



Introducing UV–visible spectroscopy at high school level following the historical evolution of spectroscopic instruments: a proposal for chemistry teachers

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Abstract

Spectroscopy is a scientific topic at the interface between Chemistry and Physics, which is taught at high school level in relation with its fundamental applications in Analytical Chemistry. In the first part of the paper, the topic of spectroscopy is analyzed having in mind the well-known Johnstone's triangle of chemistry education, putting in evidence the way spectroscopy is usually taught at the three levels of chemical knowledge: macroscopic/phenomenological, sub-microscopic/molecular and symbolic ones. Among these three levels, following Johnstone's recommendations the macroscopic one is the most useful for high school students who learn spectroscopy for the first time. Starting from these premises, in the second part of the paper, we propose a didactic sequence which is inspired by the historical evolution of spectroscopic instruments from the first spectrometers invented by Gustav Kirchhoff and Robert Bunsen in 1860 to the UV–vis spectrophotometers which became common since the 1960s. The idea behind our research is to analyze the conceptual advancements through the history of spectroscopy and to identify the key episodes/experiments and spectroscopic instruments. For each of them, a didactic activity, typically an experiment, is then proposed underlining the relevant aspects from the chemistry education point of view. The present paper is the occasion to reflect on the potentialities of an historical approach combined with a laboratorial one, and to discuss the role of historical instruments and related technological improvements to teach spectroscopy.

Keywords Historical teaching method · Ultra-violet visible spectroscopy · Light · Historical scientific instruments · Scientific museums · Chemistry education · Learning and teaching sequence

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Introduction

Spectroscopy is a very wide scientific topic with many connections with different scientific disciplines, such as Physics, Chemistry, Biology, Engineering and Material Science. At high school level, Spectroscopy-related topics are usually included in Chemistry lessons, and they are limited to a specific type of spectroscopy: ultraviolet–visible absorption spectroscopy. The reason is that this technique has a huge variety of applications in analytical chemistry, and it is considered a standard technique to study different kinds of substances, solutions and complex materials. A critical issue in teaching and learning spectroscopy at high school level is the so-called ‘*procedural approach*’. High school teachers usually provide to students simplified procedures to use scientific instruments focusing on the applications instead of the basic principles and concepts (Malina and Nakhleh 2003). Many students are concerned with the physically manipulating of the instrument to do the minimum they can do to quickly get error-free data. Students are usually able to learn “how” to use an instrument to accomplish the instructor defined goals. In general, laboratorial activities in analytical chemistry suffers of this approach: teachers tend to explain the procedure and students execute the required steps of the laboratorial activity in an acritical way. Several authors have discussed the need of a meaningful learning of chemical concepts and the different levels of chemical knowledge related to different topics (Nakhleh 1993; Hartman and Nelson 2015; Taber 2020; Blackie 2022). According to Nakhleh (1993), students attending chemistry courses desire to explore the ‘why of chemistry’ than the ‘how of chemistry’. However, at school during analytical chemistry laboratories and, for instance, during spectrophotometric analytical activities, students are focused on the ‘how’ rather than the ‘why’. As a result, a first critical point is that students do not understand the principles of working of the instruments. For instance, they do not learn what is the optical path, and what is the role of each optical element (i.e. mirrors, beam splitter, monochromator, and so on), since they focus only on the external features of the instrument that are useful to them (i.e. the parameters to acquire a spectrum, and so on ...). A second critical issue is that students are not motivated to learn the theory behind the functioning of an instrument, and to think about the conceptual ideas related to them during the laboratory lessons (Malina and Nakhleh 2003). Recent international scientific papers about learning and teaching spectroscopy have been concerned with the first critical point mentioned above (Carpentieri et al. 2023). Several research efforts on this aspect are summarized in a comprehensive review about home-made and student-built instruments for spectroscopy (Kovarik et al. 2020). The *do-it-yourself* instruments help students to understand the working principles, that are hidden in the sophisticated and impenetrable modern instrumentations. However, few works in the scientific literature are focused on the second issue and this is the one of the motivations of our research work.

Before formulating a possible solution to the second critical issue, focusing our attention on UV–vis spectroscopy and on the methods used to teach this topic to high school students, we noticed that the historical evolution of spectroscopic instruments is rarely present in chemistry books, and it is not usually known by chemistry teachers (Carpentieri et al. 2022). The historical approach is a useful tool to help students understand conceptual ideas (Domenici 2020, 2023a). In 1938 Bernard Jaffe (Jaffe 1938, 1955) argued that some aspects of the history of chemistry should be taught in high schools. He selected twenty points indicating the essential themes to be included in an introductory course of chemistry: among these ones, it’s worthwhile, the spectroscope of Kirchoff and Bunsen and its use in chemistry. The aims of a historical approach, as

underlined by Jaffe, can be summarized in few points: (1) developing interest in chemistry; (2) understanding that the present status of chemistry knowledge is a product of human achievements and a long history; (3) illustrating the methods of the scientific research. Starting from Jaffe and through a series of works by other authors (Lin 1998; Justi and Gilbert 2002; Gomez Sanchez and Martin 2003; Näpinen 2007), the historical and epistemological approach was demonstrated as an inspirational and motivational tool and as an effective way to teach the methods of science at high school and university levels. Beyond these aspects, some authors pointed out that learning the historical developments of concepts would facilitate the conceptual understanding of the topics (Lin 1998; Matthews 1994). Moreover, the integration of history of science in the curricula can add significance to the formal way to teach science (De Berg 1989).

According to our experience (Domenici 2008, 2020, 2023a), the historical approach combined with active teaching strategies typical of non-formal contexts, such as science museums and collections, is a useful tool in teaching and learning chemistry. To apply these teaching approaches to a particular topic, such as UV–vis spectroscopy, it is important to choose a proper educational theoretical framework. The well-known Johnstone's triangle (Johnstone 1991) was the starting point of our reflections. As deeply analyzed by Taber (Taber 2013), Johnstone was concerned with learning science perspectives as information process theory, meaningful learning issues and memory consolidation (Johnstone 2010). Even though relevant developments of the scholarship on the nature of learning chemistry have been proposed, we decided to adopt the 'Chemistry triangle' since it is still a very useful and practical tool for designing, teaching and learning sequences. As discussed in this article, the Johnstone triangle can be applied to a specific topic of the chemistry curriculum (Bradley 2014), by elaborating a content specific triangle. This theoretical framework was important to analyze the way spectroscopy is usually taught and learnt at school at the three levels of the Johnstone's triangle. From a more practical point of view, once the theoretical framework is selected and discussed, another aspect concerns the way of structuring and organizing the proposed didactic activities. For this purpose, we refer to the approach called 'teaching–learning sequence' (TLS), which is aimed to handle topic specific related issues (Meheut and Psillos 2004). As highlighted by Lijnse (1995), TLS involves the design, development and application of a teaching and learning sequence about a specific topic in a "circle evolutionary process". Within this process, research results reached after one iteration represents the starting point of the design of the didactic sequence implemented in the next iteration, in an iterative way (Ruthven et al. 2009).

Starting from these considerations, in the first part of our research, we analyzed the actual way of teaching spectroscopy at high school level proposing a Johnstone's triangle applied to the specific topic of UV–vis spectroscopy. Focusing on the macroscopic level of this triangle, we decided to center our investigations on the historical evolution of spectroscopic instruments from the first spectroscopes invented by Gustav Kirchhoff and Robert Bunsen in 1860 to the UV–vis spectrophotometers which became common since the 1960s. In the second part of the research, we developed a didactic sequence made of several activities, mostly laboratorial ones, inspired by key-instruments and key-discoveries through the history of UV–vis spectroscopy. The aim of the present paper is to present and discuss these research steps with a final proposal of didactic sequence to introduce UV–vis spectroscopy at high school level and first introductory undergraduate courses, while the experimentation of the sequence within a pilot study with high school students is in progress and it will be reported in a future work.

Johnstone's triangle and the relevance of the macroscopic level in teaching chemistry

In 1982 Alex Johnstone stated that chemists view their subject “*on at least three levels*” and “*jump freely from level to level in a series of mental gymnastics*” (Johnstone 1982). These levels were identified as: (1) the descriptive and functional level at which chemists observe and describe the phenomena; (2) the representational level at which chemists use the symbolic language of the discipline, made of chemical and mathematical symbols and their relationships; (3) the explanatory level at which chemists use particulate models of matter to explain the chemical phenomena. Successively Johnstone (Johnstone 1991), to illustrate graphically this multilevel thinking of chemistry, used a triangle with three apices labelled as macro, sub-micro and symbolic ones, which represent the three levels mentioned above. He borrowed this scheme (see Fig. 1) from geologists, who use such diagrams to represent the proportions of components in a family of minerals.

According to Johnstone, the expert chemist continuously moves along the sides or inside the triangle while thinking of chemistry. The triangle is certainly a powerful representation of the knowledge of chemistry that over the years has become paradigmatic. However, the triangle model has proved to be even more relevant for teaching and learning chemistry. As a matter of fact, by describing his “multi-level thought” Johnstone highlighted how complex chemistry may be from the perspective of a novel learner and questioned the logic of introductory teaching. Before the development of this triangle model, he had already adopted a cognitive model inspired to the information processing theory (Johnstone 2010), pointing out the need for the researchers to simplify and unify their approach in describing the human learner. As deeply analyzed in a recent paper (Hartman et al. 2022), the role of cognitive science and of the theory of information processing in the development of the well-known Johnstone's model was fundamental. According to this model the new information should enter the student's working memory through a filter, be held there temporarily and eventually processed. In this space, all new information interacts with themselves and with the information drawn from the long-term memory, before making sense and being stored in the long-term memory. Within this model two aspects are relevant according to the author (Johnstone 2010). Firstly, the filter is driven by what the learners already know, by what interests them and by what is already in the long-term memory. The idea

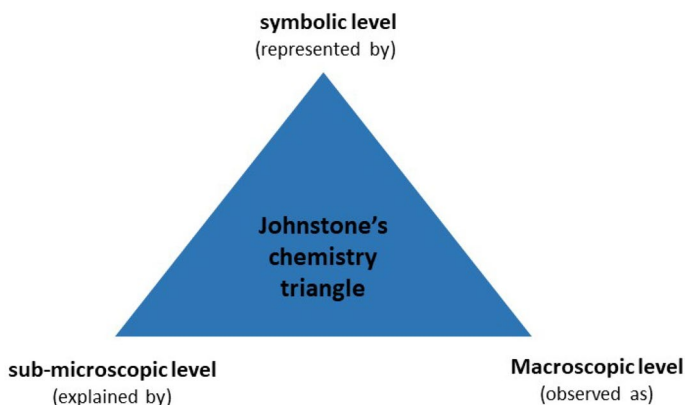


Fig. 1 The Johnstone's triangle also referred in the text as 'Chemistry triangle'

of a filter has allowed us, researchers and teachers, to thoroughly take into account some relevant issues. How the new information is related to the existing knowledge and how important it is to plan teaching to underline the links with any prior knowledge the students may have. Secondly, the working memory can hold a limited amount of information (Johnstone 1984). According to Johnstone the multilevel nature of chemistry is the major source of cognitive overload for students. When a chemistry topic is taught on three levels at once the quantity of information that needs to be manipulated is too large for novice learners. Thus, the triangle model is a very useful tool for estimating the cognitive load being placed in the working memory and how many levels are involved in the teaching process. From these critical points stem a significant conclusion (Johnstone 1993): “*Much useful, helpful chemistry can be taught at macroscopic corner*”. This means that if the teachers start from the macroscopic level of chemistry, they can select a starting point appropriated for the student’s long-term memory. Moreover, in this way teachers address one level at a time. There were other relevant points raised by Johnstone that offer insights into how to improve chemistry teaching (Johnstone 1997; Johnstone and Otis 2006), but we neglect them in this short summary that was not intended to be exhaustive of all implications drawn by the author in his extensive research work.

Johnstone’s triangle and the historical approach in teaching chemistry

Sjöström and Talanquer (2014) defined the Johnstone’s triangle “*the most well-known and influential content model in chemistry education*”. According to the authors the definition of “*content model*” refers to a type of didactic model that provides a framework for the organization of the subject matter knowledge, the so-called “*what questions*”. The Johnstone’s triangle has been used as a general content model that characterizes different types of chemical knowledge, by highlighting the three levels of teaching and learning chemistry: the macroscopic, sub-microscopic and symbolic ones. In this first version of the triangle-shaped model there is no concern about the historical aspects of chemistry. Multifaceted and integrated approaches to chemistry teaching which include humanistic and historical aspects are at the bases of the so-called ‘*tetrahedron model*’, proposed by Mahaffy (Mahaffy 2004) where an additional fourth vertex, the human apex, was added. This new model was classified by Sjöström and Talanquer (Sjöström and Talanquer 2014) as a “*relevance model*” that highlights the aims and the relevance of chemical education by adding the human element to the disciplinary triangle. They have recognized in the Mahaffy’s tetrahedron model different levels of complexity represented by different layers from the bottom triangle to the humanistic apex: Pure Chemistry, Applied Chemistry, Socio-chemistry and Critical-Reflexive Chemistry, according to a scale of increasing complexity, moving from the bottom toward the apex. At the ‘Applied Chemistry’ layer, historical facets of chemistry knowledge and practice are not considered. Within the ‘Socio-chemistry’ layer chemical ideas or practices are seen as products of historical developments of chemistry knowledge and subject to change in the light of new discoveries (Sjöström and Talanquer 2014). At the highest level of complexity toward the human apex there is the ‘Critical Reflexive Chemistry’ layer within which essential questions are addressed including ethical and philosophical issues. Talanquer proposed also a more complex model (Talanquer 2011) with a multidimensional space of chemistry knowledge characterized by different types, scales, dimensions and approaches.

A relevant relationship between Johnstone's triangle and the history of chemistry was pointed out by Bradley (2014). Bradley applied the Johnstone's triangle to the topic of the history of chemistry and used this model to represent the typical character of chemical progresses. The author illustrated how the chemical knowledge evolved during history thanks to the fundamental scientific results obtained by three important chemists Dalton, Berzelius and Lavoisier, placed at the three different corners of the triangle. Between 1780 and 1814 Lavoisier described and classified materials and substances and their transformations, using senses (macroscopic level), Dalton described the chemical substances in terms of particles (sub-microscopic level), Berzelius invented new symbols to represent micro-explanations and macro-descriptions (symbolic level).

In our analysis, up to this point, we have been considering the history of chemistry as metachemistry or one of the five metachemical knowledge fields pointed out by Sjöström (2006) who defined them as the meeting of knowledge between chemistry and different sub-areas of the humanities. As explained with more details in the next paragraph, in the present research work the history of chemistry will play a key role since it inspired the design of the core ideas of our proposal for a new didactic sequence.

A content specific Johnstone's triangle about UV-vis Spectroscopy

In our research work, the Johnstone's triangle has been applied to the problem of how teachers approach UV-Visible absorption spectroscopy at high school level or at first introductory undergraduate courses at the University level. We elaborated a spectroscopy triangle to explain the three different levels of teaching (and learning) of basic concepts of spectroscopy (Fig. 2). In the literature there are few examples of applications of Johnstone's triangle (Bradley 2014; Fahmy 2016) to specific topics. Among these works, a very interesting one for the purpose of the present research is the work by Bradley (Bradley 2014), who recognized the Johnstone's triangle as a core closed cluster concept. These types of diagrams in contrast to standard hierarchic concept maps do not expand only vertically in tree-like structures but spread laterally by crosslinks between vertical developments of

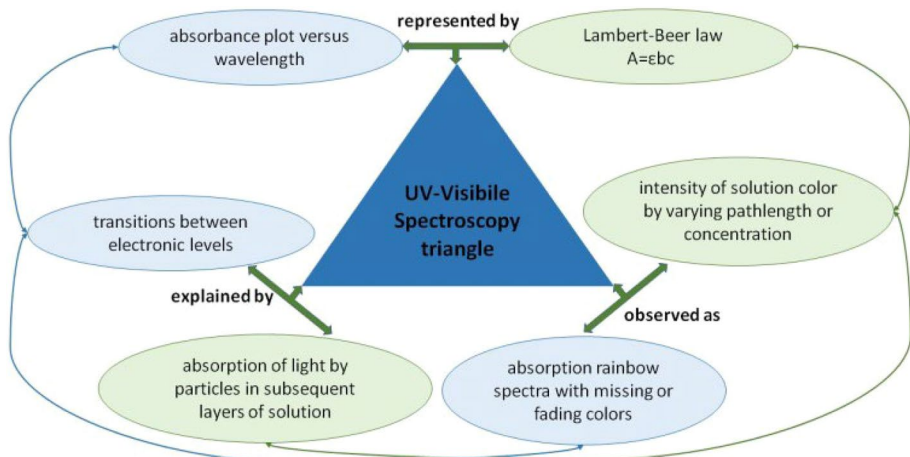


Fig. 2 The proposed 'UV-visible spectroscopy triangle'

concepts. By this cluster structure all the relationships among concepts are made explicit and they have the relevant feature of pointing out the interrelation between the concepts and the different aspects of a topic. These systemic diagrams are indeed complete by themselves. Further, a cluster structure implies multiple pathways for addressing or presenting the concepts related to a specific topic. Starting from one cluster map, different didactic sequences may be developed, by choosing any starting and arrival point and the path between them that better suits with the curriculum requirements. According to us, the building of a closed cluster concept map on the topic of UV-Visible spectroscopy may be a very useful tool for the purpose of exploring the basic concepts of spectroscopy to be introduced at high school level.

To represent the spectroscopy triangle, the three vertices of it, namely the symbolic, sub-microscopic and macroscopic levels of teaching and learning, have to be identified. In the following, these three levels are described based on the fundamental concepts of spectroscopy. UV-Visible absorption spectroscopy is an instrumental analytical technique which is usually introduced at high school level (Carpentieri et al. 2023). When doing laboratorial activities about spectroscopy, students usually observe a spectrum or a linear regression fitting curve. UV-vis absorption spectra are graphical plots that show how absorbance (A) varies as a function of the wavelength (λ). Spectra are characterized by a particular shape, reflecting the nature of the substance under investigation. They can be associated to the qualitative aspects of absorption of light by matter, as they are characteristics of the nature of the chemical specimen. Spectra can be indeed placed at the symbolic vertex of the spectroscopy triangle (Fig. 2). Linear regression curves are obtained from the fitting of experimental data of the measured absorbance values of a set of standard solutions *versus* the concentration of these standard solutions. The linear relationship between absorbance and concentration is translated in the mathematical equation of the well-known Lambert-Beer law, as it will be explained later. This fundamental law relates the absorption of light by a solution to the concentration of the absorbing molecules diluted in the solution. This empirical relationship allows students to calculate the concentration of a solution of unknown concentration by measuring the absorbance of the solution. The Lambert-Beer equation concerns the quantitative aspect of the phenomenon of absorption of light by matter as it is applied to determine the quantity of a solute in a solution. The Lambert-Beer equation can be indeed added to the symbolic vertex of the triangle (Fig. 2). Accordingly, the symbolic level of spectroscopy includes qualitative and quantitative aspects, represented by the spectral plots and the Lambert-Beer equation, respectively. This twofold character is also present in the other two levels of the triangle: the sub-microscopic and macroscopic ones. Moving from symbolic to sub-microscopic level, the absorbance peaks observed on a typical absorption spectrum are related to the electronic transitions, which can be placed at the sub-microscopic level. Electrons of the solute can change their energetic state moving between a lower and a higher energy level, by absorbing incident light energy equal to the energy difference between the two states. The electronic transitions represent the qualitative explanation of the phenomenon, since they explain why an absorber (i.e. molecule, ion, atom, ...) absorbs a specific wavelength in relationship to its characteristic electronic structure. The quantitative aspects of UV-Visible spectroscopy at a sub-microscopic level are related on how much light is absorbed, that depends on the amount of absorber particles that light encounters when it passes through a solution. In other words, the intensity of absorbed light depends on how many layers of solution are passed through by the light and how many particles are in each layer. In Fig. 2, the crosslinks between qualitative aspects (light blue line) of the symbolic and sub-microscopic levels and between the quantitative aspects (light green line) of symbolic and sub-microscopic levels are highlighted. The

macroscopic vertex of the spectroscopy triangle requires careful thoughts. The phenomenological or macroscopic thinking level is meant as what can be observed and experienced and it is the starting point in teaching chemistry, as discussed in the previous section. We have already pointed out that during the high school lessons students are usually trained to observe the spectral plot on the computer screen connected to the spectrophotometer, but what is the real phenomenon of absorption of light by a solution, underlying this symbolic representation? At the macroscopic level the absorption of light can be observed as the fading or disappearance of certain colors of the rainbow-like spectra of incident light when it passes through a solution. The rainbow-like spectra show intensity of color of bands *versus* wavelength (namely the color at a macroscopic level), while the absorption spectral plot shows absorbance *versus* wavelength. Absorbance is not an observable entity as it is an algorithm, nevertheless students can understand absorbance visually comparing the rainbow-spectra of light before and after passing a solution. Unfortunately, the rainbow-like spectra are not commonly experienced by students within classroom activities whilst they are reported in several works (Kovarik et al. 2020; Lietard et al. 2021). On the other side, what is the observable phenomenon correlated with the symbolic Lambert–Beer law? Absorption of light at a specific wavelength determines indeed the color of the solution, as the color is the product of additive mixing of unabsorbed colors. Further, the intensity of the color depends on how much light is absorbed. To experience the Lambert–Beer law, students can observe the change in intensity of the color of the solution by varying the thickness of the solution or/and by varying the concentration of the solution.

By keeping in mind this triangle model (Fig. 2), we can figure out at which levels (macroscopic, sub-microscopic and/or symbolic ones) UV–Visible spectroscopy is commonly taught at high school level. During the theoretical lesson in the classroom teachers usually explain the electronic transitions, the Lambert–Beer law and the most important spectral features, focusing mostly on the sub-microscopic and symbolic levels. During the practical activities in the laboratory, they usually teach the procedure for registering a spectrum or for achieving a calibration line and calculating the unknown concentration of the sample in a solution. All these aspects are on the symbolic level. We can briefly conclude that UV–Visible spectroscopy is rarely taught at a macroscopic level. According to us, this is quite surprising. In fact, visible spectroscopy is based on the interaction between visible light and matter, thus changes in light are observable at a macroscopic level as changes of colors in a spectrum or of the intensity of the color of a solution. The sense of sight is not used at high school level to introduce spectroscopy to students as it should be. This is even more amazing if we look at the history of spectroscopy. The first light detectors were indeed the human eyes: they remained the unique detectors until spectroscopic instruments became similar to the actual ones, in the 1930s. The earlier spectroscopic instruments, as it will be shown in the next paragraphs, moved from optical, visual and photographic instruments and finally they were replaced by the electronic ones. In the late 1930s, by the advent and spread of photoelectric and photoconductive detectors, as phototubes and electron multiplier tubes, the light signal was converted into electrical signal and recorded as such. Since the 1940s, the image of rainbow-like spectra and the color of solutions, that is, observable phenomena of the absorbed light, have been progressively lost due to the so-called ‘*electronic revolution*’, even though many visual instruments had been surviving in the laboratories until the 1960s. On the other hand, the development of photodetectors presented the advantage of being much more sensitive than the previous ones.

For the purpose of our research, the investigation of how these earlier instruments were made, how they worked and what are their operational principles suggested the design of key-experiments to promote the teaching of spectroscopy at a macroscopic level. In

the following section, the core ideas for didactic experiments are suggested as a result of the study of the historical evolution of UV–visible spectroscopy and spectroscopic instrumentations.

The history of UV–vis spectroscopy and instrumental developments

The historical investigation that follows is grounded in several historical studies reported since the 1930s in the scientific literature and it does not pretend to be new from an historiographical point of view. However, it is fundamental for our educational approach aim to design effective activities based on the reconstruction of the history of spectroscopic instrumentations. At the origin of UV–Visible spectroscopy there are two distinct research strands: on one side the observation and study of the spectra and on the other side the measurement of the intensity of the color of a solution. On the first side, in 1666, Newton's experiments marked the beginning of the study of spectra, starting from the solar one. In the second half of the nineteenth century some scientists observed the characteristic bright colors imparted by burning salts and during the period from 1820 and 1855 many researchers observed the spectra of colored flames produced by various chemical compounds, to distinguish among similar colored flames of different elements and the spark spectra produced by metals (Thomas 1991; Pearson and Aaron 1951). On the other side, in the first half of the eighteenth century, colorimetric studies started with the works by Pierre Boucher, who studied quantitative aspects of absorption of light passing through transparent glass layers and, separately, by Johann Heinrich Lambert, who translated own similar observations into mathematical equations (Malinin and Yoe 1961). Successively, after a century, Felix Bernard and August Beer quantitatively extended these studies by employing light passing through colored filters and by measuring the absorption of colored solutions (Malinin and Yoe 1961). As it's evident from the points mentioned above, in the historical evolution of spectroscopy we can find experiments related to both the spectra and the color of a solution.

From the spectroscopes to the spectrometers

Concerning the study of spectra, the first type of instruments was the spectroscope (Fig. 3a), invented by Gustav Kirchhoff and Robert Bunsen in 1860, even though it was first assembled in its basic components by the German optician Josef Fraunhofer in 1814 (Pearson and Ihde 1951).

The qualitative analysis of emission spectra was established thanks to Bunsen and Kirchhoff's achievements in 1860 (Thomas 1991) and thereafter new chemical elements were discovered by spectroscopic analysis (Weeks 1932). The emission spectrochemical analysis is indeed older than the absorption one (Jarrell 2000). Historically the analysis of spectra is commonly associated to the study of emission spectra, but it had been also used to study absorption spectra since the early days (Pearson and Ihde 1951). It is interesting to note that the suffix—*scope* in the word “*spectroscope*” properly refers to a device used to observe something. In its simplest form the spectroscope doesn't allow to measure quantitatively the intensity of lines in the spectrum nor the related wavelengths, but only to observe by an eye-piece the spectrum produced by a light beam passed through a slit and a dispersive element as a prism, as schematized in Fig. 3b. Furtherly, a mechanism to assign

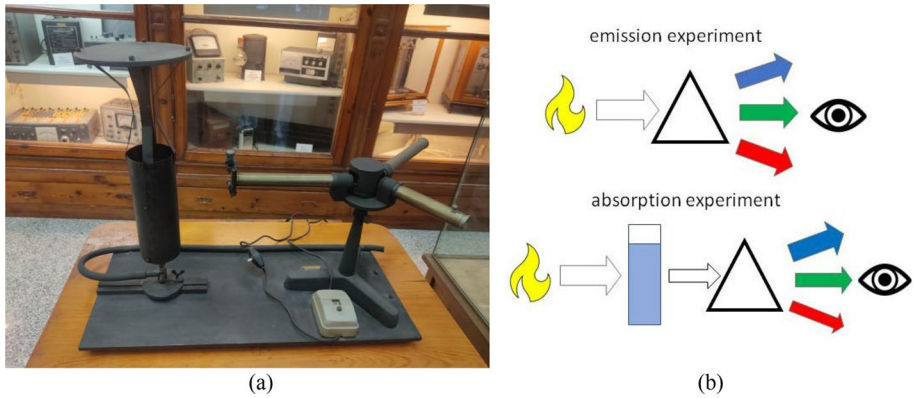


Fig. 3 **a** A Kirchhoff-Bunsen Spectroscope with a Bunsen burner. (Preserved at “Primo Levi Museum”, “La Sapienza University” of Rome). **b** Basic design of emission and absorption experiments with a historical spectroscope

a number to each line of a spectrum was introduced, as in linear scale prism spectroscopes or divided circle prism spectroscopes (Jensen 2014d).

A convenient educational experiment related to this instrument is the building of a home-made spectroscope and the observation of the spectra of different light sources, as proposed in many experiments reported in the literature (Kovarik et al. 2020; Carpentieri et al. 2023). The key elements of two basic experiments (emission and absorption) with a home-made spectroscope are represented in Fig. 4a. An example of home-made spectroscopes done by a student during an introductory undergraduate course (Domenici 2023b) is reported in Fig. 4b.

Spectrograph, as the one reported in Fig. 5a, was born in the 1890’s, and in 1900 the world’s first commercial spectrograph was produced (Jarrell 2000; Ewing 1974). The suffix—*graph* refers to an instrument able to record the spectra, in which the eye-piece was replaced by a photographic plate and by which the entire spectrum was recorded simultaneously. The operating scheme of the spectrograph is shown in Fig. 5b.

Examples of home-made educational spectrographs are reported in the literature, from instruments with a very elaborate design (Thorn 1964) to instruments with a very

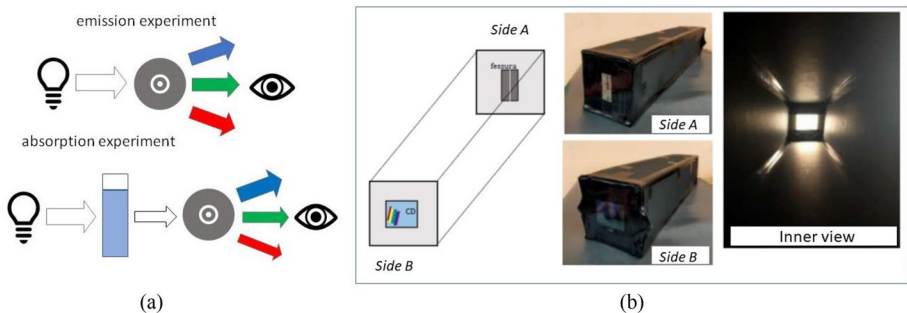


Fig. 4 **a** Basic design of emission and absorption experiments with a homemade spectroscope. The dispersing element is a DVD or a CD. **b** Example of home-made spectroscope done by a student by using a box, a DVD piece (side B) and a razor blade as slit (side A)

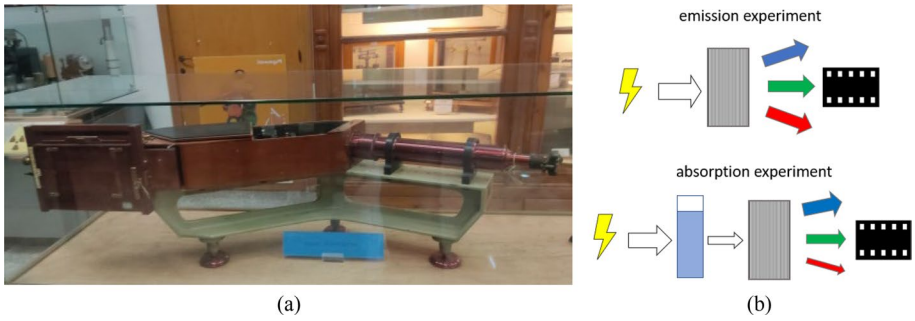


Fig. 5 **a** The historic spectrograph ‘Adam Hilger of London’ of the 1920s. This instrument is preserved at “Primo Levi Museum”, “La Sapienza University” of Rome. **b** Basic design of the emission and absorption experiments with a historical spectrograph

simple arrangement (Kolb 1966). A practical experiment which is inspired by the historical spectrograph can be performed by assembling a home-made spectrograph which is different from a spectroscope due to the different positions of the light source, the grating and the photographic device, which nowadays can be replaced by a digital photo-camera. The arrangement of all these elements is relevant to take a photo of the entire spectrum. An example of the schematic arrangement of these elements to build a home-made spectrograph is represented in Fig. 6. This kind of home-made spectrographs allows students to obtain colored spectrograms (i.e. photos of spectra).

It should be noted that the original historical spectrograms presented black and white spectra instead of colored ones. By the 1920s and 1930s the wavelength of spectra had been exactly measured and energy levels had been identified by means of spectrographs, but most measurements were achieved by visual estimating the relative blackness of spectral lines, by the so-called ‘*bracketing*’ (Jarrell 2000; Muller 1940). Since the

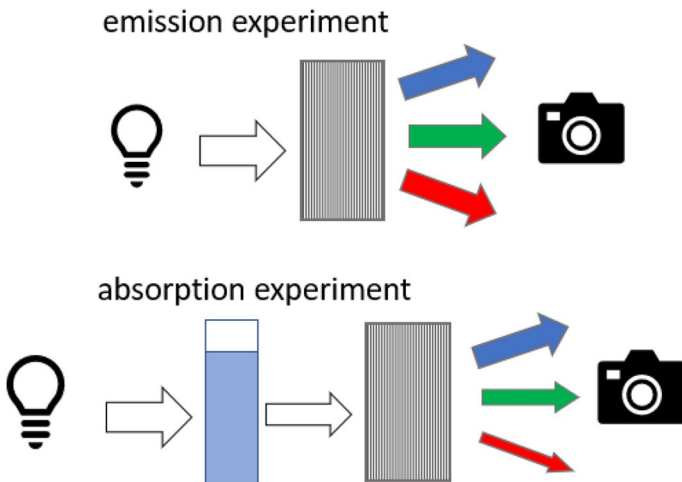


Fig. 6 Basic design of emission and absorption experiments with a homemade spectrograph

1930s, the transmission or density of photographic spectrograms were measured line by line, with improved accuracy, by means of auxiliary tools, such as the densitometers.

A further educational experiment to be proposed to students is the transformation of the recorded digital photo of the colored spectrum into a graphical plot, similar to that displayed on the modern spectrophotometer screen. The conversion of an image into a spectrum, can be performed thanks to available digital tools or free software (Domenici 2023b) able to extract the pixel intensity values, for each pixel of the image. Interestingly, spectrographs were not only restricted to the analysis of emission spectra, but they were also employed in the study of absorption spectra (Gans 1944). In this case, the sample is placed between the source and the slit. Similar experiments can be designed by using home-made spectrographs, as reported in the scheme of Fig. 6.

In the 1910s, spectrometers were introduced for the first time: they were similar to spectroscopes, but with modified elements which enabled the observer to directly measure the wavelengths of emitted or absorbed light. For instance, the constant deviation wavelength spectrometer (see Fig. 7) was designed by Adam Hilger with a quadrangular prism fixed on a rotating table at the intersection between two arms forming 90° : the collimator and the telescope. The shape of the prism, called Pellin-Broca prism, ensures that the light beam of a selected wavelength passes the prism with a constant deviation of 90° . The observer could read the wavelength of the light beam thanks to a calibrated spirally grooved drum attached to the table on which the prism sits could be rotated (Jensen 2014d). This mechanism is the same principle of operation of a monochromator.

In the 1940s, the development of electron multiplier type phototubes made possible a new device: the direct readers (Munch 1945; Jarrell 2000; Baird 2000). These instruments were grating spectrographs arranged so that light of each spectral line passed through the exit slits and fell on the cathodes of multiplier phototubes. The instrument accommodated many photomultipliers, because the spectral lines that needed to be measured were different for each specific type of chemical compound (Munch 1945; Jarrell 2000; Baird 2000).

The history of colorimeters

So far, we have reported the evolution of spectroscopic instruments able to record the spectra. If we move to the historical evolution of instruments measuring the color or color changes, a very important instrument is the colorimeter. Historically, it was an

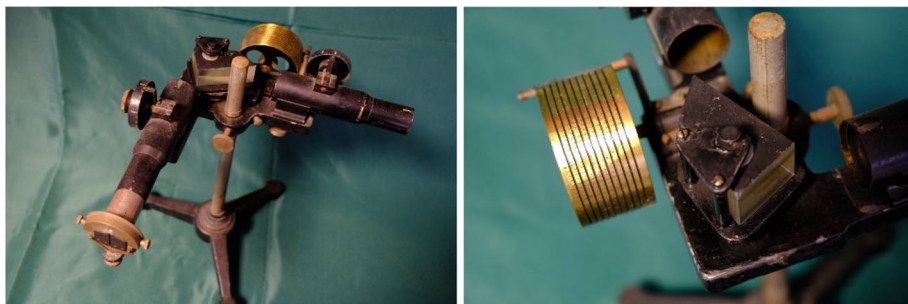


Fig. 7 Two views of a constant deviation wavelength spectrometer designed by Adam Hilger (estimated period from 1904 and 1921). This instrument is preserved at the Department of Chemistry and Industrial Chemistry, University of Pisa in Pisa (Historical History Museum at DCCI 2024)

instrument for the quantitative evaluation of the color of a chemical specimen. Now, the term ‘*colorimeter*’ is intended to define an instrument able to measure the relative transmission or reflection of a selected wavelength or spectral regions. The earlier colorimeters for chemical analyses, however, measured the intensity of color by visual comparison (Altemose 1986) and they were made by a series of glass tubes, as the ones shown in Fig. 8a. The simplest method of evaluating the concentration of the colored solution was developed in the second half of the nineteenth century by Julius Nessler (Stock 1994; Jensen 2014a). The method consisted in preparing a series of standard solutions of the solute that needed to be quantified in an unknown sample solution. Then all solutions, the standard ones and the unknown ones, were inserted into flat bottomed tubes of equal cross section with equal liquid level. The operator compared (‘*bracketed*’) the unknown solution to a slightly darker and slightly lighter standard solutions, by looking down each tube. Such procedure is called ‘*visual interpolation*’, as the one schematized in Fig. 8b. At the end, the operator could only approximate the unknown concentration establishing a range of concentrations (Jensen 2014a).

A further and more precise method was developed with the first colorimeters, such as the Duboscq (Fig. 9a) and Wolff (Fig. 9b) colorimeters, invented respectively in 1868 and 1879, and other color comparators or visual colorimeters (Stock 1994; Lewin 1960a; Muller 1940; Ewing 1974; Jensen 2014a). The basic principle of working of these historical colorimeters is the so-called ‘*color-matching*’ between the color of a sample with unknown concentration and the color of a standard solution. The standard solution was progressively poured in a tube to a level at which its color matched the color of the sample solution, inserted in a second tube. The color of the two solutions was observed from the top. By this way the intensity of light transmitted through the sample solution is visually compared to that of a standard solution. The concentration of the unknown solution can be determined by using the ‘*Duboscq equation*’: $b_{st} \cdot C_{st} = b_{sa} \cdot C_{sa}$. Here, b is the level (height) of the liquid in the tube and C is the concentration of the solute. The values of b_{st} and b_{sa} were measured on the tubes, the concentration of the standard solution, C_{st} , was known and C_{sa} could be calculated.

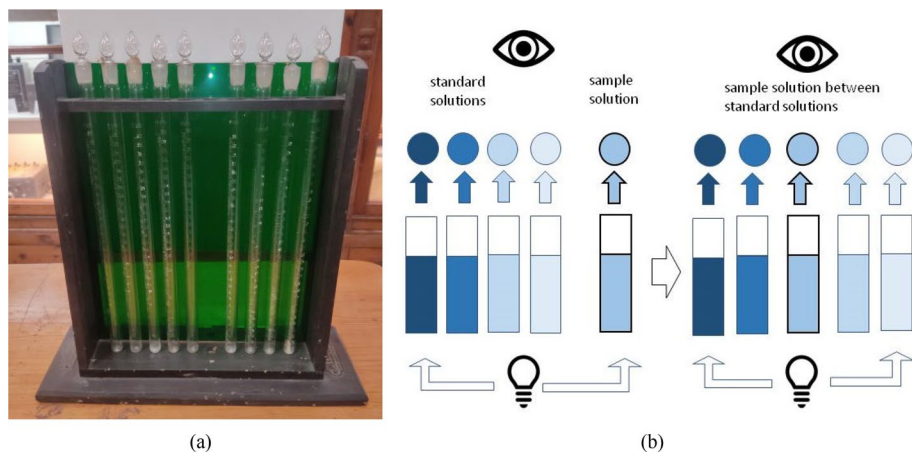


Fig. 8 **a** Eggertz tubes preserved at “Primo Levi Museum”, “La Sapienza University” of Rome. **b** Basic design of an “*interpolation*” experiment by using the historical Nessler (or Eggertz) tubes

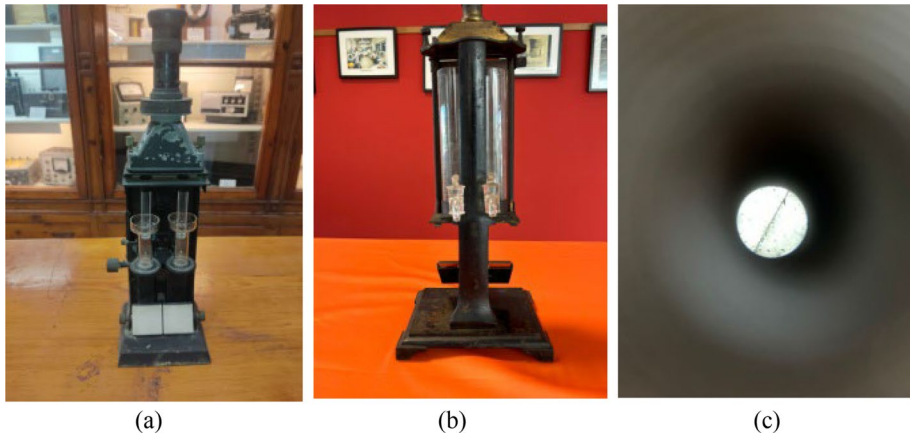


Fig. 9 Two historical models of visual colorimeters: **a** the colorimeter invented by J. Duboscq in 1868 (preserved at “Primo Levi Museum”, “La Sapienza University” of Rome); **b** the colorimeter invented by C.H. Wolff in 1879, with graduated glass cylinders, called Hehner cylinders (preserved at the Department of Chemistry and Industrial Chemistry, University of Pisa). **c** Image observed by the split optical field eyepiece of the Wolff colorimeter used for matching the colors of the solutions in the two cylinders

These instruments present two important features: (1) the pathlengths through the sample and standard solutions can be adjusted mechanically with elevated precision; and (2) the colors of the solutions are observed in a split-circle image (see Fig. 9c), as contiguous areas in an eye-piece. This last improvement allowed to achieve the ‘*color matching*’ with higher sensitivity with respect to the Nessler or Eggertz tubes.

As seen in Fig. 9a, in the Duboscq colorimeter the pathlengths were the distances from the inner side of the bottom of a bigger flat glass cylinder to the underside of the bottom of a smaller glass cylinder that could move up and down inside the bigger one. The solutions were placed in the bigger vessel, while the smaller ones were empty. A scheme of working principles of the Duboscq colorimeter is shown in Fig. 10a. In the Wolff colorimeter (see Fig. 9b) the pathlengths were adjusted by opening the stop-cocks of two graduated cylinders, but the basic principle was the same as the Duboscq colorimeter.

From the educational point of view, two simple experiments can be designed based on these historical instruments that involve the observation and the comparison of the color of different solutions from the top of equal beakers or other glass cups, standing on a white surface, as a white paper. In the first experiment, a set of standard solutions of the same solute of the sample can be prepared and poured in equal cups, and the intensity of the color of the sample solution can be interpolated between the slightly darker color and slightly lighter color of two standard solutions, as reported in the scheme reported in Fig. 8b. An effective experiment based on a similar visual interpolation was performed with high school students as reported in Carpentieri et al. (2022), suggesting that this experiment is convenient from a practical point of view and quite effective to introduce the role of the optical pathlength in the Lambert–Beer law. In the second experiment, a standard solution is chosen slightly less intensely colored than the sample solution. Initially the liquid levels of the two solutions are equal, then the standard solution is poured in its cup until the colors of two solutions are matched by viewing the two solutions from the top and lastly the liquid level is measured to determine the concentration of the sample solution, as

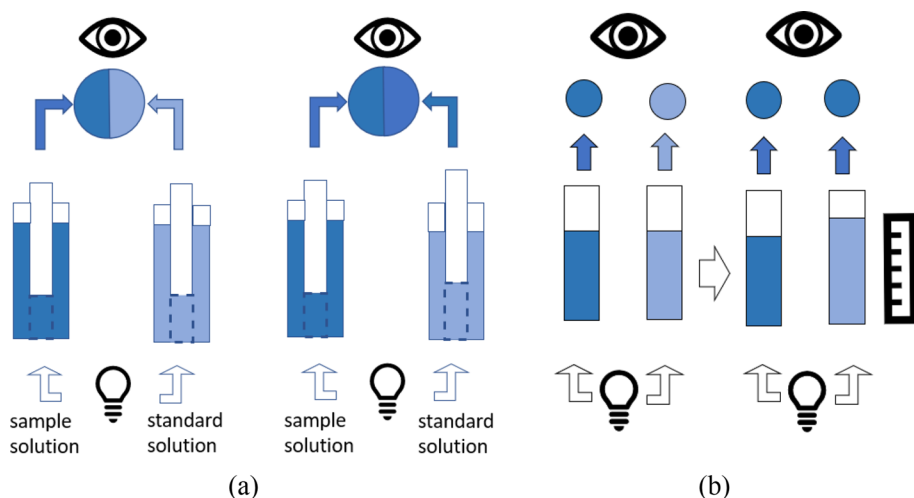


Fig. 10 **a** Basic design of the color matching experiment done with the historical Duboscq colorimeter. **b** Scheme of an experiment, inspired by the historical Duboscq colorimeter, to measure the unknown concentration of a sample solution

shown in the scheme in Fig. 10b (Charlton et al. 2007). This experiment basically reproduces the operating mechanisms of the Duboscq colorimeter (Fig. 9a).

Bernard's historical experiment

The Lambert–Beer law applies only to monochromatic light, but monochromaticity does not matter when the detector is the human eye (Stock 1994; Jensen 2014a) because several colors cannot be distinguished. Moreover, with the colorimeters, the Lambert–Beer relationship simplifies in the ‘*Duboscq equation*’, since the light intensity and the extinction coefficient, which is typically wavelength-dependent, disappear. In the Lambert–Beer equation, indeed, the molar attenuation coefficient, ϵ , represents a bridge between the qualitative and the quantitative sides of the symbolic level. To show the molar attenuation coefficient on the macroscopic level, the experiment of the French scientist Felix Bernard can be relevant. In 1852, Bernard published his work entitled “*Thèse sur l’absorption de la lumière para les milieux non cristallins*”, showing that by increasing the thickness of a transparent colored solution, or the pathlength, the transmitted light was not only weakened in intensity, but the color itself was changed and in some cases colorless bodies became colorful by increasing its thickness up to a certain value (Malinin and Yoe 1961). In his experiments Bernard examined the solar spectrum passing throughout a colored solution and observed that only some colors of the solar spectrum were absorbed, and the others were transmitted. Moreover, by increasing the pathlength through the solution, the transmitted colors diminished their intensity in different degrees, depending on the color (see the scheme reported in Fig. 11). We know that this effect is due to the molar attenuation coefficient, which is dependent on the wavelength, thus on the colors. An experiment can be designed inspired by Bernard’s work to present on a macroscopic level of teaching the molar attenuation coefficient and to introduce students to the important Lambert–Beer equation.

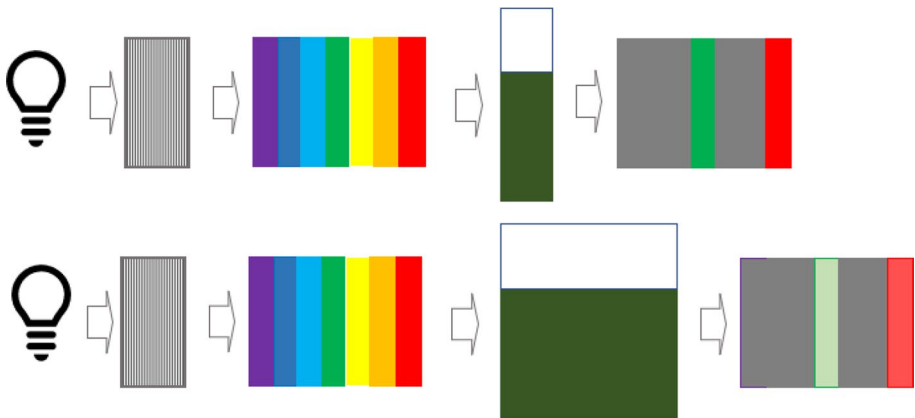


Fig. 11 Scheme of an experiment inspired by one of the historical Bernard's experiments

From filter photometers to modern spectrophotometers

All visual colorimeters continued to be used until the 1960s, even though the filter photometers began to replace them (Altemose 1986; Jensen 2014a). An interesting aspect from the educational point of view is that so far, in the experiments inspired by visual colorimeters or color comparators, absorbance does not appear. Absorbance, A , is an algorithm of the intensity of light, in fact it is defined as: $A = -\text{Log}(I/I_0)$. Here, I is the transmitted light passing through the sample and I_0 is the source light or the light passing through a reference sample. Both incident and transmitted lights can be measured by a photometer. The word '*photometer*' properly refers to a device which makes a measurement of the intensity of light and no longer the intensity of color (Lewin 1960a, b). Filter photometers employed a filter to select a band of wavelengths, most commonly the filter being placed between the sample and the detector (Lewin 1960a; Ewing 1974; Jensen 2014b) (see Fig. 12a).

Dual channel visual filter photometers (1925–1930s) (Ewing 1974; Jensen 2014b), as the ones shown in Fig. 12b, and d, allowed the observer to compare the light passing through the sample solution and the light passing through the solvent alone in a split optical field similar to that of visual colorimeters. The matching was obtained by attenuating mechanically the reference beam. These visual filter photometers were replaced by electronic instruments in the 1930s, as the dual channel and single channel photometer models shown in Fig. 12c and d (Jensen 2014b). Moreover, in the filter photometers light that passed through the sample fell upon a photodetector.

Based on historical filter photometers, with their relatively simple working principles, several educational activities can be performed. To reproduce home-made filter photometers, digital camera can be used. In fact, smartphones typically include digital camera featuring an array of RGB filters and a light detector in each of its pixel. To perform a laboratorial activity several free applications to read the R, G or B values by using the photo-camera of a smartphone are available (see for instance the *ColorMeter App* and others cited in Domenici 2023b). A simple arrangement for an educational experiment is shown in Fig. 13. Light from a white light source is reflected on a white paper or a card, then it passes through the sample solution placed in a home-made holder and it is analyzed by a digital photo-camera as a convenient one of the three RGB values.

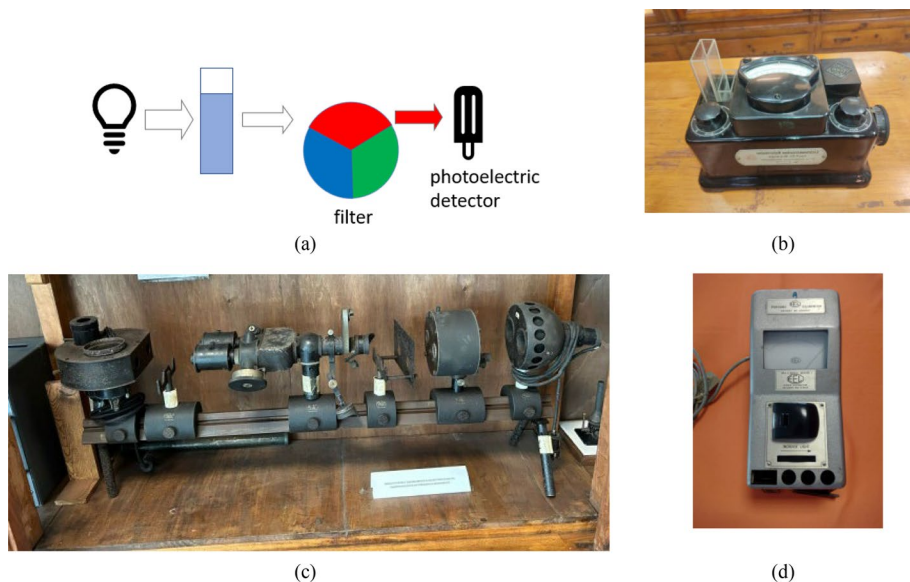


Fig. 12 **a** Basic design of an historical photoelectric filter photometer. **b** A dual channel photoelectric filter photometer by B. Lange, manufactured in the 1940s (preserved at “Primo Levi Museum”, “La Sapienza University” of Rome); **c** a dual channel visual filter photometer, introduced by Carl Pulfrich and manufactured by Carl Zeiss Co. in 1925, with a variety of alternative light sources, cells and holder accessories (preserved at the Department of Chemistry and Industrial Chemistry, University of Pisa); **d** a single channel photoelectric photometer, EEL, of the 1960s, preserved at the Department of Chemistry and Industrial Chemistry, University of Pisa (Historical History Museum at DCCI 2024)

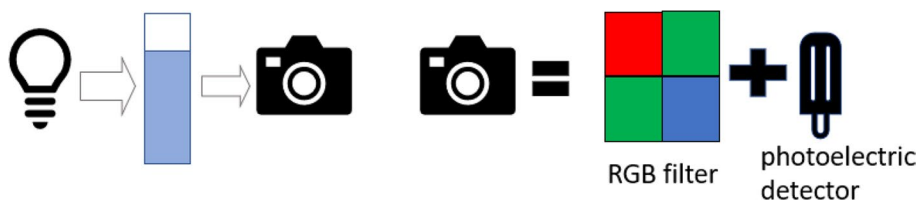


Fig. 13 Basic design of a homemade photoelectric filter photometer

With the advent of photoelectric detectors monochromaticity does matter. In the 1950s the need of improvement in monochromators to study the line shape and width of emission and absorption spectra was evident (Jarrell 2000). The working principle of the monochromator had already been available in the rotating prism table of the spectrometer with its wavelength reading device, as mentioned above. A spectrophotometer measures the intensity of light at a specific wavelength, and it results, at a conceptual level, as a combination of two instruments: a spectrometer that measures the wavelength, and a photometer, that measures the intensity of light. Since 1873, the instrumental apparatus was assembled (Jensen 2014c; Ewing 1974) as a visual modular spectrophotometer, composed precisely by a spectrometer and a visual photometer. The first one, designed by Karl von Vierordt, consisted of a Bunsen spectroscope with calibrated scale and a visual double slit photometer, while, later in the 1920s, other modular visual spectrophotometers were produced as

the ‘*Color Analyzer*’ by Keufel and Essen, and the ‘*Universal Spectrophotometric Outfit*’, by Bausch and Lomb.

In the same years, Hardy at MIT (Boston, USA) had been already developing a technologically advanced instrument: the first UV–Visible self-recorded spectrophotometer made available commercially since 1938. At that time, this instrument was really quite expensive. Other cheaper instruments were produced later, becoming widespread in the chemistry laboratories. Examples of these spectrophotometers are the Beckman UV–Visible Spectrophotometer produced in 1941 and the UV–Visible spectrophotometer ‘*Spectronic 20*’ in 1953 (Altemose 1986; Jensen 2014c). Historical instruments are shown in Fig. 14 in two exemplary models held at the Museum of Chemistry in Rome (Italy). These spectrophotometers were not actually self-recording instruments. In fact, spectra were hand plotted by interpolating discrete data points. The first self-recorder UV–Visible spectrophotometer which remind the actual instruments in chemistry laboratory is the ‘*Cary II*’ which was commercialized in 1947 and became common since the 1960s (Jensen 2014c).

Discussion of the key ideas of the proposed experiments inspired by history of spectroscopy

In the previous section of the paper, we have proposed a set of key ideas for the design of valuable teaching experiments about UV–Visible Spectroscopy, inspired by the working principles of historical instruments. The historical evolution of qualitative and quantitative spectroscopic analyses and related instrumentations had been comprehensively investigated to identify such key ideas with the aim of bringing the introduction of UV–Visible Spectroscopy to students at the macroscopic level.

In the present section we take a depth look at the key ideas presented before, also summarized in Table 1, by highlighting how they can promote the conceptual understanding of UV–Vis spectroscopy at the macroscopic, sub-microscopic and symbolic levels. In this paper, we focus on the explanation of these key-ideas, underlining the conceptual aspects and educational potentialities, while the results obtained from the experimentation of these activities with students will be reported in a further paper.

A homemade spectroscope (see Fig. 4) allows students to easily understand the principle of working of different optical elements (i.e. slit and prism) and their role inside the instrument. Moreover, students can observe the solar spectrum and compare it with



Fig. 14 Two models of spectrophotometers: **a** A “*Spectronic 20*” spectrophotometer (only visible), Bausch & Lomb, 1955; **b** A UV–visible spectrophotometer, introduced by Beckman in 1941 and made by the National Technical Laboratories of South Pasadena, CA. Both instruments are at “Primo Levi Museum”, “La Sapienza University” of Rome (Italy)

Table 1 Key ideas and main concepts promoted by historical instruments or technical developments in the history of UV–Vis spectroscopy. In the Table, the reference to the schemes of the educational experiments is reported

Historical instrument or experiment	Key ideas of the educational experiments	Scheme of the didactic experiment
Kirchhoff-Bunsen spectroscope	Understanding the working principles of this instrument and its optical elements, such as the slit and the prism. Observing a typical rainbow-spectrum. First qualitative introduction of emission spectra. Comparing the emission spectra obtained from different light sources on a qualitative point of view. First qualitative introduction of the concept of absorption spectrum	Figure 4
The spectrographs	Observing the features of an absorption spectrum with a higher level of details. When observing the light absorption phenomenon, students should associate the color decrease or color disappearance with the position of the absorption peak in the spectrum	Figure 6
The Nessler tubes	Understanding the role of the concentration of a solute on the observed color of a solution. Understanding the role of the pathlength on the observed color of a solution. Understanding the method used to determine the concentration of unknown samples by means of a visual interpolation. First introduction of the ‘visual calibration curve’	Figure 8b
The colorimeters, such as the Duboscq colorimeter or the Wolff colorimeter	Understanding two variables present in the Lambert–Beer law: the pathlength, b , and the concentration of ‘absorber particles’, C . Understanding that the observed color of a solution depends on the amount of solute (absorber particles). Using the Duboscq equation to determine the concentration of an unknown solution by means of a visual method	Figures 10b
The Bernard’s experiment	Understanding the meaning of the ‘molar extinction coefficient’ in the Lambert–Beer law. Understanding the fact that each absorber (chemical substance) absorbs different amount of light at different wavelengths	Figure 11
The dual channel photoelectric filter photometer	Understanding what the transmittance is and its relationship with the absorbance. Directly measuring the transmitted light. Having an overall view of the Lambert–Beer law and its limitations	Figure 13

the spectra of different light sources (Carpentieri et al. 2023). In addition to emission spectra, in a similar experiment, students can use a colored filter (or a colored solution) placed between the light source and the spectroscope to observe an absorption spectrum. Students can observe the fading or the disappearance of some colored band with this simple apparatus, thus introducing the concept of light absorption.

A homemade spectrograph, as the one represented in Fig. 6, makes comparable and reproducible colored spectrograms (photos of spectra). With this device students can observe specific features of different recorded spectra with more details with respect to the spectroscope. The use of a spectrograph can help students understanding the connection between a rainbow-like spectrum and a graphical spectrum, and to move from the macroscopic to symbolic level. It's worth noticing that the absorbance is a 'not-observable' variable, while the intensity of transmitted light that appears in rainbow spectra is an observable variable accessible to students. As already mentioned in the previous paragraph, student can relate the position of the faded colored bands in rainbow-like absorption spectra to that of the absorbance peaks of classical spectral plot. The height of the absorbance peaks could be related to the degree of fading in rainbow-like spectra by suitable experiments (Carpentieri et al. 2023; Domenici 2023b).

Subsequent experiments in the didactic sequence are inspired by colorimetry, which in chemistry is a specific branch of chemical analysis for measuring the unknown concentration of a colored solution (Mellon 1952; Lewin 1960b). Color is the most evident consequence of absorption of light by matter. Unfortunately, the topic of color (color perception, colors' origin and different reasons why matter is colored in nature, ...) is not usually covered during chemistry lessons (Carpentieri et al. 2022, 2023). The link between color and absorbance should be addressed after clarifying that the color of a light source is an additive mix of spectral colors. As described in the previous section, starting from the historical colorimeters several significant experiments can be designed and proposed to students addressing different concepts (see Table 1). The experiment proposed in Fig. 8b, for instance, is inspired by the Nessler tubes and it allows students to start exploring some of the variables present in the Lambert–Beer law. The experiment is a kind of visual interpolation of the color of the sample, whose concentration is unknown, between the most similar colors of two standard solutions (see scheme in Fig. 8b). The interpolation is the core of this experiment, since it is necessary to estimate the unknown concentration of a sample by a visual calibration curve. Analogously, in modern spectrophotometric instruments, the concentration of unknown solutions is determined with an automatized procedure where the building of a calibration curve is the key aspect.

The next experiment inspired by historical colorimeters is shown in Fig. 10b. It has the aim to help students investigating the meaning of the variable 'b' (i.e. the optical pathlength) and 'C' (i.e. the solute concentration) in the Lambert–Beer equation (see Eq. 1). The dependence on the pathlength is very difficult to be experienced by students by means of traditional spectrophotometers, since the pathlength is usually fixed. However, understanding of role of the optical path is crucial to a meaningful understanding of the mathematical form of the Lambert–Beer law, here in the Logarithmic form:

$$\log \frac{I_0}{I} = A = \epsilon \times b \times C \quad (1)$$

The same law can be expressed in another form, evidencing the relation between the intensity of incident light, I_0 , and the intensity of transmitted light, I :

$$I = I_0 e^{-\epsilon b C} \quad (2)$$

Both exponential and logarithmic functions are quite hard to understand for high school students. A way to help students understanding this law is to consider that a continuous exponential function corresponds to a discrete geometrical progression. The physicist Pierre Bouguer, indeed, in the second decade of the eighteenth century, imagined a transparent body to be divided in parallel layers of the same thickness and investigated what happened through each layer by measuring the decrease of light power through increasing number of equal sheets of glass (Malinin and Yoe 1961). He reached the conclusion that each layer should absorb not equal quantities, but proportional quantities and then the light will always be diminished in a geometric progression. This historical fact suggests a convenient explanation of the absorption of light passing through a transparent solution layer by layer and this explanation can be supported by experiments like that shown in Fig. 10b, with adjustable pathlengths. Similar experiments have been recently designed for high school students to introduce the concepts of optical path, concentration and the mathematical relationships reported in Eqs. 1 and 2 (Matteoni 2024).

The last variable to be considered in the Lambert–Beer equation is the molar extinction coefficient, ϵ in Eqs. 1 and 2, to which the experiment reported in Fig. 11 is referred. This variable is empirically obtained by students from the slope coefficient of the calibration line, but its meaning is usually unclear. Bernard, as reported by Malinin (1961), stated that *‘the emergent light, is not only weakened in intensity, but the tint itself is changed in nature. Thus bodies which, at a certain thickness, appear to transmit white light without alteration and are colorless, cease to be when their thickness becomes appreciable. For example, ocean water appears green at slight depths and blue when deeper’*. The experiment reported in Fig. 11 allows students to relate an abstract coefficient to fascinating phenomena, such as the changeable color of the ocean water, and to move again from symbolic to macroscopic levels. Students can observe that the extinction coefficient is a function of wavelength because it is different for each color. It accounts, furthermore, for the shape of the traditional spectral plot in which different peaks have different heights corresponding to different degrees of fading in the rainbow absorption spectra.

Up to this point of the proposed didactic activities inspired by the historical developments the intensity of transmitted light, transmittance or absorbance are not directly measured. Historically, as we described in the previous section, filter photometers introduced to the measurement of the intensity of light and to the transmittance, T , that is, the ratio between I_0 (intensity of the light source) and I (intensity of light after passing through the solution of a specimen). To measure the intensity I_0 the light is passed through a reference solution that usually contains the solvent alone (Jensen 2014b). In the experiment reported in Fig. 13, a RGB analyzer application on a smartphone, for instance, can be used as the light detector. Student may use the R, G, B channel values as light intensity values by estimating the color of light that is absorbed by a colored solution of a chemical species (Carpentieri et al. 2022).

Students continue to explore the Lambert–Beer law by focusing on the measurement of the intensity of light and no longer on the intensity of color. In addition to the three elements of a basic spectrophotometer, namely a light source, a sample in a holder and a detector, a fourth one can be inserted, namely a wavelength selector. This is relevant to understand the key role of the monochromator in modern spectrophotometric instruments. Experiments as the one represented in Fig. 13 can be furtherly modified and adapted with a homemade filter photometers and bench spectrophotometers to compare the fitting of data by using the Lambert–Beer equation. This experiment highlights the issue that was the

chief limitation of historical filter photometers, namely the breadth of the band of wavelength (Lewin 1960a; Altemose 1986; Jensen 2014b) which can cause deviations from the Lambert–Beer law. The strategy of reasoning on a piece at time of the Lambert–Beer equation and its elements according to us could help students to add significance to it and promote conceptual understanding of all the implications of this fundamental law. As we argued in the introduction of this paper, conceptual learning is actually superior to algorithmic learning as the former help students to understand deeply the unique features of a topic (Pushkin 1998; Stamovlasis et al. 2005).

Another aspect we would like to underline in this work is the role of scientific museums and collections of historical scientific instruments in chemistry education. As previously reported (Domenici 2008, 2022, 2023a), scientific collections have extremely high potentialities as non-formal context of learning and teaching. The possibility to explore the evolution of scientific instrumentations and devices specific to chemistry, such as the glassware (Domenici 2023a), represents a great stimulus for chemistry teachers in the planning and design of lessons and/or laboratorial activities for their students. On the other hand, the visit to a science museum with students, either high school students or undergraduate ones, has positive effects on their engagement and development of high order thinking skills (Domenici 2022). In this paper, we were inspired by some historical spectroscopic instruments held at the Department of Chemistry and Industrial Chemistry at the University of Pisa (Historical History Museum at DCCI 2024) and at the ‘Primo Levi’ Museum of Chemistry host inside the Department of Chemistry of the University ‘La Sapienza’ in Rome. These instruments are usually seen by the visitor of the museums as static historical objects, however, they can tell a great history and, as explored in recent works (Carpentieri et al. 2022; Domenici 2023b), they can be used for didactic and laboratorial activities. In the present work, we have shown as historical scientific instruments relate to the history of spectroscopy, and their deep knowledge, can inspire several experiments about central ideas and key-concepts that are typically presented at school on a sub-microscopic and symbolic levels, instead of a macroscopic/phenomenological one.

Conclusions

The present work is focused on a deep reflection about how UV–vis spectroscopy is commonly taught at high school level and first introductory undergraduate courses. In the framework of chemistry educational learning and teaching models, an original topic specific version of the Johnstone’s triangle applied to the topic of UV–vis spectroscopy is here proposed and discussed. From the analysis of the actual way of teaching UV–vis spectroscopy, it emerges that the macroscopic level of the ‘UV–vis spectroscopy triangle’ is not commonly treated at school, despite of its fundamental role as already highlighted by Johnstone (Johnstone 1993). Starting from these considerations, we decided to focus on the evolution of spectroscopy through history to search significant aspects which could help chemistry teachers to introduce key concepts of UV–vis spectroscopy at a macroscopic level. In the present paper, we have selected several fundamental steps in the development of historical instruments and relevant historical experiments starting from the first spectrophotometers realized in the 1860s to observe the emission and absorption spectra to the modern spectrophotometers commonly found in analytical chemistry laboratories. For each historical instruments or experiments we have identified the key ideas and concepts related to the macroscopic vertex of the ‘UV–vis spectroscopy triangle’ that are not usually addressed at

high school level. Based on this analysis, a sequence of experiments and activities has been proposed inspired by these historical instruments to let students observe and directly experience several central aspects of UV–Vis spectroscopy, such as the absorption of light, the relationship between fading or disappearance of a color and the phenomenon of absorption of a particular wavelength of light, the role of the optical pathlength and the concentration in the intensity of absorbed light, the meaning of the molar attenuation coefficient and so on. As reported for other relevant topics in chemistry (Quílez 2004, 2019) the historical/epistemological approach was of help in analyzing the topic of UV–vis spectroscopy from a didactic and educational point of view. The experimentation of the whole didactic sequence proposed and discussed in this paper with high school and first year undergraduate students is still in progress, and it represents the further step of our research investigations.

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Author Contributions Maria Antonietta Carpentieri: conceptualization, investigation, methodology, formal analysis, writing—original draft preparation. Valentina Domenici: conceptualization, methodology, supervision, funding acquisition, project administration, writing—review & editing.

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Declarations

Conflict of interests There are no conflicts of interest to declare.

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