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Using analogies for introducing synchrotron light in high school

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Abstract: The aim of this paper is to propose the use of analogies for teaching principles of synchrotron radiation for high-school students. Analogy is an important tool for teaching new abstract subjects based on familiar content. In this paper, we suggest the use of Teaching With Analogies Strategy (TWAS), which is an approach to overcome the didactic obstacles in introducing abstract physics content to students. The authors expect that this work may contribute to the students' understanding of synchrotron radiation, reflecting the needs and interests of secondary school teachers.
Keywords: teaching physics with analogies; synchrotron light; high school teachers; physics education; physics teaching

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Introduction

There is a consensus among physics education researchers regarding the need for the inclusion of modern and contemporary physics in high school (Pessanha, Pietrocola, 2017). One of those topics is synchrotron light (Arce-Larreta *et al*, 2021; Micklavina, Almqvist, Sörensen, 2014). By synchrotron light (SL) or synchrotron radiation (SR) we understand the electromagnetic radiation emitted by a charge that moves with relativistic velocity and undergoes an acceleration perpendicular to its velocity, having polarization properties. SL is emitted by a charge moving in an arc determined by a deflecting magnetic field. This radiation is observed in extragalactic sources such as the Crab Nebula. It is also produced on Earth in SL laboratories. SR does not have the same emission pattern as blackbody radiation, that is, it is non-thermal. Its intensity, unlike blackbody radiation, increases towards lower frequencies. It also has characteristic polarization in the plane perpendicular to the magnetic field around which the charges are spiraling. SR is intense, collimated, and has a broad spectrum, ranging from infrared to x-ray. This spectrum can be modified by varying the curvature of the trajectory. Thanks to its unique properties, SL has become a research tool in various fields of science. This radiation can be used as a super microscope, probing dimensions of atomic orders.

There are currently around 50 synchrotron light sources in operation in just over 20 countries. SL sources are multidisciplinary laboratories, and their applications are linked to the production of technology, the production of medicines, the identification of diseases, the development of new materials, among other applications that are important for the development of a society.

It has been suggested that the involvement of teachers and students in activities involving accelerators and synchrotron facilities has a high impact on education (Arce-Larreta *et al*, 2021;

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Micklavina, Almqvist, Sörensen, 2014). Motivated by a recent in service teacher training course in SL, (Acioly *et al*, 2020; Acioly *et al,* 2021) , held in the new Brazilian SL source, at the National Center for Energy Research and Materials, Campinas , Brazil, this paper presents alternatives for High School teachers to apply in their classes the contents of physics and existing applications in synchrotron light sources. As these contents need to be taught in some way in the school curriculum, this paper aims to present some strategies to adequately address them.

Method: Teaching With Analogies Strategy (TWAS)

There are some didactic-epistemological barriers linked to the didactic transposition of modern physics in general and in SR in particular. Pessanha and Pietrocola (Pessanha, Pietrocola, 2017) suggested four kinds of didactic-epistemological obstacles in contemporary physics: phenomenology, language/formalization, conceptual structure, and ontological. The phenomenological obstacle is due to fact that the SR associated phenomena are not accessible in everyday life or in High School labs as simple experimental set-ups. The language/formalization obstacle appears since the SR mathematical formalism cannot be transposed to the school with basic algebra and geometry. This difficulty can be removed by using conceptual and qualitative concepts, for instance, through analogies. The conceptual obstacle is because the concepts present in SR are non-intuitive. Finally, the ontological obstacle owes to the fact that the SR subjects are not part of common sense such as photons or quantum energy.

An analogy is a comparison based on similarities between two concepts (Kipnis, 2005; Glynn, Duit, Thiele, 2012; Treagus, Harrison, Venville, 1998), one known and one unknown, more specifically, analogy is a mapping from a base domain to a target domain. Teaching is successful when the ideas of the target domain can be aligned with the apprentice's knowledge (base domain). Thus, teaching with analogies (Glynn, Duit, Thiele, 1995; Gentner, Holyoak, 1997; Harrison, Treagust, 2006) grants learning based on previous knowledge. The advantage of using analogies depends on both the learner's understanding of the base domain and on the efficacy of the mapping linking the two ideas.

Results and Discussion: Analog strategies for the application of concepts present in synchrotron light sources in high school

To make a physics class more attractive for high school students, we can use different strategies such as the use of experimental demonstrations (Araújo, Abib, 2003) and the use of analogies (Santos, Nunes, 2013). Didactic transposition (DT) (Chevallard, 1991) is a useful tool to bring the contents present in research centers to high school. DT is an adaptation of scientific knowledge for pedagogical and educational purposes, to make connections between different types of knowledge. Chevallard (Chevallard, 1991) defined DT as the process in which a content undergoes a set of adaptations to become able to occupy a place among the teaching objects. Teaching with analogies is an example of DT.

As an initial example of using analogies for teaching, it is possible to explore the clear application of the interaction of radiation with matter in SL sources, the photoelectric effect. There are suggestions in the literature on how to introduce the photoelectric effect to high school students (Barretto, 2022; Whalley, 2005; Kovacevic, Djordjevich, 2006). In the following, we present some strategies for high school teachers to investigate this topic, using analogies based on SR.

Production of SL at the storage rings

When a charge is accelerated, it emits radiation, but for this radiation to be effective, it is necessary that the energy generated by this acceleration (in the form of photons) has traveled great distances from the initial position of the charge. As a result, only a part of the energy flow produced by this charge manifests itself as radiation, and part of this energy accompanies the charge along the entire trajectory.

An analogy that suggests a visualization of this phenomenon is represented by Machado (Machado, 2006), in which he suggests imagining flies around a garbage bag. From there, as we slowly move the bag, the flies will follow. However, as we move it faster, some may move too far away from the bag. The flies that remain around the bag are analogous to the portion of the electromagnetic field attached to the charge. The flies that move away from the bag represent the radiation emitted by the load. To illustrate the generation of SL, we can use analogies like this one.

Another example is when we think of a vehicle with a light on making a turn, where it is constantly illuminating a certain region. The path taken by light, on the tangent, is the representation of SR, when a beam of relativistic electrons bends due to the dipole.

Figure 1 shows the geometry of SR in two situations: in part A the geometry of the radiation emitted by the accelerated charge when its speed is much lower than the speed of light, essentially exhibiting a dipole component. In part B, the figure shows angular collimation, with a small aperture angle, when its speed is comparable to the speed of light. In this case, the radiation is analogous to a searchlight or lighthouse emitting radiation in the same direction of motion as the electron.

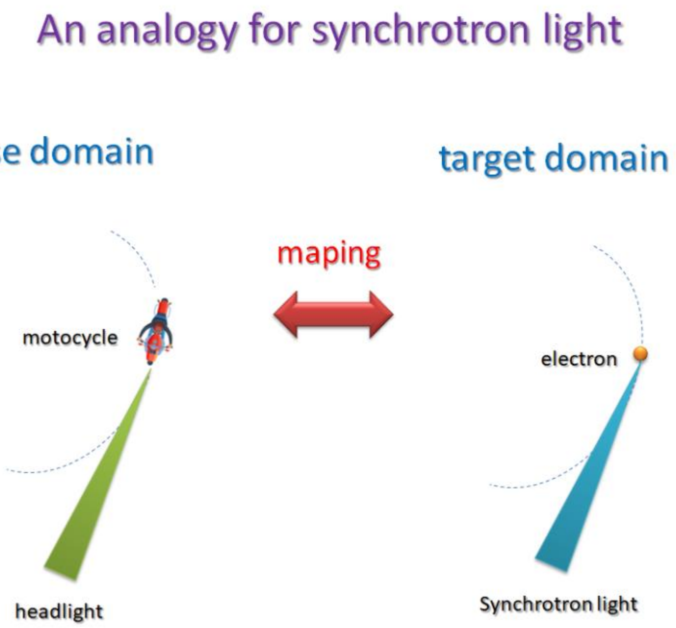

Figure 1. Emission patterns of an electron in a circular orbit. Base domain the headlight of a motorcycle; Target domain: the radiation pattern emitted by a relativistic electron in a circular orbit

Atomic absorption: a spring-mass system

Themes that relate the interaction of a classical oscillator with electromagnetic radiation, through the discussion of atomic absorption, appear in curricula in the subjects of the introduction of modern physics, and present the emergence of spectral lines (Santos,2020; Velloso, Acioly, Santos, 2020). We can consider a very simple model of an electron bound to an atomic nucleus and subject to the action of an incident photon. In a classical model, we could represent the electron subject to a central Coulomb force due to the nucleus. This electron has its own (natural) frequency due to the nucleus, which is also an elastic restoring force. The electron-core system forms an oscillating dipole, giving rise to a radiation field due to the oscillation of the accelerated electron. But we have seen that an accelerating charge emits radiation, so the electron must be subjected to an extra force, known as a radiation reaction, analogous to a damped oscillator. For High School, we suggest using the mechanical analogue, the forced and damped mass-spring system Fig. 2.a and Fig. 2.b.

a) System of interest b) Analog system

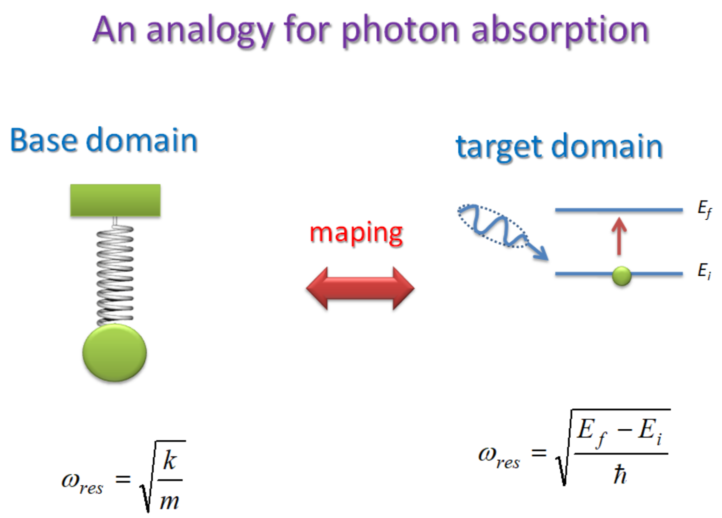

Figure 2. An analogy for the resonant atomic absorption process (target domain). When the frequency of the incident photon coincides with the resonance frequency of the atomic system, absorption occurs. Base domain (The analogous mechanical system): a spring-mass system with its characteristic frequency

There are several works suggesting how to apply these contents in high school using low-cost materials such as stopwatches, pendulums, and free software (Bonventi, Aranha, 2015; Santos, 2013). The construction of these concepts needs to be a sequence of wave content, in which the teacher will work on the amplitude, period and frequency, then moving on to simple harmonic motion, to introduce the damped and forced oscillations, which are traditionally worked only in the university levels.

Another Suggestions for other applications that are already in the literature

In addition to the analogies, we suggest, for future works, the approximation of the concepts present in synchrotron light sources with other strategies, such as the use of low-cost materials, the elaboration of experiments with easy access to the student and the use of history as construction of the concepts, as the following three examples show.

The use of CD and DVD as a diffraction grating

The phenomena of reflection and diffraction are present in the daily lives of students and in synchrotron light sources, in addition to being relatively attractive due to the easy-to-understand examples. Monochromatizating is a phenomenon that involves both concepts. To illustrate X-ray monochromatizating, it has been suggested to use CDs and DVDs as a teaching strategy (Kettler, 1991; Catelli, Libardi, 2010).

Conceptual, historical, and experimental approach of electric and magnetic fields to represent the movement of electrons in the synchrotron

Electromagnetism is part of the curricular structure of basic schools in the final stages of studies, and the representation of the movement of protons in the LHC or of electrons in Sirius, can be worked with simple examples.

A first example is the reason why the particles align and perform the movements in these large machines, which is their immersion in magnetic fields, which can be represented with the use of magnets and easily accessible ferromagnetic materials, such as coins and paper clips. Another example is to show that circular accelerators are not necessarily a circle, but a polygon with many sides, in which in straight lines the particles gain speed due to electric fields, and in curves they maintain a constant speed, immersed in the magnetic field.

The use of some of these approaches, both historical (Magalhães, Santos, Dias, 2002), and in the construction of low-cost experiments (Moraes, Alves, Novais, 2019; Macedo, 2016) are already some examples for the construction of the concept of electric and magnetic fields, which contribute with several methodological proposals using the concepts of particle accelerators in basic education (Sinflorio et al, 2006; Wiener et al, 2016).

How to see light beyond the visible: Infrared

Synchrotron light comprises electromagnetic radiation ranging from infrared to x-ray. To approximate the contents of radiation that are not visible to the human eye, there are several suggestions with accessible materials (Micha et al, 2011), and that are on the border of the visible spectrum, such as infrared.

Cell phones cameras and webcams can be used to bring the understanding of light in the infrared frequency closer to students. For instance, the detection of infrared light emitted by remote controls by cell phone cameras, after removing the infrared filter may produce visible images as for example, the recording of the heating of a resistance connected to electrical energy (Micha et al, 2011).

Conclusion

The radiation generated by a synchrotron light source is more present in our lives than we realize. This work ends with proposals to bring the concepts present in modern science closer to the concepts found in high school, through easy-to-understand analogies and examples. This is a research initiative in physics teaching that was motivated by the Sirius School for High School Teachers (ESPEM).

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