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Reconstructing the history of light and the birth of photon: Integrating nature of science into introductory quantum mechanics

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Abstract
History of science (HOS) in physics education constitutes an established research domain, with many scholars arguing that HOS can support learners' understanding of both scientific concepts and the nature of science (NOS). The history of light and the birth of quantum mechanics (QM), in particular, are philosophically rich domains whose historical development offers strong potential for NOS-focused science instruction. Despite this potential, HOS-informed approaches within QM and physics teaching have not yet become mainstream classroom practice. One major barrier is the limited availability of accessible HOS-based teaching resources that align with existing curriculum requirements and can be readily implemented by teachers. To address this gap, we present a reconstruction of the history of light, tracing developments from medieval theories of vision to the modern quantum concept of the photon through a sequence of eight historical episodes. The resulting narrative is an educational science story that aligns with introductory QM curriculum and is designed for flexible implementation across diverse educational contexts, including optics and QM instruction, while facilitating NOS learning in regular physics or science lessons. The educational story was pilot tested in a high school in the Philippines with year 9 students. Based on our implementation experience, in addition to the historical narrative, this paper also presents pedagogical strategies and practical guidance for classroom instruction. We discuss considerations for adoption of the story in regular schools, curriculum development, and NOS-related research.

Keywords: nature of science, physics education, history of science, quantum physics, high school, photon, photoelectric effect, storytelling, instructional material

INTRODUCTION

Advocacy for incorporating history of science (HOS) into physics education is well established, with historians of science and physics educators consistently arguing that it enhances conceptual understanding, fosters positive attitudes, and supports students' understanding of the nature of science (NOS) (Thomas Becker et al., 2024). While various HOS-based teaching approaches exist—including reperforming historical experiments, historical case studies, role-play, and storytelling—historical storytelling has gained particular attention due to its affective and cognitive benefits for student learning (Güler & Ünal, 2023; Maharaj-Sharma, 2024; Tuveri et al., 2024). However, empirical studies on designing and implementing HOS-based storytelling in physics education remain limited, with a recent systematic review concluding that the research on HOS-informed physics teaching is "*primarily theoretical*" with little attention to "*concrete implementation*" (Thomas Becker et al., 2024, p. 3041).

Although HOS in physics education is a well-established research domain, HOS-informed teaching has not yet become mainstream classroom practice. Two main reasons account for this gap. First, the lack of a structured theoretical framework for constructing science narratives has long hindered the development of physics-specific historical stories. This gap was addressed by Klassen (2009), who proposed a comprehensive framework for designing science stories,

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Contribution to the literature

- We reconstructed the history of light and present it as an educational story that aligns with introductory QM course content at both high school and undergraduate level.
- We utilize historical events as gateways for integrating NOS learning with regular classroom science instruction about the properties of light and the photon concept.
- The story is presented with a practice-oriented approach, including practical implementation strategies and classroom guidance informed by the primary author's experience piloting the narrative in grade 9 high school classrooms in the Philippines.

which was subsequently applied successfully in biology education by other researchers (Dai et al., 2021; Williams & Rudge, 2019). However, few studies have utilized Klassen's (2009) framework in physics education contexts, and fewer still report detailed design and implementation experiences from quantum mechanics (QM) topics using this framework.

Second, designing HOS-based teaching resources presents significant practical challenges. Teachers face various obstacles such as insufficient instructional guidance, limited preparation time, difficulties selecting appropriate historical events, and uncertainty regarding primary sources (Forato et al., 2012; Henke & Höttecke, 2015; Höttecke & Silva, 2011). Additionally, concerns about subject-matter expertise, the complexity of historical content (Leone & Rinaudo, 2020), and perceived limited relevance of HOS for standardized assessments further reduce adoption of HOS by teachers (Lima et al., 2024). Further, the scarcity of curriculum-aligned HOS-informed physics teaching materials and limited historical content in textbooks constrain implementation (Henke & Höttecke, 2015; Niaz et al., 2010). Developing physics-specific historical stories using a structured framework could therefore generate implementable teaching resources and enable further empirical investigation of their educational value.

In response to these gaps, specifically the scarcity of readily available, curriculum-aligned HOS-based physics teaching resources, this paper presents a historical science story on the nature of light as an instructional product, together with a presentation of how the product can be implemented in the classroom. We employed Klassen's (2009) framework—which draws from narrative explanation theory—to design our story and provide detailed implementation guidelines based on our implementation. The story traces the history of vision, light and the birth of the photon concept, aligned with introductory QM curricula typically covered in secondary and undergraduate physics (Krijtenburg-Lewerissa et al., 2017; Stadermann et al., 2019). The narrative is structured through eight episodes, each with a clearly articulated pedagogical purpose and accompanying implementation strategies informed by our pilot testing with year 9 students.

The presented story is a final instructional product that was developed after identifying and applying specific design principles from existing literature. In this paper, we focus on the product itself, which has intrinsic value for instructors as a ready-to-use resource that does not add excessive workload and reduces barriers for classroom implementation. Any instructor can implement and integrate the historical episodes presented here with the pedagogical implementation strategies provided. We acknowledge that a detailed process underpinned the development of this product, involving the identification of fundamental design principles for HOS-based teaching sequences and the application of those principles to develop a theoretical framework that guided the story's design, development and implementation. Detailed studies presenting the design principles, the process of identifying those principles, and the theoretical framework guiding the work are currently under preparation and will be communicated in future publications. This approach will broaden the scope and enable these principles to be applied to other physics topics.

The presented story is addressed to both teachers and researchers. Teachers can directly use the written narrative and implementation strategies, whereas for the research community we have provided historical details along with primary sources that assisted in developing the narrative. In our presentation of the story in this paper, we provide additional commentary based on our implementation experience and how we utilized each historical episode to achieve specific learning objectives. The story was communicated to students in two complementary ways. First, students received the written narrative as individual episodes corresponding to when the related topics were covered in the classroom. Second, we designed active learning activities around these historical episodes and related concepts. Thus, the story was operationalized through both the written narrative and active learning approaches structured around the historical episodes.

This paper is structured as follows. We first provide a brief literature review on the history of light and the photon concept, along with documented student learning difficulties on these topics and a brief sub-section defining NOS in this research. We then present the objectives and rationale for our choice of topic for the story. Next, we detail the narrative together with descriptions of and guidance on instructional strategies.

After that, we discuss some additional considerations, potential limitations of story-based instruction. Finally, we present concluding remarks.

LITERATURE REVIEW

The literature in this section comprises three key areas that collectively informed the design of our story. First, historical accounts are presented that were utilized to teach NOS and conceptual knowledge related to the nature of light. Second, this review addresses documented student learning difficulties when engaging with light and photon concepts. Finally, this section concludes with a concise description of NOS as per existing literature and reform documents.

History of Light, Vision, and Light-Matter Interactions

The study of the nature and properties of light has occupied a special place in human history, igniting debates and curiosity not only within the scientific community but also among philosophers. Consequently, various studies, for example, Zubairy (2016) and Vohnsen (2004) have traced the historical development of understanding light. Similarly, Klassen (2011) and Stuewer (2000, 2006) cover historical episodes related to the photon concept and light-matter interactions, whereas some other studies highlight the quasi-historical accounts popularized in textbooks associated with these concepts (Klassen et al., 2012; Niaz et al., 2010; Persson, 2018). Studies of radiation phenomena such as blackbody radiation and radiation-matter interactions—including the Compton effect and photoelectric effect—have played a paradigm-shifting role in human understanding of nature, as these concepts ultimately resulted in the birth of QM (Ayene et al., 2019; Klassen, 2011; Stuewer, 2006).

Studies cited above are valuable scholarship as they provide historically accurate accounts of scientific development related to light and birth of QM. However, most textbooks do not include these historical accounts and mostly present an oversimplified quasihistorical account (Niaz, 2014; Niaz et al., 2010; Passon, 2022; Persson, 2018). For instance, Young's famous double-slit experiment is often presented to students as definitive evidence supporting the wave theory of light, marking the demise of Newton's corpuscular theory. However, a historically accurate account reveals a more nuanced picture. Thomas Young's contributions were largely overlooked for nearly two decades, as Newton's social stature and the influence of other French corpuscularists sustained the dominance of corpuscular theory even after Young's experiment (Frankel, 1976). It was not until approximately two decades later, when Fresnel and Arago provided compelling evidence for wave theory through the phenomena of diffraction of light, that Newton's corpuscular theory was completely abandoned in favor of wave theory (Frankel, 1976).

Similarly, while textbooks attribute the explanation of the photoelectric effect solely to Einstein's photon concept, few convey that classical wave theory-based and non-photon descriptions were initially considered plausible and more widely accepted than the photon theory for almost two decades after Einstein's landmark paper (Klassen, 2011; Niaz et al., 2010). Einstein's photon hypothesis was initially rejected by the scientific community. In a similar vein, the misconceived explanation that we see objects due to rays being emitted from our eyes—a theory known as extramission theory, was universally entertained for several centuries, corroborated by the work of ancient scholars and philosophers (Akdogan, 1984; Cottrell & Winer, 1994; El-Bizri, 2005; Lička, 2020; Lindberg, 1967).

In designing the story presented in this paper as well as the associated instructional strategies, we synthesized these historical papers, along with literature on effective NOS instruction from broader science education scholarship (Abd-El-Khalick et al., 2024; Bugingo et al., 2024; McComas et al., 2020) and designing science stories (Klassen, 2009; Norris et al., 2005).

Main Cause of Learning Difficulties Related to Light and the Photon Concept

Teaching concepts related to light—including both classical optics and the wave model, as well as quantum mechanical descriptions such as the photon model and light-matter interactions—is a challenging task (Balabanoff et al., 2020, 2022; Henriksen et al., 2018; Taslidere, 2016). These concepts are often counterintuitive to students' everyday experiences with light, such as feeling sunlight or observing rainbows (Balabanoff et al., 2020). Notably, even the classical wave model is abstract and counterintuitive; phenomena like diffraction and interference, traditionally taught through the classical electromagnetic (EM) wave model, are not directly observable through daily experiences. As Galili and Hazan (2000) state, a learner's everyday experiences neither confirm the wave nature (classical description) nor the particle nature (quantum model) of light. Instead, light appears to the learner as a continuous and stationary entity. Macroscopically observable optical phenomena are simply a result of countless interactions at the microscopic or quantum level, which human senses cannot directly observe. Thus, students develop many deep-rooted misconceptions that germinate from their everyday experiences with light, which often do not align with established scientific knowledge and explanations of these phenomena (Taslidere, 2016). This makes it difficult for teachers to address students' alternate conceptions, and in many cases, these misconceptions persist even after formal instruction (Yalcin et al., 2009). Primary reason for this is that students often fail to appreciate the abstract and functional role of scientific models and instead view them as something physical (Schmid et al., 2026; Ubben & Bitzenbauer, 2023).

Furthermore, when students progress to quantum mechanical frameworks, the difficulty intensifies, particularly when addressing phenomena like the photoelectric effect. Such understanding requires conceptualizing sub-atomic interactions and forms of light beyond direct observation (Balabanoff et al., 2020, 2022; Özcan, 2015). Unlike other physical sciences where tangible experiences may facilitate reasoning, understanding properties of light demands abstract thinking at both classical and quantum scales. Consequently, learners frequently struggle to reconcile fragmented classical ideas with counterintuitive quantum concepts. Numerous studies have shown that students inconsistently apply classical and quantum models of light to explain light-matter interaction (Balabanoff et al., 2020; Özcan, 2015; Taslidere, 2016). Even when providing "correct" answers, students' underlying reasoning may be flawed due to lack of understanding about the roles of scientific models in explaining the nature of light (McKagan et al., 2009; Özcan, 2015; Steinberg et al., 1996; Taslidere, 2016). This poses a significant challenge for teachers who have to design creative instructional tools to make those concepts more accessible and concrete for their students.

The nature of learning difficulties described above, specifically, lack of a functional understanding of models to describe light (Bitzenbauer & Ubben, 2025; Ubben & Bitzenbauer, 2023; Ubben et al., 2023), indicates that a NOS approach to QM education may be beneficial in addressing some of these misconceptions. For instance, if explicit attention is given to communicating the inferential NOS (Abd-El-Khalick et al., 2024, p. 1681), this will promote a more functional understanding of scientific models in QM. This may in turn enhance conceptual clarity about the nature of light and light-matter interactions (Bitzenbauer & Ubben, 2025; Ubben & Bitzenbauer, 2023). Below, we briefly describe how NOS is defined in our research.

What Is the Nature of Science?

NOS refers to the epistemological foundations and characteristics of scientific knowledge and scientific inquiry (Eshach et al., 2013; Lederman, 2013). There is no universal definition of NOS (Kampourakis, 2016). However, there is consensus on several common characteristics of science and how scientific knowledge is produced. This view posits that scientific knowledge is (Abd-El-Khalick et al., 2024; Bell et al., 2003; Kampourakis, 2016; Liang et al., 2008):

(a) empirical, based on observations and evidence,

(b) trustworthy, yet tentative and subject to revision as new evidence emerges,

(c) based on inferences, as scientists cannot directly observe most phenomena they study but make various inferences to explain those observations,

(d) creative with imagination being an integral part of any scientific investigation,

(e) not generated through a rigid step-by-step "scientific method",

(f) affected by society and culture, and

(g) subjective or theory laden, i.e., scientists' theoretical background and personal beliefs may affect their interpretations and observations.

Furthermore, the consensus view entertains a distinction between scientific laws and theories, the two being equally valid yet different forms of knowledge. Contrary to popular belief, in addition to theories, scientific laws can also be modified, changed and abandoned in light of new evidence (Abd-El-Khalick et al., 2024).

Explicit instruction in NOS is crucial for developing scientific literacy and fostering students' understanding of how scientific knowledge is generated and advanced (Khishfe & Abd-El-Khalick, 2002; Rudge & Howe, 2009). In designing our story, we incorporate aspects of NOS to help educators address some of the most challenging learning difficulties associated with this topic. Where relevant, we emphasized NOS aspects using an explicit-reflective NOS instructional approach (Rudge & Howe, 2009), building on reconstructions of specific historical events to model how instructors can use these historical episodes to integrate NOS learning in their instruction.

OBJECTIVES AND RATIONALE

Objectives

The main objectives of this paper are to:

(1) reconstruct the history of light and the birth of the photon concept as a science story that aligns with course content of introductory QM;

(2) present the story as a ready-to-use instructional material providing guidance for integrating NOS learning with the science content; and

(3) share descriptions of and insights from implementing this story in a year 9 classroom.

Rationale for Focusing on the Story of History of Light

There are three main reasons we chose to present the history of light as an educational story. First, the topic of light demonstrates broad applicability across educational levels—from primary school science (colors, vision, eyes, and light sources) through to advanced STEM courses at university (e.g., lasers, nanomaterials, optoelectronics, semiconductors, and quantum technology). Consequently, parts of our designed story and individual NOS-focused episodes are relevant

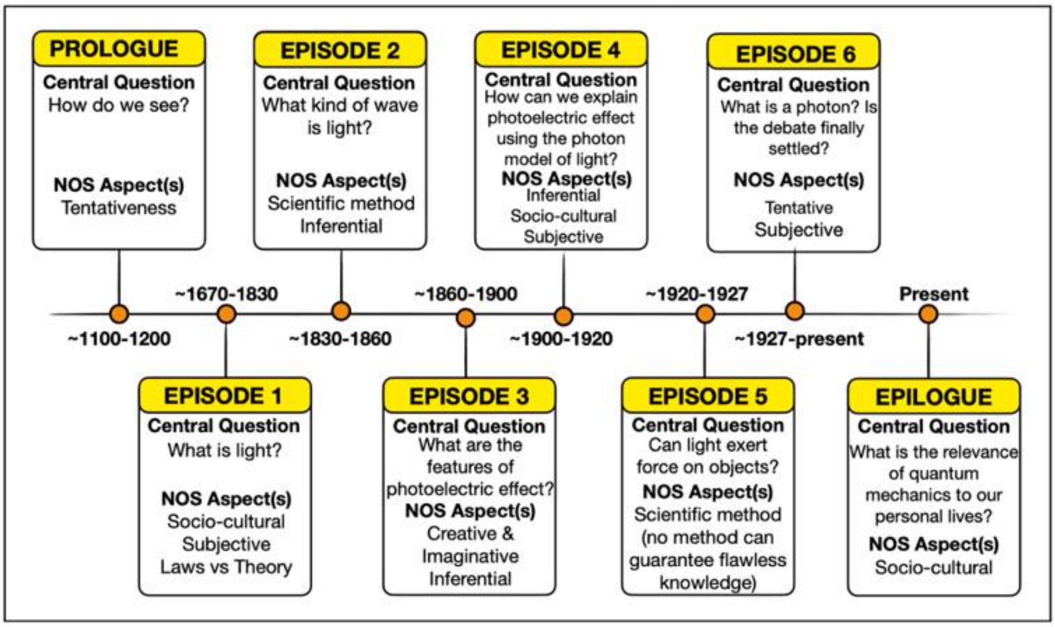

Figure 1. Visual summary of our story comprising eight episodes, including one prologue and one epilogue (each episode presents a central question alongside easily accessible target NOS aspects corresponding to that episode) (the authors' own elaboration)

across diverse educational contexts and student populations. Therefore, the individual historical episodes can be readily adapted and integrated to suit varying learner needs. For instance, the Prologue aligns with primary school science, introducing mechanism of vision to learners aged 10-13 (de Hosson & Kaminski, 2007). Contents of Episode 1-Episode 4 and Episode 6 of our story align with typical high school QM curricula, covering the photoelectric effect, photon concept and wave-particle duality (Stadermann et al., 2019).

Finally, Episode 5 and the epilogue are better suited for undergraduate level, where light-matter interactions, superposition, and entanglement are typically covered in detail (Krijtenburg-Lewerissa et al., 2017). At higher educational levels, Episode 5 can be extended with mathematical tools such as semi-classical approaches to light-matter interaction. In our story, we introduced the photon concept, citing the inadequacy of the wave model of light. However, as pointed out by Passon (2022), after 1927, semi-classical methods wherein light is treated as an electromagnetic wave interacting with quantum entities (atoms) do not require the photon for explaining the photoelectric effect. Thus, these additional details can be strategically introduced or removed depending on educational level and learning objectives.

Second, as will become evident in the story itself, the history of light provides rich opportunities for accessible NOS learning, with each historical episode providing unique opportunities for reflection on NOS within regular classroom teaching. Third, the nature of light, starting from the EM radiation model to the photon description, is typically how QM is introduced to students at any introductory course in high school and/or undergraduate level (Krijtenburg-Lewerissa et al., 2017; Stadermann et al., 2019).

Some episodes in the presented narrative form part of the historical narrative of the photoelectric effect and the photon concept. Klassen (2011) provides a detailed historical account of the photoelectric effect, and much of the inspiration for this work along with the larger research project of which this study is part stems from Klassen's (2009) pioneering work on storytelling in science education (Klassen & Froese Klassen, 2013). While Klassen's (2009) work establishes the historical foundation and addresses quasi-history, our approach differs fundamentally: we aim to highlight the utility of Klassen's (2009) narrative approach for NOS learning within mainstream teaching by piloting and reporting our experience-based strategies. We emphasize how to enact and implement this history in the classroom, demonstrating how each episode connects to the larger narrative arc and how we utilized this story to achieve specific NOS and conceptual learning objectives.

THE STORY OF LIGHT AND THE BIRTH OF PHOTON

To achieve the objectives mentioned above, the primary author crafted a historically accurate science story tracing the development of knowledge related to the nature of light. The story is titled "*The story of light: Journey to the birth of light quanta*". The historically accurate narrative is composed of eight episodes, as shown in **Figure 1** (one prologue, six main episodes, and one epilogue), designed to integrate NOS learning with introductory QM concepts. The narrative has been trialed through empirical testing with high-achieving year 9 students in a school in the Philippines, spanning six 50-minute teaching sessions. The narrative aligns with the year 9 instructional course titled "introduction to quantum theory". The course content consists of topics such as blackbody radiation (qualitative), EM radiation model, photoelectric effect, and wave-particle duality.

The eight episodes of the designed educational science story address (**Figure 1**):

(a) intromission theory of vision overthrowing the prevailing extramission theory;

(b) controversy regarding the wave versus particle theories of light;

(c) theoretical prediction of EM waves by Maxwell and Hertz's experimental confirmation, resulting in the "accidental" discovery of the photoelectric effect;

(d) Lenard's systematic experimentation on the photoelectric effect and his trigger hypothesis;

(e) Einstein's revolutionary proposal of the light quanta and its initial unanimous dismissal by the scientific community,

(f) the Compton effect resulting in final acceptance of Einstein's photon concept;

(g) wave-particle duality within the context of single-photon interference; and

(h) modern applications of the photon in quantum computing and existing technologies and the aftermath of the acceptance of photon.

While typical textbook treatments employ quasi-historical approaches that overlook pedagogically valuable historical facts (Klassen et al., 2012; Niaz et al., 2010), the designed/proposed narrative spans a broader historical scope, from ancient vision theories through to modern quantum mechanical treatments of light and includes some historical aspects that are often neglected in textbooks. In the following sub-sections, we first briefly describe how the narrative was implemented in practice during our pilot experiment. Next, we present the story.

Implementation Strategies and Recommendations for Integrating the Story with Classroom Teaching

How the story was communicated to students in our teaching experiment

In our teaching experiment, the science story was delivered to students in written form as individual episodes. Each episode was provided as a reading preamble on guided worksheets on the day the related topic was introduced in the classroom. For instance, when the EM wave model of light and the photoelectric effect were introduced, students received a worksheet containing Episode 2 of the story. This episode covered Hertz's discovery of radio waves, the accidental discovery of the photoelectric effect, and the initial features observed by Hertz and later by Hallwachs (Klassen, 2011). Students were advised to read the preamble carefully before attempting the worksheet exercises. The written narrative within each guided worksheet directed student engagement with subsequent collaborative classroom activities and formative assessment exercises. The narrative text presented to students was largely similar to that shown here, with minor stylistic adjustments; for student ease of reading, the story was presented without references. In this paper, we present the story with full references to maintain an academic tone and to guide readers to the historical sources we consulted. Further, the references and primary sources presented with the narrative may be of value to research scholars interested in HOS or designing HOS informed teaching resources.

In the guided worksheets, the reading preamble was followed by collaborative exercises that targeted both science content and enacted explicit reflective NOS learning through the story (Rudge & Howe, 2009). For instance, to supplement classroom teaching corresponding to the content of Episode 2, the following is an example of how we used the historical episode to enact explicit reflective NOS instruction:

> Let us discuss what we learnt about the "method of scientific investigation". Now, let us reflect on Episode 2 and consider the methods scientists use in investigations. Compare the approaches taken by Maxwell, Hertz, and Hallwachs (this was followed by brief description of each scientists' approach to highlight the difference between theoretical and experimental research). Based on these examples and comparing the approaches of earlier scientists in the story (Alhazen, Newton, and Young), what can you conclude about the methods of scientific investigation? (a) Is there a universal scientific method, or do different scientists use different methods?

Similarly, the historical events covered in the story were also used to guide students towards target scientific concepts. For instance, continuing with the example of Episode 2 mentioned above, through a YouTube video, students engaged with a visual demonstration of Hallwachs' experiment on the photoelectric effect (QuantumBoffin, 2021). Using a predict-observe-explain approach, they predicted the effects of visible and ultraviolet light on a negatively charged zinc plate, then observed the demonstration and explained their observations. This approach was replicated across all teaching sessions, where relevant historical episodes were shared as preambles within guided worksheets alongside diverse learning activities such as YouTube videos (FloatHeadPhysics, 2024; Inventions, 2018), experimental demonstrations, teacher questioning (Tawfik et al., 2020), guided worksheets, and interactive simulations (Supurwoko et al., 2017; van den Berg et al., 2020; Wieman et al., 2008).

In the following subsections, we present the story in eight episodes. We have separated the main content of the story, i.e., the narrative text, from our pedagogical commentary. The indented block of text at the start of each episode provides a synopsis of instructional strategies based on our implementation, as well as instructor guidance and commentary on the narrative. The regular text below the indented text presents a detailed account of the historical events, i.e., the story narration. Each episode concludes with a "*pedagogical rationale and achievable learning goals*" section that highlights the most readily communicable NOS aspects and science concept that can be taught via that historical episode.

Prologue – Al-Haytham's Lamp to the Future

> We begin instruction with the question: "How do we see?" Vision and light are closely related concepts, yet curricula often address light without discussing vision theories. In our intervention, we used this episode as an opportunity to introduce the socio-cultural dimension of science. Specifically, we conveyed to students that diverse cultures—from ancient India and China to the Greek and Arabic worlds—contributed towards understanding vision, emphasizing that science is a collective human endeavor. We used the central question of this episode to elicit learners' prior conceptions about vision, which enabled us to anticipate their existing understandings and misconceptions. Further, we used this episode to achieve other NOS-related learning objectives. Specifically, we conveyed to students that what they take for granted today—that we see because light enters our eyes from an external source—was not the accepted fact for many centuries. Conversely, what they may find absurd—that light is emitted from our eyes—was once considered established truth (Cottrell & Winer, 1994; Lička, 2020). This historical event conveys the tentative nature of scientific theories and the evolution of knowledge within scientific discourse. This question also allows instructors to diagnose students' alternate conceptions about NOS before challenging them by introducing competing historical theories. In our intervention, we used the YouTube video 1001 Inventions and the World of Ibn Al Haytham (Inventions, 2018) followed by guided inquiry worksheets that incorporated an explicit-reflective approach to promote NOS understandings (Voss et al., 2022).

Our story begins with a simple question that intrigued ancient civilizations for centuries: "*How do we see*?" This deceptively simple question introduces two competing theories of vision that dominated scholarly thought for centuries. Extramission theory proposed that light is not an external entity but rather emanates from the eyes, striking objects and revealing them to us (Cottrell & Winer, 1994; Lička, 2020; Zubairy, 2016). Intromission theory, by contrast, advocated that light is an external entity that enters our eyes, enabling us to see (Lindberg, 1967). What may appear intuitive and obvious today—that light is an external entity—was in fact not always scientifically accepted. Scholars such as Euclid and Ptolemy, through advanced reasoning encompassing perception of focus and attention supported by geometrical methods, argued that light is emitted from the eyes. Although few medieval philosophers challenged the extramission theory of vision, it continued to dominate the scientific discourse due to the reputation of its proponents. It was Ibn al-Haytham, in the 10th-11th century, who challenged this entrenched view by drawing on Aristotle's ideas, geometry, and rigorous experimental verification to advance intromission theory. Through carefully designed experiments, Ibn al-Haytham tested his theory, providing empirical evidence that contradicted the extramission model and confirmed that light is an external entity rather than something emitted by the eyes. His work, formally presented in the Book of Optics, gained widespread popularity in the West and ultimately led to the decline of extramission theory by the 11th century (Lindberg, 1967). Other theories of vision that predicted a mixture of both intromission and extramission were also prevalent during this period, reflecting the complexity of scientific thought during the medieval era (Akdogan, 1984; El-Bizri, 2005; Lička, 2020; Winer & Cottrell, 2004; Zubairy, 2016).

Pedagogical rationale and achievable learning goals

This episode can be used by instructors to bring forth the cultural richness of science. Contrary to typical textbook presentations, this approach highlights the significance of Al-Haytham's work and conveys to students that diverse cultures have contributed towards science, challenging the Western- and Euro-centric narratives often presented in curricula and textbooks (Chacón-Díaz, 2022) and portraying science as a dynamic, culturally embedded enterprise rather than a mere collection of decontextualized facts. Depending on classroom demographic composition, instructors can draw examples from scientific contributions belonging to the cultural contexts of their students, enabling them to recognize their own socio-cultural heritage within the HOS (Jardim et al., 2021). For instance, in our intervention with Filipino students, during implementation of this episode, we discussed the indigenous Filipino knowledge base and its contribution to scientific discourse.

Furthermore, this episode enables instructors to anticipate learners' alternate conceptions about vision.

For example, the misconception that light is emitted from the eyes is quite common (Cottrell & Winer, 1994; de Hosson & Kaminski, 2007; Winer & Cottrell, 2004; Winer et al., 2002). This historical parallel elicits students' current understanding while validating their thinking by demonstrating that their ideas were once endorsed by prominent medieval philosophers. This validation can simultaneously challenge them to reconsider their conceptions in light of empirical evidence. Additionally, this episode can be used to facilitate understanding of the tentative nature of scientific theories, illustrating that even ideas championed by intellectual giants, such as Ptolemy and Euclid, can be overturned through rigorous empirical investigation and that scientific acceptance requires both social validation and empirical evidence.

Episode 1 – The Debate Begins: Newton's Corpuscles Versus Young's Wave

After clarifying the nature of vision through intromission theory, we pose the next logical question to advance classroom discussion: "What is light?" To align classroom instruction with historical narrative, we use this question to introduce students to the characteristics of a wave and contrast it with properties of a localized particle: "Is light a collection of localized particles travelling in space; or a wave, like a ripple in water?" In our intervention, we used this historical episode to introduce Newton's corpuscular theory of light and compare it with Huygens' wave model (Frankel, 1976; Raftopoulos et al., 2005). We used this historical debate to clarify how contrasting explanations can account for the same phenomena—for example, reflection and refraction—as described differently by Newton's corpuscular theory and Huygen's wave theory. Through this, we highlighted the relationship between scientific laws and theories, and the subjective nature of NOS. Newton and Huygens described similar phenomena through completely different theories, yet their theories explained the laws of reflection and refraction equally well, and in some respects, both provided equally valid explanations. In later episodes, we recall Newton's corpuscles to introduce the quantum nature of photons, by comparing them with the classical light particles proposed by Newton that according to his corpuscular theory followed classical laws of motion. Additionally, we used this episode to communicate another critical NOS aspect: scientific acceptance depends not solely on empirical evidence but also on social and cultural factors. Contrary to popular belief, Young's double-slit experiment was largely ignored due to the social influence of corpuscular theorists, and corpuscular theory continued to dominate scientific discourse for many decades, with wave theory remaining sidelined (Frankel, 1976). We leveraged this lesser-known historical fact to demonstrate to students how institutional hierarchies and societal factors shape scientific progress. Many historical accounts similar to the one described above are often overlooked in mainstream teaching and textbooks in favor of a "quasi-historical" approach (Klassen et al., 2012; Niaz et al., 2010; Passon, 2022; Persson, 2018). The primary author, a physicist and physics scholar himself, was unaware of this historical detail and believed that Young's double-slit experiment marked the end of Newton's corpuscular theory, which, as Frankel (1976) highlights, was not the case.

Once intromission theory gained widespread acceptance, scientists pursued the next logical question: if light is an external entity, what are its fundamental properties? Two competing schools of thought emerged (Frankel, 1976). Newton formulated corpuscular theory, proposing that light consists of tiny particles (corpuscles) travelling in straight lines (Raftopoulos et al., 2005; Shapiro, 2002). This idea was embraced and developed by prominent French scientists, including Laplace, Malus, and Biot (Frankel, 1976). The opposing view advocated by the likes of Huygens, Hooke, Young, Arago, and Fresnel argued instead that light propagates as a wave, a disturbance travelling through a medium, rather than as discrete point-like particles (Frankel, 1976; Vohnsen, 2004).

Despite strong theoretical arguments by wave theorists, Newton's and other corpuscularists' formidable reputation ensured corpuscular theory's dominance for decades (Cantor, 1983, p. 9; Frankel, 1976). In 1801, Thomas Young performed the double-slit interference experiment, dubbed "*the most beautiful*" experimental set-up in physics (Crease, 2002; Rosa, 2012). Young's results showed interference patterns—the unmistakable hallmark of waves—providing powerful evidence that light was indeed a wave (Young, 1802, 1804). Despite presenting his findings to the British scientific community, Young's ideas gained little acceptance (Frankel, 1976, pp. 175-176). The authority and influence of French corpuscularists like Laplace, Biot, and Malus delayed wave theory's acceptance (Frankel, 1976).

Around 1819, Fresnel submitted a mathematical model to an *Académie des Sciences* competition predicting that light moves as a wave and can produce both diffraction and interference patterns (typical wave characteristics) (Vohnsen, 2004). Poisson, a committed corpuscularist on the evaluation committee, studied Fresnel's proposal and derived from Fresnel's model that a bright spot would emerge at the center of the shadow of an opaque circular disc—an impossible consequence he thought would refute wave theory (Vohnsen, 2004). Yet when Fresnel and Arago experimentally verified the prediction, the bright spot appeared, confirming diffraction patterns and demonstrating that light was indeed a wave. Fresnel won the competition, seemingly settling the debate (Forato et al., 2012; Frankel, 1976; Vohnsen, 2004). This episode appeared to convey the victory of wave theory, until an accidental discovery in late 19th century would again threaten the relevance of classical wave theory.

Pedagogical rationale and achievable learning goals

For NOS related learning objectives, this episode could be used to guide students to recognize that socio-cultural factors greatly influence scientific advancement and at times may even negatively impact science. Empirically and logically sound ideas from less influential figures may take considerably longer to gain acceptance, as exemplified by how Thomas Young's research was overlooked in French academic circles dominated by corpuscularists (Frankel, 1976). Despite providing compelling evidence for light's wave nature through the double-slit experiment, Young could not overturn corpuscular theory. Further, Newton's explanation of the laws of reflection and Huygens' contrasting explanation using wavefronts (Cantor, 1983) can be utilized as a pedagogical lever to convey the relationship between scientific laws and theories—that is, theories explain laws and both are equally important forms of knowledge (Abd-El-Khalick et al., 2024).

For modern physics teaching, as described by Nautiyal et al. (2025, p. 6), this episode can be effectively used to introduce the nature of quantum particles by comparing the nature of photons with Newton's classical corpuscles of light. Thus, later, when photons and wave-particle duality are introduced, Newton's corpuscles can act as a conceptual bridge to quantum nature of photons, enabling students to recognize that photons and other sub-atomic particles are different from everyday objects they see around them.

Episode 2 – Hertz's "Accidental" Spark That Ignited a Revolution

> In Episode 1, by introducing properties of waves and showcasing wave characteristics of light, students engaged with the understanding that light has wave characteristics and hence can transfer energy. By using analogies of ripples in water, light can be visualized as a disturbance in space carrying energy. The intention was to guide students towards appreciating that light has energy associated with it. Building on this narrative, Episode 2 poses the next question that ties classroom discussion with our story: "What kind of wave is light?" Through this episode, students explore that according to the wave model of light, light propagates as a transverse EM wave with oscillating electric and magnetic fields. To arrive at this understanding, we designed learning activities around a guiding question that we posed in our intervention: "Just as water oscillates in water ripples, what vibrations are associated with light as it propagates through space as described through a wave model?" The usefulness of this analogy is that instructors can explicitly target the common misconception that light itself oscillates in the form of photons (Balabanoff et al., 2020; Taslidere, 2016). In addition to the scientific concepts, this analogy was also used to convey the inferential NOS and the role of models. The primary author explicitly conveyed to students that the EM wave model with oscillating electric and magnetic fields is not an "exact replication" of how light looks, aiding in their functional understanding of models as tools to understand specific phenomena rather than exact descriptions of physical reality. Further, the contrasting scientific approaches of the purely theoretical work by Maxwell and purely experimental work by Hertz, were used alongside the accidental discovery of the photoelectric effect, to bring forth the "myth" of the scientific method aspect of NOS (Abd-El-Khalick et al., 2024). These examples were used to convey that there exists no universal method to do science. Scientists do not always follow a strict step-by-step procedure; as in the case of the discovery of the photoelectric effect, Hertz did not start by first forming a hypothesis and then studying it.

The debate over light's properties and its nature seemed resolved after Fresnel's and Arago's work on diffraction (Zubairy, 2016). By the second half of the 19th century, corpuscular theory was abandoned, and wave theory dominated physics institutions (Frankel, 1976). Next, James Clerk Maxwell proposed an elegant unification of electricity and magnetism in his landmark work, "*Dynamical theory of the electromagnetic field*" (Maxwell, 1865), predicting that light itself was an EM wave. Inspired by Maxwell's work, Heinrich Hertz conducted experiments to verify these predictions and, in the process, discovered radio waves—a discovery that would later revolutionize modern communication, contrary to Hertz's own expectations (Süsskind, 1965).

With Hertz's verification, the mystery of light appeared to be solved: light was an EM wave. Many physicists believed fundamental questions about physical reality had been answered. For instance, Nobel laureate Albert Michelson declared, "*… it seems probable that most of the grand underlying principles have been firmly established …*" (Kargon, 1977, p. 512). Yet, while testing Maxwell's predictions in 1887, Hertz encountered an unexpected challenge: sparks generated due to radio waves in his experiments were too faint to observe reliably. When ultraviolet light was directed between two metal electrodes, the sparks became noticeably more powerful (Giliberti & Lovisetti, 2024b, pp. 161-162). After months of investigation, Hertz realized ultraviolet wavelengths enhanced spark generation but could not explain why. His student Wilhelm Hallwachs carried forward this investigation (Hallwachs, 1889) and demonstrated that ultraviolet light caused metal surfaces to lose electric charge when illuminated (Klassen, 2011). These negative charges, ejected due to light, were later named "photoelectrons," and the accidental discovery came to be known as the "photoelectric effect." Initially a minor footnote in HOS, this would later lead to one of the 20th century's most revolutionary scientific ideas (Klassen, 2011; Stuewer, 2006)— emerging from an unexpected source: a little-known young German patent clerk working in Switzerland (Stix, 2004).

Pedagogical rationale and achievable learning goals

By this episode's end, students are guided to understand wave characteristics of light and visualize light though EM radiation model as a disturbance with oscillating electric and magnetic fields. We used YouTube videos to help students visualize these abstract constructs such as EM waves and demonstrate Hertz's discovery and Hallwachs' experiments (Errante, 2016; FloatHeadPhysics, 2024; Physics, 2019; QuantumBoffin, 2021). In addition, these videos were supplemented by predict-observe-explain strategies to actively recreate Hallwachs' experiments via a YouTube video demonstration (QuantumBoffin, 2021).

For NOS learning objectives, instructors can use this episode to address the "myth" of the scientific method and the inferential NOS (Abd-El-Khalick et al., 2024). This can be achieved by emphasizing that scientific models like the EM wave model do not depict exact physical reality; rather, they are tools to explain specific characteristics and make inferences (Ubben et al., 2023). Further, contrasting Maxwell's elegant mathematics with Hertz's experimental approach can promote the understanding that there exist diverse ways of doing science. Finally, the "accidental" nature of the discovery of the photoelectric effect can be used as a context to communicate informed views regarding the "myth" of the scientific method—a key NOS aspect. Through the example of Hertz's discovery, which was neither intentional nor preceded by formal hypothesis formation, we can design learning activities around this historical episode to scaffold students towards understanding that science is not always a deliberate, step-by-step process following the conventional sequence of hypothesis formation, data collection, and analysis—contrary to common misconception. Instead, science relies on imagination, creativity, and sometimes, chance.

Episode 3 – Lenard Uncovers the Secrets of the Photoelectric Effect

> One of the main learning objectives related to light-matter interaction in the previous episode, i.e., Episode 2 was to introduce students to the phenomenon of the photoelectric effect—that light striking a metal causes electron ejection. To continue the narrative in this episode, we posed the question: "What are the features of the photoelectric effect?" and utilized interactive PhET simulations (Perkins et al., 2006; Wieman et al., 2008) with guided inquiry-based worksheets to virtually reconstruct Lenard's experiments on the photoelectric effect (Giliberti & Lovisetti, 2024b) . The focus of this episode should be on understanding the features of the photoelectric effect phenomenon itself without introducing the photon model. In our intervention, students gave their own reasoning and compared it with experimental outcomes of PhET, arriving inductively at the main features of the photoelectric effect (Sokolowski, 2013), just as scientists of that era did. For NOS learning objectives, we used this episode to address the inferential and creative dimensions of science: Lenard's method of indirectly calculating electron energies by applying reverse voltage required to stop them from reaching the collector plate (Giliberti & Lovisetti, 2024b; Lenard, 1902) demonstrated that scientists rarely rely on direct observations alone but instead interpret data, make indirect calculations, and construct inferences. We reminded students of all scientists encountered thus far—Hertz, Maxwell, Lenard, Al-Haytham—and compared their approaches to highlight that, despite differing methods, all employed creativity at different investigation stages. We also acknowledged Lenard's tragic legacy in our teaching: his scientific contributions were diluted due to his anti-Semitic views and active involvement in the Nazi movement (Mulligan, 1999), portraying scientists not as superhuman figures but as regular human beings with limitations, biases, and moral failings. Acknowledging human flaws, bad judgements and problematic aspects of their personalities enables us to present a human view of both science and scientists.

Philipp Lenard, who worked as Hertz's assistant from 1891-1894 (Mulligan, 1999), undertook detailed experimental studies of the photoelectric effect. In the early 20th century, Germany faced significant economic pressure as the United States emerged as a dominant industrial powerhouse. The German government recognized the critical importance of advancing scientific research in electricity, heat, and radiation, providing substantial institutional support that positioned Germany as a pivotal hub for experimental and theoretical physics (Giliberti & Lovisetti, 2024a, p. 10).

Within this socio-economic context, Lenard conducted meticulous experiments using refined apparatus, yielding surprising results that were difficult to explain with classical wave theory at that time. The energy of ejected photoelectrons depended on light frequency, not intensity, as classical theory predicted. Nonetheless, to explain his experimental results, Lenard proposed the "trigger hypothesis". According to trigger hypothesis, light merely triggered the release of electrons already present in the metal, with electron energy coming from within the metal itself, not supplied by light (Giliberti & Lovisetti, 2024b; Klassen, 2011, p. 725; Niaz et al., 2010). Despite inconsistencies—photoelectrons were emitted only above a certain threshold frequency, regardless of light brightness—the trigger hypothesis remained accepted because no better explanation existed (Klassen, 2011). In 1905, a young German patent clerk working in Switzerland, would offer a radically different explanation that accounted for Lenard's results more completely.

Pedagogical rationale and achievable learning goals

This episode could be used to identify the main features of the photoelectric effect, enabling students to arrive at their own explanations of this phenomenon (Sokolowski, 2013). The instructor should avoid introducing the photon concept at this point. Rather, students should develop and share their own explanations based on what they know about waves and the wave nature of light, then compare their explanations with Lenard's findings. This approach will be beneficial in the next episode as students will be able to appreciate the relevance of the photon model in greater detail once they experience first-hand the failings of classical EM wave model in explaining the photelectric effect.

This episode, alongside subsequent episodes, can be used to integrate elements of 21st century skills with mainstream classroom teaching. In essence, 21st century skills include problem solving, critical thinking, collaboration, and creativity (Roehrig et al., 2021). These elements of 21st century skills are relatively easily accessible in learning activities associated with this episode. Students explored relatively unknown territory, inductively constructing explanations of their observations. In our intervention, students worked in groups, collected data, analyzed it, and provided inferences about possible mechanisms responsible for the photoelectric effect and the effects of intensity, applied voltage, and frequency on photoelectric emission.

In terms of NOS learning, this episode, through the story of Lenard's life, offers an excellent opportunity to present a more realistic picture of science and scientists, showcasing how personal biases and political beliefs can shape the trajectory of one's scientific career and interests. We used Lenard's life as one of the many examples to showcase the human perspective of science. In Lenard's case, his affiliation with Nazi Germany led him to completely oppose Einstein's research in the latter phase of his life. These difficult and unpleasant aspects enable us to convey to students that scientists are ordinary human beings, just like them, with their own weaknesses. This may improve their attitude towards science and motivation to pursue it when they realize scientists are not superhuman figures.

Further, relatively easy aspects of NOS to teach through this episode include the creative and inferential NOS. Instructors can explicitly convey to students that despite having no direct way to observe electrons, scientists are able to discover their properties in great detail through indirect methods and creativity. Lenard exemplifies this: he devised a creative method to precisely calculate maximum energies of ejected photoelectrons indirectly by calculating the reverse voltage required to stop the most energetic electrons from reaching the collector plate.

Episode 4 – Einstein's Revolution: Genius Idea Meets Staunch Rejection

To advance on the learning objectives of the previous episodes and to align the narrative with classroom discussion, this episode is an ideal time for introducing the photon model of light to students through the central question: "What is the photon model of light and how does it explain the results of the photoelectric effect?" Previous research indicates that students struggle to apply classical wave model and photon model of light and use these models inconsistently for explaining the photoelectric effect (Balabanoff et al., 2020; Özcan, 2015). Further, many misconceptions related to the photoelectric effect often stem from students attempting to explain it using classical physics principles and everyday experiences with light (Balabanoff et al., 2020; Taslidere, 2016). To address these difficulties, using an inferential NOS approach to teach this topic— emphasizing the role of models to explain different phenomena—is particularly useful here. Specifically, we ensured that students compared the predictions of the wave model with experimental results from their PhET simulations. To convey the specialty of the photon model, they compared it with the classical wave model through guided discussion around questions like: light has wave characteristics and every wave has energy, so light ejecting electrons seems intuitive based on energy transfer. Then what is surprising here? Why did Einstein's photon model become regarded as revolutionary? Through guided activities, we conveyed to students that brighter light is analogous to a stronger, bigger wave that should knock off an electron with greater speed. But that does not happen; hence, we introduce the features of the photon model and compare them with experimental findings aligned with the photon model predictions. In summary, this episode focuses on clarifying the role of models and predictions of each model with experimental evidence. In doing so, additional features of a scientific theory (beyond explanatory) such as testability and predictiveness can also be communicated.

The young German patent clerk mentioned earlier in the story was none other than Albert Einstein (Stix, 2004). Einstein's 1905 light quantum hypothesis (Einstein, 1965) was nothing short of radical for its time. Building on Planck's idea of energy quanta, Einstein proposed that light itself is made of discrete packets of energy, which he then termed "*light quanta*" (better known as photons today), each with energy proportional to its frequency. This bold idea explained the puzzling features of the photoelectric effect: the existence of a threshold frequency, the direct link between photon energy and stopping potential, and the independence of photoelectron energies from light intensity. Where classical EM wave theory failed, Einstein's hypothesis offered a mathematically rigorous yet elegant solution.

This proposal challenged the well-established wave theory of light and, on surface, seemed to revert to the long-discarded Newtonian corpuscular theory of light. This was one of the main reasons for its opposition by the contemporaries of Einstein (Klassen, 2011; Klassen et al., 2012; Niaz et al., 2010). Despite its strong theoretical foundation and successful explanation of all experimental photoelectric effect results, Einstein's light quanta hypothesis was rejected strongly by the scientific community. Decades of empirical support for wave theory, combined with the radical nature of the proposal that looked irreconcilable with interference and diffraction made acceptance difficult (Stuewer, 2006).

Robert Millikan, a meticulous experimentalist, described the photon model of light as "*bold, not to say reckless*" (Holton, 1999, p. 233) and set out to disprove it (Klassen, 2011). He conducted extraordinarily precise measurements of electron energies and the effects of frequency on the photoelectric emission. His results contradicted his intentions, confirming Einstein's photoelectric equation with remarkable accuracy. The proportionality constant he measured yielded Planck's constant, matching values from blackbody radiation (Millikan, 1916). Remarkably, despite this experimental confirmation, Millikan refused to accept the photon theory of light, dismissing it as untenable even in his Nobel lecture (Holton, 1999). The scientific community similarly resisted, clinging to classical wave theory-based trigger hypothesis. Ironically, Millikan's attempt to disprove Einstein secured Einstein the Nobel Prize – not for his famous work on relativity, but for deriving the law (or equation) of the photoelectric effect (Giliberti & Lovisetti, 2024b; Klassen, 2011).

Pedagogical rationale and achievable learning goals

This episode focuses on highlighting the photon model of light, properties of photons, and how Einstein's explanation differed from those of Lenard and Millikan. We reiterate that the classical and photon models should be explicitly covered—that is, their differences. To facilitate understanding, it is helpful to explain how Einstein modified Planck's concept of energy quanta. As Klassen (2011) highlights, it is a common misconception that Einstein's light quanta proposal was a "*natural extension*" of Planck's proposal of energy quantization presented by him in his theory of blackbody radiation (p. 720). While Planck proposed that energy could only be absorbed or emitted in quanta by a blackbody, Einstein applied that concept to radiation itself, essentially saying that light itself comes as quanta of energy, with each quantum proportional to frequency. All these details will enable students to appreciate the quantum model of light and serve as gateway to QM. Further, students will be scaffolded to realize why the photon concept is considered a revolution not only in physics but in human thought itself, as it marked a departure from tried and tested classical mechanics concepts and resulted in the paradigm shifting breakthrough, i.e., the birth of QM.

In terms of NOS, this episode offers rich avenues for discussing the subjective and social NOS through Millikan's strong criticism of Einstein's light quantum (photon) hypothesis (Millikan, 1916; Millikan, 1995) and unanimous rejection of Einstein's proposal by the scientific community, respectively (Klassen, 2011). Rather than accepting Einstein's explanation, Millikan restated Lenard's trigger hypothesis to explain his experimental results, which actually verified Einstein's photoelectric equation. This historical incident illustrates that scientific observations are not interpreted objectively; theoretical background and personal beliefs shape how science is conducted. Two scientists examining identical observations can offer contrasting explanations, demonstrating the subjective dimensions of scientific interpretation.

Further, despite the photon model supported by solid mathematical reasoning in Einstein's original paper (Einstein, 1965) and providing precise predictions that match the experimental observations of the photoelectric effect, the photon concept was rejected rather "*disdainfully*" by the physicists of that era (Klassen, 2011, p. 727). At this point, instructors can call back to Episode 1 to reiterate social aspect of science by asking students: "*Just like Thomas Young's work on interference, Einstein's photon model also took almost two decades to gain widespread acceptance and was largely ignored during this period. What does this tell you about the social nature of science?*" Classroom discussions should guide students to appreciate the social NOS, i.e., "*internal sociology of the scientific enterprise*" (Abd-El-Khalick et al., 2024, p. 1682). Thus, instructors can use this episode to convey how scientific knowledge emerges through collective scrutiny within established forums for communication and critical evaluation, which strengthen objectivity by mitigating individual scientists' biases and "*idiosyncrasies*" (Abd-El-Khalick et al., 2024, p. 1682). Einstein's proposal alone was insufficient; the scientific community required substantial evidence before abandoning classical wave theory, which had served them exceptionally well till then.

Episode 5 – Compton Rescues the Photon Concept: Scientists Finally Accept the Photon

> Through previous episodes, aligned learning activities were designed to develop several key concepts about light, notably that light exhibits both particle and wave characteristics, and some phenomena like interference and diffraction can be easily described using the wave model, whereas certain experimental observations such as the photoelectric effect are better described by the photon model of light. The wave model has specific limitations in the case of the photelectric effect. In addition, previous episodes and classroom discussions were designed to facilitate understanding of the photoelectric effect through the photon model, as Einstein proposed, representing light or photons as a quantum or packet of energy. Following Klassen's (2011) suggestion to avoid misconceptions, within the context of the photoelectric effect, light or photons should only be represented as a packet of energy. However, in the context of the Compton effect, light should be described as a packet of both energy and momentum (Strnad, 1986). To scaffold student understanding around this concept, we advance the narrative by exploring the following question: "Can light exert force on objects?" The purpose of this is to express, through Compton scattering, that light is a packet of both energy and momentum. This promotes a more nuanced understanding of the photon concept amongst students and builds upon knowledge acquired through previous episodes. However, it is important to recognize that student learning is influenced by multiple factors beyond pedagogy alone—teaching and learning can be a complex and sometimes unpredictable process. These counterintuitive concepts may take considerable time to gain acceptance. Through guided inquiry and classroom dialogue, some students may accept these ideas, whereas others may require additional support or time despite instructional efforts.

Despite Einstein's light quantum hypothesis explaining every feature of the photoelectric effect, acceptance of it remained limited (Klassen, 2011). Beyond Einstein and his close friend Paul Ehrenfest, almost no one accepted that light could be composed of discrete packets of energy. Classical theories served physics well, and most physicists demanded more irrefutable evidence before abandoning wave theory.

At this juncture, it is also helpful to highlight to students the efforts of scientists to eliminate the photon concept entirely by proposing alternative explanations for the photoelectric effect and light-matter interactions. For instance, Bohr-Kramer-Slater (BKS) proposed the BKS theory of light-matter interactions in their attempt to reconcile "*quantum discontinuities with the wave theory of light*" (Ehberger, 2026, p. 96). More details on the history, motivation, concepts and ultimate demise of the BKS theory are outlined by Ehberger (2026). Similarly, Richardson applied principles of thermodynamics to explain the photoelectric effect (Katzir, 2006). To enrich students' understanding of the scientific enterprise, these historical alternatives can be used to communicate the "*culture*" of physics (Galili, 2016; Nautiyal et al., 2025) by emphasizing that many different interpretations, apart from those presented in textbooks, were proposed and played a role in scientific discourse. Thus, these alternate explanations and their ultimate demise can also be used to teach subjective, tentative, social and empirical NOS.

Now, we turn to the core focus of this episode: Arthur Holly Compton's work on high-energy X-ray scattering (Klassen, 2011; Stuewer, 2000, 2006). While studying X-ray scattering after it strikes a metallic target, Compton observed a phenomenon that aligned with issues noted by other experimentalists of his era. He found that X-rays, after striking an aluminum target, emerged with lower energy (longer wavelength) than the incident radiation. J. J. Thomson's classical theory of scattering, rooted in wave theory and classical electrodynamics, predicted that scattered radiation should retain the same energy as the original radiation (Stuewer, 2006). Initially, Compton had full confidence in Thomson's classical theory and resisted explaining the scattering using Einstein's photon concept. Instead, he chose to apply classical wave concepts, such as the Doppler effect. More technical details are provided by Stuewer (2000, 2006).

In summary, Compton attempted to explain his experimental results unsuccessfully on two occasions (Stuewer, 2000, 2006). Stuewer (2006) described these attempts as "*false theory*" being confirmed by both "*good experimental data*" (p. 552) and "*spurious experimental data*" (p. 551). On his third attempt, Compton embraced not one, but two of Einstein's revolutionary ideas—light quanta and relativity. He modelled the interaction as a collision between a photon and an electron in a high-energy relativistic regime, where energy and momentum were conserved. This simple visualization along with the complex calculations explained his results precisely and the effect came to be known as the Compton effect. Finally, in 1926, the term "*photon*" was proposed by chemist Gilbert Lewis (Lewis, 1926) in a different context and was later formally adopted by physicists to describe Einstein's light quantum.

Compton's work extended Millikan's findings, providing direct experimental proof that photons, in addition to energy, also carry momentum. Light could exert force on matter, delivering a measurable "kick" to electrons. The evidence was overwhelming, and the scientific community could no longer resist. The balance now tilted in favor of photon theory, which began to be taken seriously. After a few years, wave theory was finally overturned in favor of a quantum picture (photon model) of light (Klassen, 2011; Niaz et al., 2010). Yet a deeper question remained: what is a photon? Merely a tiny "*particle of light*?" or something altogether new—a quantum entity defying classical physics. This episode in history marks the emergence of ideas so counterintuitive that Einstein—credited with introducing the photon concept and thereby considered the father of QM by many—himself would strongly oppose the interpretations that followed. Nevertheless, a new generation of physicists, willing to embrace these novel ideas and move beyond classical determinism, would be ready to tackle and advance concepts so fundamentally at odds with intuition and classical physics.

Pedagogical rationale and achievable learning goals

As highlighted in the preamble, the main scientific content that needs to be conveyed through this episode to students is that photons, or light, can transfer momentum in addition to energy. The billiard ball analogy, along with the famous vector diagrams of Compton scattering (Stuewer, 2000), provides an ideal platform to convey this concept. In our intervention, we also used this episode to explicitly highlight the differences between two processes: the Compton effect and the photoelectric effect. This comparison conveys that the nature of the interaction plays an important role in determining which characteristics are observed. This approach follows the suggestion given by Klassen (2011).

Further, having focused on the inferential aspect of NOS in previous episodes, this episode should again be used to communicate the inferential NOS and features of scientific models. Explicitly conveying that the scattering process and diagrams represent the most accurate way of explaining results and not exact replication of involved physical processes. Using the billiard ball analogy, we highlight the difference between billiard balls and sub-atomic quantum particles. In actual quantum mechanical calculations, the precise point-like position of photons and electrons—unlike the trajectory of a ball—is not possible, and scientists cannot directly observe that interaction. Instead, they make inferences about it through calculation of energies of scattered photons and electrons. This can serve as a gateway to more advanced concepts like the uncertainty principle.

In terms of NOS learning, we use this episode to address primarily one of the most common NOS misconceptions: the belief that if scientists follow some "scientific method," their results will always be correct. Through the example of Compton, who failed twice and published results that were inaccurate (Stuewer, 2000) and was also criticized for his conclusions, we once again highlight the myth of the scientific method—that no universal "*scientific method*" can guarantee generation of flawless knowledge. Research indicates this is one of the most commonly misunderstood aspects of NOS amongst both students and teachers (Bugingo et al., 2024; McComas et al., 2020).

Episode 6 - What Is a Photon? Is the Debate Finally Settled?

> Episode 4 introduced light as a packet of energy through the photoelectric effect, while Episode 5 presented the Compton effect as evidence that photons possess both energy and momentum. The central question, captured in the episode title, prompts students to synthesize their understanding. Through the learning activities woven around the historical narrative in previous episodes, students have been introduced to and guided towards engaging with these properties of light—properties that differ from their everyday experiences. This is an opportune moment to introduce more counterintuitive quantum concepts. We further scaffold students towards appreciating the fundamentally different properties of quantum particles like photons (compared to classical everyday objects) through a callback to Episode 1, asking: if photons, like Newton's corpuscles, have momentum—does this mean Newton was right? What distinguishes photons from Newton's corpuscles? Single-photon double-slit interference via PhET simulations reveals the answer: quantum entities fundamentally differ from everyday objects in that they do not follow classical physics frameworks. This experiment serves as a gateway to wave-particle duality, the uncertainty principle, and the observer effect in QM. We

utilized this episode to promote functional thinking about models in QM by scaffolding students to explain the nature of photons through predict-observe-explain strategies and guided worksheets, where students compared their predictions of single-photon double-slit experiment with experimental observations in PhET simulations.

Einstein's light quantum theory remained sidelined for almost two decades until Compton's research (Klassen, 2011). After Compton's work, the photon concept gained acceptance (Stuewer, 2000) and QM was developed further by subsequent generations of scientists. This started with de Broglie, who won a Nobel Prize for proposing that just as light, which we knew as a wave, has particle characteristics, then particles, like electrons, must also have wave characteristics (De Broglie, 1929). His theoretical prediction was experimentally verified with electron diffraction experiments (Davisson & Germer, 1927), earning him the Nobel Prize and establishing the concept of matter waves and wave-particle duality. This concept of wave-particle duality is the working principle of most, if not all, modern semiconductor-based technologies that have transformed our lives and materialized in the second industrial revolution (Dowling & Milburn, 2003). Erwin Schrödinger would later incorporate the concept of matter waves into the theory of wave mechanics (Wessels, 2013), which remains the foundation of quantum theory today. Heisenberg arrived at a rigorous mathematical formulation of similar results using a different approach—matrix mechanics (Heisenberg, 1985). Together, these developments marked the formal establishment of quantum theory within a comprehensive mathematical framework. UNESCO designated 2025 as the international year of quantum science and technology, commemorating the 100th anniversary of Schrödinger's and Heisenberg's respective proposals of wave and matrix mechanics, and the birth of modern quantum theory (Bongs, 2025).

A consequence of this formal development of QM as a theoretical paradigm was a totally new framework where at the most fundamental level reality is probabilistic rather than deterministic. A new generation of physicists would rise to the challenge, advancing ideas so counterintuitive that the very torchbearer of the quantum revolution—Einstein himself—would refuse to believe them (Einstein, 1949), just as Millikan and others had once refused to accept Einstein's own radical idea of the light quanta (photon).

Pedagogical rationale and achievable learning goals

Our approach and recommendations aligned with Jho et al. (2023). The authors pointed out that traditional instruction on the photoelectric effect typically focuses on teaching it solely from the perspective of the particle nature of light, rather than emphasizing wave-particle duality. In this chapter, by addressing the central question "Light comes as photons, but what is a photon?" and letting students explore this via single-photon double-slit experiments, we teach this topic through wave-particle duality. This is relatively more integrated approach as it connects the photoelectric effect and the photon concept to other advanced QM concepts that students may encounter in the future. Jho et al. (2023) similarly emphasized the importance of this holistic approach towards teaching the photoelectric effect. We used this to advance and introduce concepts such as superposition, entanglement, Schrödinger equation, and uncertainty principle.

In terms of the NOS, the question "Is the debate settled?" guides students towards appreciating the tentative and evolving NOS by emphasizing that scientific knowledge is never absolute. Through this episode, we convey that even the photon model of light and QM cannot be considered as absolute truths and these models may evolve as we gain new empirical insights in future. The mystery of light's nature is intentionally left as an open-ended question within our story, with scope for future refinement as science advances.

Furthermore, this episode once again presents an excellent opportunity to humanize science (and scientists) and highlight how the narrative comes full circle. We made deliberate efforts to communicate to students that just as prominent scientists of Einstein's era refused to accept his radical ideas about light quanta, Einstein himself—now a prominent figure—resisted the counterintuitive and probabilistic nature of QM. In his later work, Einstein authored one of the most famous and highly cited papers in physics—his response to QM (Einstein et al., 1935). In this paper, he argues against the standard interpretations of QM and related concepts such as non-locality, entanglement, and superposition. These concepts, which emerged from Schrödinger and Heisenberg's theory of QM, are today the backbone of quantum research. At that time, their work presented more questions than answers—for instance, counter-intuitive concepts such as quantum non-locality, superposition, and entanglement remained deeply puzzling phenomena that challenged the intuition based on our everyday experiences at the macroscopic level. However, a new generation of physicists—including, among many others, Feynman, Kramers, Pauli, Born, Fermi, Oppenheimer, and Dirac—embraced these radical ideas and further built upon them to develop modern quantum theory in its full glory.

The foundational contributions of scientists other than Einstein should be explicitly highlighted in teaching to convey to students that QM was a collective scientific endeavor. While many scientists contributed equally—and in some cases more substantially than Einstein—to developing modern quantum theory, prominent figures like Einstein often receive disproportionate recognition. Highlighting the contributions of scientists who are relatively lesser-known to the general public, though well-recognized within the scientific community, counters the "superhuman genius" myth and emphasizes that even these overlooked figures made critical contributions to the conceptual and mathematical frameworks upon which modern quantum physics rests.

Epilogue – The Quantum Revolution Continues to Transform Our Lives

> This episode can serve a dual purpose: to build upon the single-photon interference and quantum nature of subatomic particles introduced in previous episodes, and to promote the relevance of the learning topic to students' everyday lives, personal goals, and ambitions. The central question guiding this episode is: "What is the relevance of QM to our personal lives." The implementation depends on the educational context and level at which the episode is delivered. For our intervention with year 9 students, this was the culmination, and we used it to promote the relevance of the learning topic to their everyday technology and personal aspirations. For instance, everyday technology based on the photon concept and its applications were discussed. In addition, the relevance of this learning topic to their future careers in STEM education and possibilities in quantum technology industry careers were communicated, albeit briefly due to time constraints in the regular schedule. Similarly, for undergraduate level, this episode can introduce the concept of quantum technology and how these fundamental properties of superposition and entanglement are driving the second quantum revolution. Research has indicated that relevance is a core construct affecting attitudinal and motivational dimensions related to learning outcomes. In terms of the nature of science, this episode reinforces that scientific knowledge continues to evolve and that concepts derived from quantum mechanics are now foundational to modern technology.

The photon concept revolutionized technology. Semiconductor devices, solar cells, LEDs, fiber optics and lasers all exploit photon-electron interactions (Garnett et al., 2021) . The fundamental principles governing most, if not all, modern technology exploit the photon model of light and light-matter interactions (MacFarlane et al., 2003). The quantum revolution extends further. Superposition and entanglement—principles governing quantum particles—now have shown the potential to power quantum computers and quantum key distribution systems (Weissman et al., 2024), enabling unbreakable encryption and solving problems beyond the reach of existing technology.

Einstein once resisted to accept quantum indeterminacy. Today, scholars aim to harness it for practical applications. The debate over light's nature is not settled; instead, it opened doorways to technologies reshaping our world. The quantum revolution, born from a simple question about light, remains humanity's most transformative scientific endeavor.

Pedagogical rationale and achievable learning goals

The primary objective of this episode (Epilogue) is to further establish the relevance of the learning topic to students' personal ambitions, usefulness, and future career goals (extrinsic relevance), as well as its relevance in broader societal terms. Research indicates that enhancing relevance—both intrinsic relevance (the immediate applicability of learning material to passing an exam or securing employment) and extrinsic relevance (aligning content with learners' future goals and ambitions)—strengthens motivation and learning outcomes (Fedesco et al., 2017; Means et al., 1997).

Further, relevance is also a core motivational construct (the "R") in the ARCS model of instructional design—other constructs being attention, confidence, and satisfaction (Keller, 2010). To embed relevance this episode can be used to highlight practical applications of quantum concepts in our everyday technology and potential future benefits of quantum technologies. In addition, this episode could be used to highlight usefulness of this topic for future STEM careers, careers in quantum technology industry and higher education in many STEM domains.

For NOS learning, in this specific case, strengthening topic relevance also aligns with the "socio-cultural" aspect of science. Specifically, in our intervention, we explicitly highlighted to students that major global powers are investing heavily in quantum technology research and the development of next-generation quantum devices. This means that scientists pursuing research in this domain have greater access to funding compared to many other research areas, because governments and institutions prioritize quantum technology due to its transformative potential. This observation illustrates a key social NOS concept: what science gets funding and what does not reflects social and political priorities. We explicitly conveyed to students that quantum technology is a priority for global economies, and developing expertise in this domain enhances their prospects for future employment in both academic research and industry, whilst fostering critical thinking and problem-solving skills.

DISCUSSION AND CONCLUSION

Considerations for Instructors: Adapting the Story in Their Classrooms

As with any instructional product, there are certain considerations that we unpack for instructors interested in using our story or a similar approach in their classrooms. First and foremost, for observing meaningful NOS learning gains, historical storytelling must be accompanied by explicit-reflective NOS instruction (Rudge & Howe, 2009). This means that instructors explicitly target NOS as one of the learning outcomes of the lesson and provide ample opportunities for students to reflect on target NOS ideas through their own learning, using historical context as a platform to promote thinking about these NOS aspects (Deng et al., 2025). The sophistication of NOS concepts means that it may be unreasonable to expect students to grasp these ideas implicitly only through historical storytelling without guidance and scaffolding students towards informed NOS ideas (Bugingo et al., 2024; Khishfe & Abd-El-Khalick, 2002). We have provided an example, demonstrating how the historical episodes were used to enact explicit-reflective NOS instruction. One of the main utilities of HOS for teaching is that it provides an organic platform to discuss NOS ideas with science teaching. If the presented story is not accompanied by explicit-reflective NOS instruction, then a major opportunity to leverage HOS's unique potential for NOS learning will be squandered.

To assess NOS learning outcomes, we used a modified version of the student understanding of science and scientific inquiry (SUSSI) developed and validated by Liang et al. (2008). It is a dual-response instrument that facilitates triangulation by allowing mixed-methods data collection. Our analysis of SUSSI responses revealed an overall positive shift in students' NOS understanding after the story-based instruction. To evaluate the effectiveness of our proposed story, interested instructors can also use this instrument in their context.

A second consideration is a word of caution regarding historical storytelling-based teaching. As highlighted by Rudge and Howe (2009, p. 565), simply reciting (or reading) historical vignettes—such as each episode of this story—as a foundation for discussing scientific concepts and NOS can quickly become a "*passive experience*" for learners. Therefore, to address this challenge, the primary author employed multiple active-learning strategies during the intervention. Rather than employing HOS as passive narration, effective classroom implementation requires using storytelling as a foundation for active learning. For instance, utilizing a blended learning environment, the primary author presented the main debate of Episode 1 (wave versus particle theory of light) as an interactive comic in simple presentation slides. During the classroom discussion, the teacher posed questions as a comic books style presentation where the students role-played Newton and Young, guiding these scientists towards determining their next course of action to convince the scientific community of their respective theories of light. Similar other creative strategies such as pedagogical memes (Sidekerskienė & Damaševičius, 2025), interactive videos, simulations, visualizations and collaborative guided-inquiry based worksheets can be applied instead of presenting the story simply as narration or reading material.

CLOSING NOTES

Enhancing NOS literacy is one of the main objectives of global education policy reforms as it is considered a crucial component of scientific literacy. HOS is considered one of the main approaches to teaching about NOS. Both HOS and NOS are well-established research domains with decades of research (Matthews, 2014; McComas et al., 2020). However, despite these research efforts, both teachers and students continue to hold the same NOS misconceptions highlighted by McComas (1996) nearly 30 years ago, as reported in recent studies (Bugingo et al., 2024; Gerondio et al., 2024). This suggests that despite growth in research efforts, NOS education is still not mainstream practice and there exists a wide gap between NOS research and practice in regular classrooms. Thus, accelerated efforts are needed to assist educators and researchers to implement resources for NOS education that can align with regular teaching curricula.

In response, we reconstructed the history of light and the birth of the photon concept as an educational science story spanning eight episodes, from ancient theories of vision to the modern quantum mechanical description of the photon. Our contribution demonstrates how specific historical events can integrate NOS within regular teaching. The story serves as an instructional resource for secondary and undergraduate instructors wishing to integrate NOS in introductory QM courses, and as a model adaptable to other topics using similar pedagogical approaches. We employed an explicit-reflective NOS approach, highlighting accessible NOS aspects, achievable learning objectives, and implementation strategies for each episode, supported by commentaries based on our pilot testing with year 9 students in the Philippines. Thus, it is expected that this story will serve as useful research-informed instructional material that may reduce the friction of action among teachers and allow them to integrate NOS learning with their existing classroom practices. In future publications, we will detail the fundamental design principles and application of those principles that guided the development and implementation of the story in classroom. This will enable development and classroom implementation of similar stories in other science topics.

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REFERENCES

Abd-El-Khalick, F., Summers, R., Brunner, J. L., Belarmino, J., & Myers, J. (2024). Development of *VAScoR*: A rubric to qualify and score responses to the views of nature of science (*VNOS*) questionnaire. *Journal of Research in Science Teaching, 61*(7), 1641-1688. https://doi.org/10.1002/tea.21916

Akdogan, C. (1984). Avicenna and Albert's refutation of the extramission theory of vision. *Islamic Studies, 23*(3), 151-157. https://www.jstor.org/stable/20847267

Ayene, M., Krick, J., Damitie, B., Ingerman, A., & Thacker, B. (2019). A holistic picture of physics student conceptions of energy quantization, the photon concept, and light quanta interference. *International Journal of Science and Mathematics Education, 17*(6), 1049-1070. https://doi.org/10.1007/s10763-018-9906-y

Balabanoff, M. E., Al Fulaiti, H., Bhusal, S., Harrold, A., & Moon, A. C. (2020). An exploration of chemistry students' conceptions of light and light-matter interactions in the context of the photoelectric effect. *International Journal of Science Education, 42*(6), 861-881. https://doi.org/10.1080/09500693.2020.1736358

Balabanoff, M., Kaur, S., Barbera, J., & Moon, A. (2022). A construct modelling approach to characterize chemistry students' understanding of the nature of light *International Journal of Science Education, 44*(6), 873-895. https://doi.org/10.1080/09500693.2022.2055190

Bell, R. L., Blair, L. M., Crawford, B. A., & Lederman, N. G. (2003). Just do it? impact of a science apprenticeship program on high school students' understandings of the nature of science and scientific inquiry. *Journal of Research in Science Teaching, 40*(5), 487-509. https://doi.org/10.1002/tea.10086

Bitzenbauer, P., & Ubben, M. S. (2025). The structure of learners' perceptions of models (not only) in quantum physics: Spotlight on fidelity of gestalt and functional fidelity. *EPJ Quantum Technology, 12*, Article 16. https://doi.org/10.1140/epjqt/s40507-025-00316-7

Bongs, K. (2025). Celebrating the international year of quantum science and technology. *EPJ Quantum Technology, 12*, Article 30. https://doi.org/10.1140/epjqt/s40507-025-00336-3

Bugingo, J. B., Yadav, L. L., Mugisha, I. S., & Mashood, K. K. (2024). Improving teachers' and students' views on nature of science through active instructional approaches: A review of the literature. *Science & Education, 33*, 29-71. https://doi.org/10.1007/s11191-022-00382-8

Cantor, G. N. (1983). *Optics after Newton: Theories of light in Britain and Ireland, 1704-1840*. Manchester University Press. https://lccn.loc.gov/83007954

Chacón-Díaz, L. B. (2022). A textbook analysis to uncover the hidden contributors of science and mathematics. *Science & Education, 31*, 193-211. https://doi.org/10.1007/s11191-021-00246-7

Cottrell, J. E., & Winer, G. A. (1994). Development in the understanding of perception: The decline of extramission perception beliefs. *Developmental Psychology, 30*(2), 218-228. https://doi.org/10.1037/0012-1649.30.2.218

Crease, R. P. (2002). The most beautiful experiment... *Physics World, 15*(9), Article 19. https://doi.org/10.1088/2058-7058/15/5/23

Dai, P., Williams, C. T., Witucki, A. M., & Rudge, D. W. (2021). Rosalind Franklin and the discovery of the structure of DNA. *Science & Education, 30*, 659-692. https://doi.org/10.1007/s11191-020-00188-6

Davisson, C., & Germer, L. H. (1927). The scattering of electrons by a single crystal of nickel. *Nature, 119*, 558-560. https://doi.org/10.1038/119558a0

De Broglie, L. (1929). The wave nature of the electron. *Nobel Lecture, 12*, 244-256. https://www.nobelprize.org/uploads/2016/04/broglie-lecture.pdf

de Hosson, C., & Kaminski, W. (2007). Historical controversy as an educational tool: Evaluating elements of a teaching-learning sequence conducted with the text "dialogue on the ways that vision operates". *International Journal of Science Education, 29*(5), 617-642. https://doi.org/10.1080/09500690600802213

Deng, F., Shi, Z., Tian, P., & Sun, D. (2025). Explicit-reflective teaching and students' understanding of nature of science: A meta-analysis. *Research in Science Education, 56*, 579-601. https://doi.org/10.1007/s11165-025-10287-5

Deutsch, I. H. (2020). Harnessing the power of the second quantum revolution. *PRX Quantum, 1*, Article 020101. https://doi.org/10.1103/PRXQuantum.1.020101

Dowling, J. P., & Milburn, G. J. (2003). Quantum technology: The second quantum revolution. *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences, 361*(1809), 1655-1674. https://doi.org/10.1098/rsta.2003.1227

Ehberger, M. (2026). The BKS theory and the light-quantum hypothesis: Virtual entities and transitions to intermediate states, but in different conceptual frameworks (1923-1925). In *Representing the unobservable. Science networks. Historical studies, vol 68* (pp. 85-169). Springer. https://doi.org/10.1007/978-3-032-09188-8_4

Einstein, A. (1949). Reply to criticisms. In A. Einstein (Ed.), *Albert Einstein philosopher scientist* (pp. 665-688). Harper & Brothers Publications.

Einstein, A. (1965). Concerning an heuristic point of view toward the emission and transformation of light. *American Journal of Physics, 33*(5), Article 367. https://icg.isy.liu.se/en/phd-courses/quantum_foundations/references/Einstein1905b.pdf

Einstein, A., Podolsky, B., & Rosen, N. (1935). Can quantum-mechanical description of physical reality be considered complete? *Physical Review, 47*, 777-780. https://doi.org/10.1103/PhysRev.47.777

El-Bizri, N. (2005). A philosophical perspective on Alhazen's optics. *Arabic Sciences and Philosophy, 15*(2), 189-218. https://doi.org/10.1017/S0957423905000172

Errante, F. (2016). Heinrich Hertz radio waves experiment – The discovery of radio waves. *YouTube*. https://youtu.be/RREbbMyehZM?si=FKSIL2z5BEfULZL1

Eshach, H., Hwang, F.-K., Wu, H.-K., & Hsu, Y.-S. (2013). Introducing Taiwanese undergraduate students to the nature of science through Nobel Prize stories. *Physical Review Physics Education Research, 9*, Article 010116. https://doi.org/10.1103/PhysRevSTPER.9.010116

Fedesco, H. N., Kentner, A., & Natt, J. (2017). The effect of relevance strategies on student perceptions of introductory courses. *Communication Education, 66*(2), 196-209. https://doi.org/10.1080/03634523.2016.1268697

FloatHeadPhysics. (2024). I finally understood why light is made of photons (my mind is blown!). *YouTube*. https://youtu.be/r7k5G_6yzDw?si=ogRFuHJgxzeGUlN-

Forato, T. C. d. M., de Andrade Martins, R., & Pietrocola, M. (2012). History and nature of science in high school: Building up parameters to guide educational materials and strategies. *Science & Education, 21*, 657-682. https://doi.org/10.1007/s11191-011-9419-3

Frankel, E. (1976). Corpuscular optics and the wave theory of light: The science and politics of a revolution in physics. *Social Studies of Science, 6*(2), 141-184. https://doi.org/10.1177/030631277600600201

Galili, I. (2016). From comparison between scientists to gaining cultural scientific knowledge. *Science & Education, 25*, 115-145. https://doi.org/10.1007/s11191-015-9785-3

Galili, I., & Hazan, A. (2000). Learners' knowledge in optics: Interpretation, structure and analysis. *International Journal of Science Education, 22*(1), 57-88. https://doi.org/10.1080/095006900290000

Garnett, E. C., Ehrler, B., Polman, A., & Alarcon-Llado, E. (2021). Photonics for photovoltaics: Advances and opportunities. *ACS Photonics, 8*(1), 61-70. https://doi.org/10.1021/acsphotonics.0c01045

Gerondio, L. B., Unabia, W. A. R., Mayang, Z. M., & Alimbon, J. A. (2024). Junior high school students' views of nature of science: Evidence from a private school in Davao Region, Philippines. *International Journal of Science Education, 46*(9), 839-857. https://doi.org/10.1080/09500693.2023.2260522

Giliberti, M., & Lovisetti, L. (2024a). Black-body radiation. In *Old quantum theory and early quantum mechanics. Challenges in physics education* (pp. 3-25). Springer. https://doi.org/10.1007/978-3-031-57934-9_1

Giliberti, M., & Lovisetti, L. (2024b). The photoelectric effect and the electron charge. In *Old quantum theory and early quantum mechanics. Challenges in physics education* (pp. 159-228). Springer. https://doi.org/10.1007/978-3-031-57934-9_5

Güler, M., & Ünal, S. (2023). Tell me a story, professor! The effect of historical science stories on academic achievement and motivation in a physics class. *Research in Science & Technological Education, 41*(2), 635-652. https://doi.org/10.1080/02635143.2021.1928046

Hallwachs, W. (1889). Ueber den Zusammenhang des Electricitätsverlustes durch Beleuchtung mit der Lichtabsorption [On the relationship between electricity loss due to lighting and light absorption]. *Annalen der Physik, 273*(8), 666-675. https://doi.org/10.1002/andp.18892730811

Heisenberg, W. (1985). Über quantentheoretische Umdeutung kinematischer und mechanischer Beziehungen [On the quantum-theoretical reinterpretation of kinematic and mechanical relationships]. In W. Blum, H. Rechenberg, & H.-P. Dürr (Eds.), *Original scientific papers Wissenschaftliche Originalarbeiten. Werner Heisenberg Gesammelte Werke collected works, vol A / 1* (pp. 382-396). Springer. https://doi.org/10.1007/978-3-642-61659-4_26

Henke, A., & Höttecke, D. (2015). Physics teachers' challenges in using history and philosophy of science in teaching. *Science & Education, 24*, 349-385. https://doi.org/10.1007/s11191-014-9737-3

Henriksen, E. K., Angell, C., Vistnes, A. I., & Bungum, B. (2018). What is light? *Science & Education, 27*, 81-111. https://doi.org/10.1007/s11191-018-9963-1

Holton, G. (1999). R. A. Millikan's struggle with the meaning of Planck's constant. *Physics in Perspective, 1*, 231-237. https://doi.org/10.1007/s000160050020

Höttecke, D., & Silva, C. C. (2011). Why implementing history and philosophy in school science education is a challenge: An analysis of obstacles. *Science & Education, 20*, 293-316. https://doi.org/10.1007/s11191-010-9285-4

Inventions. (2018). 1001 inventions and the world of Ibn Al Haytham (English version). *YouTube*. https://youtu.be/MmPTTFff44k?si=GEzrMV1fFCjFqYsP

Jardim, W. T., Guerra, A., & Schiffer, H. (2021). History of science in physics teaching. *Science & Education, 30*, 609-638. https://doi.org/10.1007/s11191-020-00191-x

Jho, H., Lee, B., Ji, Y., & Ha, S. (2023). Discussion for the enhanced understanding of the photoelectric effect. *European Journal of Physics, 44*(2), Article 025301. https://doi.org/10.1088/1361-6404/acb39d

Kampourakis, K. (2016). The "general aspects" conceptualization as a pragmatic and effective means to introducing students to nature of science. *Journal of Research in Science Teaching, 53*(5), 667-682. https://doi.org/10.1002/tea.21305

Kargon, R. H. (1977). The conservative mode: Robert A. Millikan and the twentieth-century revolution in physics. *Isis, 68*(4), 509-526. https://doi.org/10.1086/351871

Katzir, S. (2006). Thermodynamic deduction versus quantum revolution: The failure of Richardson's theory of the photoelectric effect. *Annals of Science, 63*(4), 447-469. https://doi.org/10.1080/00033790600787417

Keller, J. M. (2010). The arcs model of motivational design. In *Motivational design for learning and performance* (pp. 43-74). Springer. https://doi.org/10.1007/978-1-4419-1250-3_3

Khishfe, R., & Abd-El-Khalick, F. (2002). Influence of explicit and reflective versus implicit inquiry-oriented instruction on sixth graders' views of nature of science. *Journal of Research in Science Teaching, 39*(7), 551-578. https://doi.org/10.1002/tea.10036

Klassen, S. (2009). The construction and analysis of a science story: A proposed methodology. *Science & Education, 18*, 401-423. https://doi.org/10.1007/s11191-008-9141-y

Klassen, S. (2011). The photoelectric effect: Reconstructing the story for the physics classroom. *Science & Education, 20*, 719-731. https://doi.org/10.1007/s11191-009-9214-6

Klassen, S., & Froese Klassen, C. (2013). Science teaching with historically based stories: Theoretical and practical perspectives. In M. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching* (pp. 1503-1529). Springer. https://doi.org/10.1007/978-94-007-7654-8_47

Klassen, S., Niaz, M., Metz, D., McMillan, B., & Dietrich, S. (2012). Portrayal of the history of the photoelectric effect in laboratory instructions. *Science & Education, 21*, 729-743. https://doi.org/10.1007/s11191-011-9360-5

Krijtenburg-Lewerissa, K., Pol, H. J., Brinkman, A., & van Joolingen, W. R. (2017). Insights into teaching quantum mechanics in secondary and lower undergraduate education. *Physical Review Physics Education Research, 13*, Article 010109. https://doi.org/10.1103/PhysRevPhysEducRes.13.010109

Lederman, N. G. (2013). Nature of science: Past, present, and future. In S. K. Abell, K. Appleton, & D. Hanuscin (Eds.), *Handbook of research on science education* (pp. 831-879). Routledge. https://api.semanticscholar.org/CorpusID:38983551

Lenard, P. (1902). Ueber die lichtelektrische Wirkung [On the photoelectric effect]. *Annalen der Physik, 313*(5), 149-198. https://doi.org/10.1002/andp.19023130510

Leone, M., & Rinaudo, M. (2020). Should the history of physics be rated X? A survey of physics teachers' expectations. *Physics Education, 55*(3), Article 035013. https://doi.org/10.1088/1361-6552/ab73d1

Lewis, G. N. (1926). The conservation of photons. *Nature, 118*, 874-875. https://doi.org/10.1038/118874a0

Liang, L. L., Chen, S., Chen, X., Kaya, O. N., Adams, A. D., Macklin, M., & Ebenezer, J. (2008). Assessing preservice elementary teachers' views on the nature of scientific knowledge: A dual-response instrument. *Asia-Pacific Forum on Science Learning and Teaching, 9*. https://www.eduhk.hk/apfslt/download/v9_issue1_files/liang.pdf

Lička, L. (2020). The visual process: Immediate or successive? Approaches to the extramission postulate in 13th century theories of vision. Medieval perceptual puzzles. In E. Baltuta (Ed.), *Medieval perceptual puzzles: Theories of sense perception in the 13th and 14th centuries* (pp. 73-110). IP. https://doi.org/10.1163/9789004413030_005

Lima, N. W., Heidemann, L. A., & Garik, P. (2024). Why teachers (do not) integrate history of science into physics courses. *Science & Education, 34*, 3233-3268. https://doi.org/10.1007/s11191-024-00571-7

Lindberg, D. C. (1967). Alhazen's theory of vision and its reception in the West. *Isis, 58*(3), 321-341. https://doi.org/10.1086/350266

MacFarlane, A. G. J., Dowling, J. P., & Milburn, G. J. (2003). Quantum technology: The second quantum revolution. *Philosophical Transactions of the Royal Society A, 361*(1809), 1655-1674. https://doi.org/10.1098/rsta.2003.1227

Maharaj-Sharma, R. (2024). Using storytelling to teach a topic in physics. *Education Inquiry, 15*(2), 227-246. https://doi.org/10.1080/20004508.2022.2092977

Matthews, M. (2014). *Science teaching: The contribution of history and philosophy of science*. Routledge. https://doi.org/10.4324/9780203123058

Maxwell, J. C. (1865). VIII. A dynamical theory of the electromagnetic field. *Philosophical Transactions of the Royal Society of London, 1865*(155), 459-512. https://doi.org/10.1098/rstl.1865.0008

McComas, W. F. (1996). Ten myths of science: Reexamining what we think we know about the nature of science. *School Science and Mathematics, 96*(1), 10-16. https://doi.org/10.1111/j.1949-8594.1996.tb10205.x

McComas, W. F., Clough, M. P., & Nouri, N. (2020). Nature of science and classroom practice: A review of the literature with implications for effective NOS instruction. In W. F. McComas (Ed.), *Nature of science in science instruction. Science: Philosophy, history and education* (pp. 67-111). Springer. https://doi.org/10.1007/978-3-030-57239-6_4

McKagan, S. B., Handley, W., Perkins, K. K., & Wieman, C. E. (2009). A research-based curriculum for teaching the photoelectric effect. *American Journal of Physics, 77*(1), 87-94. https://doi.org/10.1119/1.2978181

Means, T. B., Jonassen, D. H., & Dwyer, F. M. (1997). Enhancing relevance: Embedded ARCS strategies vs. purpose. *Educational Technology Research and Development, 45*, 5-17. https://doi.org/10.1007/BF02299610

Millikan, R. A. (1916). A direct photoelectric determination of Planck's" h". *Physical Review, 7*, Article 355. https://doi.org/10.1103/PhysRev.7.355

Millikan, R. A. (1995). Nobel lectures, physics 1923, the electron and the light-quant from the experimental point of view, May 23, 1924. *Nobel Lectures, 1*(2). https://www.nobelprize.org/uploads/2018/06/millikan-lecture.pdf

Mulligan, J. F. (1999). Heinrich Hertz and Philipp Lenard: Two distinguished physicists, two disparate men. *Physics in Perspective, 1*, 345-366. https://doi.org/10.1007/s000160050027

Nautiyal, V. V., Salvador, E. E. P., Brana, X. R. O., Shastri, R., Singh, V., Tyagi, A., Vidhani, B., & Prasad, V. (2025). Enhancing high school students' understanding and attitude towards quantum mechanics through discipline-culture framework and cognitive apprenticeship. *EPJ Quantum Technology, 12*, Article 104. https://doi.org/10.1140/epjqt/s40507-025-00407-5

Niaz, M. (2014). Science textbooks: The role of history and philosophy of science. In M. R. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching* (pp. 1411-1441). Springer. https://doi.org/10.1007/978-94-007-7654-8_44

Niaz, M., Klassen, S., McMillan, B., & Metz, D. (2010). Reconstruction of the history of the photoelectric effect and its implications for general physics textbooks. *Science Education, 94*(5), 903-931. https://doi.org/10.1002/sce.20389

Norris, S. P., Guilbert, S. M., Smith, M. L., Hakimelahi, S., & Phillips, L. M. (2005). A theoretical framework for narrative explanation in science. *Science Education, 89*(4), 535-563. https://doi.org/10.1002/sce.20063

Özcan, Ö. (2015). Investigating students' mental models about the nature of light in different contexts. *European Journal of Physics, 36*, Article 065042. https://doi.org/10.1088/0143-0807/36/6/065042

Passon, O. (2022). The quasi-history of early quantum theory. *Physics, 4*(3), 880-891. https://doi.org/10.3390/physics4030057

Perkins, K., Adams, W., Dubson, M., Finkelstein, N., Reid, S., Wieman, C., & LeMaster, R. (2006). PhET: Interactive simulations for teaching and learning physics. *The Physics Teacher, 44*, 18-23. https://doi.org/10.1119/1.2150754

Persson, J. (2018). Evolution of quasi-history of the Planck blackbody radiation equation in a physics textbook. *American Journal of Physics, 86*, 887-892. https://doi.org/10.1119/1.5054005

Physics, K. L. (2019). Photoelectric effect: History of Einstein's revolutionary view of light. *YouTube*. https://youtu.be/BiPEY99w8Lo?si=eNKKG9bRTUhbooha

QuantumBoffin. (2021). Demonstrating the photoelectric effect. *YouTube*. https://youtu.be/Nm1iZqLmOnc?si=2Gd8ChTtO_WXR7TY

Raftopoulos, A., Kalyfommatou, N., & Constantinou, C. P. (2005). The properties and the nature of light: The study of Newton's work and the teaching of optics. *Science & Education, 14*, 649-673. https://doi.org/10.1007/s11191-004-5609-6

Roehrig, G. H., Dare, E. A., Ellis, J. A., & Ring-Whalen, E. (2021). Beyond the basics: A detailed conceptual framework of integrated STEM. *Disciplinary and Interdisciplinary Science Education Research, 3*, Article 11. https://doi.org/10.1186/s43031-021-00041-y

Rosa, R. (2012). The Merli-Missiroli-Pozzi two-slit electron-interference experiment. *Physics in Perspective, 14*, 178-195. https://doi.org/10.1007/s00016-011-0079-0

Rudge, D. W., & Howe, E. M. (2009). An explicit and reflective approach to the use of history to promote understanding of the nature of science. *Science & Education, 18*, 561-580. https://doi.org/10.1007/s11191-007-9088-4

Schmid, J. M., Veith, J., & Bitzenbauer, P. (2026). Cognitive dimensions in students' mental models of linear light polarization. *Physical Review Physics Education Research, 22*, Article 010118. https://doi.org/10.1103/hng2-97bk

Shapiro, A. E. (2002). Newton's optics and atomism. In I. B. Cohen, & G. E. Smith (Eds.), *The Cambridge companion to Newton* (pp. 227-255). Cambridge University Press. https://doi.org/10.1017/CCOL0521651778.008

Sidekerskienė, T., & Damaševičius, R. (2025). Pedagogical memes: A creative and effective tool for teaching STEM subjects. *International Journal of Mathematical Education in Science and Technology, 56*(7), 1230-1260. https://doi.org/10.1080/0020739X.2024.2328818

Sokolowski, A. (2013). Teaching the photoelectric effect inductively. *Physics Education, 48*, Article 35. https://doi.org/10.1088/0031-9120/48/1/35

Stadermann, H., van den Berg, E., & Goedhart, M. (2019). Analysis of secondary school quantum physics curricula of 15 different countries: Different perspectives on a challenging topic. *Physical Review Physics Education Research, 15*, Article 010130. https://doi.org/10.1103/PhysRevPhysEducRes.15.010130

Steinberg, R. N., Oberem, G. E., & McDermott, L. C. (1996). Development of a computer-based tutorial on the photoelectric effect. *American Journal of Physics, 64*, 1370-1378. https://doi.org/10.1119/1.18360

Stix, G. (2004). The patent clerk's legacy. *Scientific American, 291*(3), 44-49. https://www.jstor.org/stable/26060681

Strnad, J. (1986). Photons in introductory quantum physics. *American Journal of Physics, 54*, 650-652. https://doi.org/10.1119/1.14526

Stuewer, R. H. (2000). The Compton effect: Transition to quantum mechanics. *Annalen der Physik, 512*(11-12), 975-989. https://doi.org/10.1002/andp.200051211-1216

Stuewer, R. H. (2006). Einstein's revolutionary light-quantum hypothesis. *ACTA PHYSICA POLONICA SERIES B, 37*(3), Article 543. https://ui.adsabs.harvard.edu/abs/2006AcPPB..37..543S

Supurwoko, S., Cari, C., Sarwanto, S., Sukarmin, S., Budiharti, R., & Dewi, T. S. (2017). Virtual lab experiment: Physics educational technology (PhET) photo electric effect for senior high school. *International Journal of Science and Applied Science: Conference Series, 2*(1), 381-386. https://doi.org/10.20961/ijsascs.v2i1.16750

Süsskind, C. (1965). Hertz and the technological significance of electromagnetic waves. *Isis, 56*(3), 342-345. https://doi.org/10.1086/350002

Taslidere, E. (2016). Development and use of a three-tier diagnostic test to assess high school students' misconceptions about the photoelectric effect. *Research in Science & Technological Education, 34*(2), 164-186. https://doi.org/10.1080/02635143.2015.1124409

Tawfik, A. A., Graesser, A., Gatewood, J., & Gishbaugher, J. (2020). Role of questions in inquiry-based instruction: Towards a design taxonomy for question-asking and implications for design. *Educational Technology Research and Development, 68*, 653-678. https://doi.org/10.1007/s11423-020-09738-9

Thomas Becker, M. H., Heidemann, L. A., & Lima, N. W. (2024). History of science in physics education in the last decade: Which direction we are heading? *Science & Education, 34*, 3041-3078. https://doi.org/10.1007/s11191-024-00537-9

Tuveri, M., Steri, A., & Fadda, D. (2024). Using storytelling to foster the teaching and learning of gravitational waves physics at high-school. *Physics Education, 59*, Article 045031. https://doi.org/10.1088/1361-6552/ad4b87

Ubben, M. S., Veith, J. M., Merzel, A., & Bitzenbauer, P. (2023). Quantum science in a nutshell: Fostering students' functional understanding of models. *Frontiers in Education, 8*. https://doi.org/10.3389/feduc.2023.1192708

Ubben, M., & Bitzenbauer, P. (2023). Exploring the relationship between students' conceptual understanding and model thinking in quantum optics. *Frontiers in Quantum Science and Technology, 2*. https://doi.org/10.3389/frqst.2023.1207619

van den Berg, E., van Rossum, A., Grijsen, J., Pol, H., & van der Veen, J. (2020). Teaching particle-wave duality with double-slit single-photon interference in Dutch secondary schools. In J. Guisasola, & K. Zuza (Eds.), *Research and innovation in physics education: Two sides of the same coin. Challenges in physics education* (pp. 135-143). Springer. https://doi.org/10.1007/978-3-030-51182-1_11

Vohnsen, B. (2004). A short history of optics. *Physica Scripta, 2004*(T109), Article 75. https://doi.org/10.1238/Physica.Topical.109a00075

Voss, S., Kruse, J., & Kent-Schneider, I. (2022). Comparing student responses to convergent, divergent, and evaluative nature of science questions. *Research in Science Education, 52*, 1277-1291. https://doi.org/10.1007/s11165-021-10009-7

Weissman, E. Y., Merzel, A., Katz, N., & Galili, I. (2024). Keep it secret, keep it safe: Teaching quantum key distribution in high school. *EPJ Quantum Technology, 11*, Article 64. https://doi.org/10.1140/epjqt/s40507-024-00276-4

Wessels, L. (2013). Schrödinger's route to wave mechanics. In *Quantum mechanics* (pp. 115-144). Routledge. https://www.taylorfrancis.com/chapters/edit/10.4324/9781315023700-6/schr%C3%B6dinger-route-wave-mechanics-linda-wessels

Wieman, C. E., Adams, W. K., & Perkins, K. K. (2008). PhET: Simulations that enhance learning. *Science, 322*(5902), 682-683. https://doi.org/10.1126/science.1161948

Williams, C. T., & Rudge, D. W. (2019). Effects of historical story telling on student understanding of nature of science. *Science & Education, 28*, 1105-1133. https://doi.org/10.1007/s11191-019-00073-x

Winer, G. A., & Cottrell, J. E. (2004). The odd belief that rays exit the eye during vision. In D. T. Levin (Ed.), *Thinking and seeing: Visual metacognition in adults and children* (pp. 97-119). Boston Review. https://oneonta.ecampus.com/thinking-seeing-visual-metacognition/bk/9780262621816

Winer, G. A., Cottrell, J. E., Gregg, V., Fournier, J. S., & Bica, L. A. (2002). Fundamentally misunderstanding visual perception: Adults' belief in visual emissions. *American Psychologist, 57*(6-7), 417-424. https://doi.org/10.1037/0003-066X.57.6-7.417

Yalcin, M., Altun, S., Turgut, U., & Aggül, F. (2009). First year Turkish science undergraduates' understandings and misconceptions of light. *Science & Education, 18*, 1083-1093. https://doi.org/10.1007/s11191-008-9157-3

Young, T. (1802). II. The Bakerian lecture. On the theory of light and colours. *Philosophical Transactions of the Royal Society of London, 92*, 12-48. https://doi.org/10.1098/rstl.1802.0004

Young, T. (1804). I. The Bakerian lecture. Experiments and calculations relative to physical optics. *Philosophical Transactions of the Royal Society of London, 94*, 1-16. https://doi.org/10.1098/rstl.1804.0001

Zubairy, M. S. (2016). A *very* brief history of light. In M. D. Al-Amri, M. El-Gomati, & M. S. Zubairy (Eds.), *Optics in our time* (pp. 3-24). Springer. https://doi.org/10.1007/978-3-319-31903-2_1