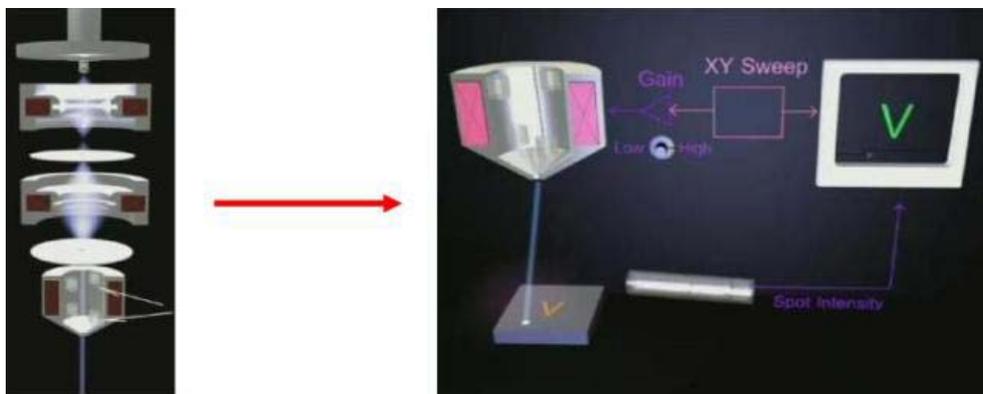
Fig. 4 – The simulation of the image formation process with UVA Virtual Lab.
The colored versions could be accessed at http://www.infim.ro/rrp/.

These simulations allowed students to understand the role of the main constitutive elements of the electron microscope: electron column and control console.

The simulation of the electrons emitted by the electron gun gives information on the role of its component parts: filament and Wehnelt cylinder. The electrons emitted by the filament (also called the emitter) are dispersed in a wide cone, but with the help of a Wehnelt cap they can be concentrated inside the gun; more than that, the quantity of the amount of electron emission can be controlled.

The simulation of the phenomena taking place at the entrance of the electron beam inside the magnetic lenses points out both their constructive characteristics, and also the result of the magnetic field action on the electron beam. The condenser lenses, situated under the electron gun are meant to demagnify the electron beam while the objective lenses, situated above the sample are meant to concentrate the sample electron and produce an additional narrowing. These features of the magnetic lenses can be deeply understood also due to the possibility of visualizing the force with which the magnetic field acts upon the electrons, the Lorentz force. Under this force the electrons move in a spiral and their trajectory is "curved" back to the optic axis.

The simulation of the image formation process consists in a few steps. To build an image, the beam needs to be moved point by point on the surface of the sample. The accessing of each point is made through the electron beam deflection in a raster on the examined surface. During simulation, it is pointed out the importance of the two scan coils: they make the electron beam, which is narrowed and concentrated after it comes out the objective lens, sweep on the surface of the sample. The second step consists in simulating the interaction between the electron beam and the sample, which results in the emission of SE and BSE. These are collected by dedicated detectors. After that, comes the simulation of the processes which take place in the scintillator, photomultiplier and amplifier before the signals be recorded and visualized on CRT. Finally, it is simulated the application of signals with the same form and frequency both to deflection coils, resulting in the

beam sweeping the surface, and also to CRT, resulting in SEM image. This last part of the simulation is pretty important because, through visualization, it favors the understanding of magnification, defined as the proportion between the length of the raster visualized on the screen and the length of the sample raster.

MyScope training for advanced research [20], allows both the visualization of the steps to be taken when using the SEM in reality, and also the achievement of these very steps by utilizing the virtual SEM.

The visualization of the sequence of operations (Fig. 5) that need to be done is exemplified on an JEOL instrument, at which the initial settings are: the type of the used signal, SE/BSE; accelerating voltage HV = 15kV; spot size, 45nm; working distance (WD), 10mm; scale 200 μm for SE and 100 μm for BSE; the sample used – sparkler on carbon tape.

The first operation to be done consists in introducing the sample into the sample chamber. Being a vacuum chamber, air must be pumped in to open it, operation called venting. After the sample is introduced inside the chamber, the air needs to be taken out, operation called evacuation.

If the chamber reaches an adequate vacuum level, the next steps are to turn HT on, activate the gun and increase the load current of the filament until the image appears on the screen. This operation is followed by the selection of the scanning way and sample position. Now we can choose magnification, adjust the focalization, contrast and brightness until the image becomes clear. At this moment the image can be saved. During the last stage the initial operations are resumed, but backwards: decrease the load current of the filament, turn HT off, vent, take the sample out of the chamber and vacuum.
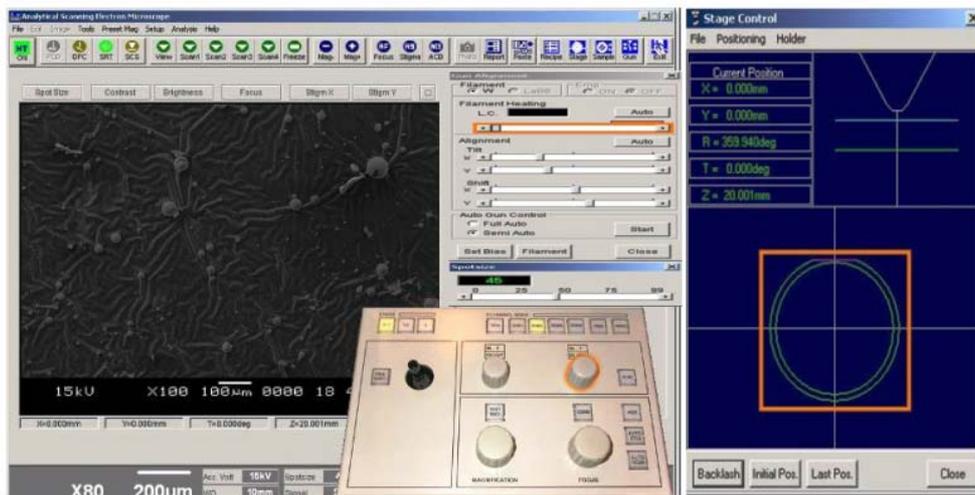


Fig. 5 – Sequence of operations when using SEM JEOL with MyScope.
The colored versions could be accessed at http://www.infim.ro/rrp/.

The use of virtual SEM allows conducting a virtual experiment, which ends in getting the topographic details of the sample surfaces: sparkler, bone, slag and rock.

The students have the possibility to follow the instructions that indicate the sequence of steps to be taken, but they themselves can manipulate the parameters that image formation and quality depend on: accelerating voltage, filament current, spot size, working distance, magnification, focus, contrast, brightness and astigmatism. If the selection of one or more of these parameters is wrong, the image cannot be saved, the errors are indicated and students have to make the corrections until the image becomes the correct one.

Having the possibility to modify the filament current, students can notice the dependence of brightness on this current: when the current increases, the brightness increases also. Therefore, they can understand the concept of filament saturation as being the point at which the electrons emission is maxim. From this point on, the increase of the current does not determine an increase of the electrons emission, the latter remaining constant. If the filament current is increased over this value, students are announced that the filament is damaged.

By modifying the parameters involved in image formation and comparing the images obtained with different combinations of parameters, the students are able to draw some conclusions, which can be later compared to those existing in the specialized literature.

For example, selecting a rock sample, accelerating voltage 30kV, spot size 5nm, working distance 8nm and high magnification, we can get images of the sample using SE signal (Fig. 6) and BSE signal (Fig. 7).

One can notice the difference between the two images, the BSE containing mainly compositional information (compositional differences between materials with different atomic numbers) and SE image showing primarily the topography of the sample.
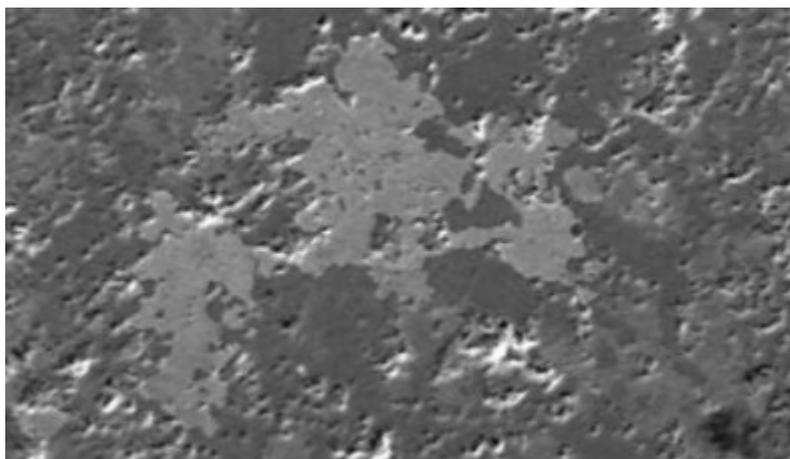


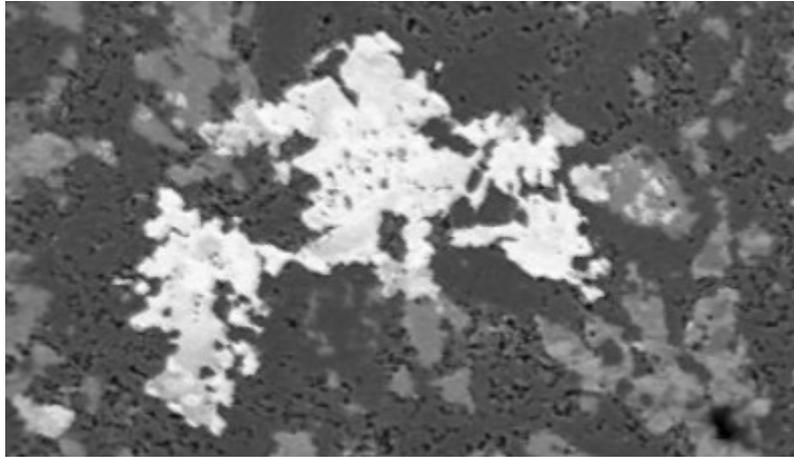Fig. 6 – Virtual SEM micrograph of a rock sample (SE).

Fig. 7 – Virtual SEM micrograph of a rock sample (BSE).

If we decrease the accelerating voltage, keeping the other parameters the same, we cannot obtain an image using the BSE signal due to the fact the BSE detector shows a low sensitivity foe low energy backscattered electrons. But also for low atomic number materials, low accelerating voltages (< 5kV) are to be used in order to obtain true surface resolution, interaction volume decreases dramatically with the acceleration voltages.

Modifying the working distance, we can notice its influence on the image formation, by comparing the images obtained with a small WD to those obtained with a big WD. Due to properties of electron-optics, the highest resolution can be obtained at small (< 5nm) WD, but for a large field of view and for a big depth of focus, bigger WD are used.

Modifying the spot size, it becomes obvious that the magnification needs to be correlated with the size in order to get the best resolution. Thus, at high magnification, small beam diameters should be used to obtain the best resolution. At low magnification the beam diameter has to be increased for a good signal to noise ratio of the acquired image.

Also, an image with a good resolution implies a proper focusing of the electron beam. This is pointed out by the necessity of correcting the astigmatism, which can be done by establishing the 0 value for X or Y, having a good focus and then modifying X or Y until the best focalization is obtained.

Unfortunately, this soft does not shows the scale in the acquired images. This would be very important for pointing out the superiority of the scanning electron microscopy. Of course, the quality of the images obtained with this virtual SEM does not equal that of the images obtained with a real SEM. Yet, the experiment is very useful since it helps achieving the didactic objectives. The evaluation of the portfolios created by students using multimedia tools showed the fact that the

objectives were reached. The students were able to describe the construction and the functioning way of SEM, to explain the mechanism of interaction between electrons and solid, to interpret images obtained with SEM and to describe SEM applications to nanotechnology.

## 3. CONCLUSIONS

The Physics is often perceived as a hard "academic" subject, whose understanding requires students to make great efforts [21]. But, use of computers and software ICT tools in classrooms and laboratories, can make physics-science easier to understand [22]. There are numerous studies which prove that using simulations, virtual experiments and technology in general can lead to a change of the negative perception regarding Physics, since the understanding of concepts becomes easier and deeper [23–28].

Even if important advantages appear, advantages that favor the understanding of the theoretical principles and the reduction of the gap between theoretical models and their concrete representations, it is still recommended not to totally replace the real experiments [29]. When there are no objective limitations it is beneficial for the students to be involved in activities aiming direct confrontations with and investigations of phenomena. Virtual experiments can raise students' interest but there are no guarantees that they do improve the understanding of the fundamental concepts. An optimal teaching-learning process can be accomplished by using them rationally and by combining proper instruments and resources [30].

As for the SEM, since the exploration of the topic is hard to do inside the classroom, there are global preoccupations to find and implement some alternative ways of approaching and fathoming it during high school years. The reason why all these steps have been made comes from the high importance of this instrument, regarded as essential scientific equipment, with almost endless applications for a wide range of scientific domains studied in high school: Biology, Geography/Geology and Technology etc.

The ExCEL (Extended Classroom for Enhanced Learning) Project brings the capabilities of scanning electron microscopy (SEM) into classrooms [31].
A part of this project consisted in purchasing a soft that permits the control and remote manipulation of a SEM (remote SEM), called WebSEM. By accessing this, it is possible to: create your own lesson plans or use the already existing ones; obtain images of samples from the data base or of own sample previously sent; use remote SEM according to a previous appointment and agreeing the WebSEM Usage Policy. This is a free service to all educators and available worldwide.

This project has been successful in increasing usage of the SEM and in raising the level of awareness concerning SEM capabilities and has had a significant impact on science education [31].

Of all the existing resources we have selected those which better corresponded to our possibilities and goals. The use of simulations and virtual experiments described above allows students to assimilate minimal knowledge about the basic SEM function principles, about the origin and formation of images, the collecting and interpreting procedures. Also, abilities for working with SEM are developed.

Yet, this does not mean that students immediately become experts in scanning electron microscopy, but they can get the basic necessary competences to do this later if they are willing to.

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