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Technological failure as an epistemic resource for physics learning: A case study of DLP projector breakdown

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ABSTRACT

Digital technologies are deeply integrated into contemporary physics education, although their malfunctions are typically treated as logistical problems rather than as phenomena for scientific investigation. This exploratory qualitative case study examined how 34 pre-service primary teachers explained the persistent white dots produced by a malfunctioning digital light processing (DLP) projector and how their explanations developed during a two-session inquiry- and model-based instructional sequence. Data were collected through structured observation and hypothesis-generation tasks, classroom discourse, model-construction activities, and final written explanations. Initially, participants commonly attributed the white dots to external or generic causes, including dust, defective pixels, image files, or signal problems. During the inquiry phase, observations showing that the dots remained fixed across changes in image content, input source, and the projector's internal menu progressively constrained these explanations and directed attention toward an internal cause. During the model-based phase, simplified representations of the DLP optical pathway and micromirror array supported more explicit causal accounts linking immobilized micromirrors with the continuous direction of light toward the screen. The findings indicate a qualitative progression from phenomenological or generic fault descriptions toward more mechanistic explanations, although this development was not uniform across participants. The study does not establish the general effectiveness of inquiry- and model-based instruction; rather, it illustrates how a stable technological malfunction can provide a context for evidence-based hypothesis evaluation and causal model construction in physics learning.

Keywords: physics education, technological failure, pre-service primary teachers, mechanistic reasoning, digital projection

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INTRODUCTION

Digital projection technologies have evolved into an integral yet unobtrusive component of modern classrooms and lecture halls, facilitating presentations, simulations, student projects, and multimedia explanations at all educational levels. Systematic reviews of multimedia utilization in higher education consistently indicate beneficial impacts on engagement and learning when these technologies are congruent with pedagogical objectives, while also acknowledging that technical limitations and failures continue to pose significant obstacles to effective implementation (Staneviciene & Žekienė, 2025). In daily teaching practice, these limits are often regarded as practical disturbances to be mitigated or circumvented, rather than as potential subjects for investigation. This dominant perspective is problematic from a physics teaching standpoint. Classroom technologies are not impartial delivery mechanisms; rather, they are material systems whose functionality, limitations, and malfunctions are dictated by physical laws. Regarding them as transparent instruments jeopardizes the clarity of the mechanical links and material dependencies that physics aims to elucidate.

Recent research in science education has highlighted the significance of authenticity in learning, defined not only as the incorporation of real-world contexts but also as learners' involvement with meaningful phenomena, practices, and artifacts that encourage interpretation and explanation (Nachtigall et al., 2024; Yonai et al., 2024). In this context, authenticity is relational rather than intrinsic; it arises when learners are encouraged to explore phenomena that are not entirely predetermined and whose explanations are not readily available. Simultaneously, studies on context-based and artifact-centered learning indicate that tangible items can serve as effective anchors for conceptual growth, provided that students are assisted in linking visible characteristics to fundamental mechanisms (Gilbert, 2006; Herrington et al., 2014). In the majority of classes, technological artifacts are typically seen just in their operational condition. Upon failure, the customary pedagogical approach is to promptly replace or repair the elements, thus reinstating the educational flow but simultaneously precluding prospects for meaningful comprehension. This routine management of malfunctions exemplifies and perpetuates a black-box perspective of technology, wherein technologies are regarded as inscrutable, cohesive, and predominantly outside the realm of scientific elucidation.

From a physics education perspective, this black-boxing represents a squandered opportunity. Philosophers of technology contend that technological systems encapsulate physical models, design assumptions, and material compromises, asserting that comprehending technology necessitates an engagement with its materiality rather than solely its functionality (de Vries, 2005; Vincenti, 1990). Research on technology-integrated science instruction indicates that conceptual understanding improves when learners are prompted to investigate the functioning and behavior of devices, rather than utilizing them solely as instructional tools (Hew & Brush, 2007). Failure, specifically, provides a distinctive epistemic insight into system architecture. Engineering evaluations highlight that failures are not external abnormalities of design but inherent expressions of material limitations, deterioration, and compromises (Petroski, 2012). When a system malfunctions, underlying components, dependencies, and constraints are frequently exposed. Such instances can disrupt learners' simplistic beliefs about technology and encourage more developed mechanistic analysis.

Despite the established literature on anomalous data, cognitive conflict, authentic inquiry, and learning through engineering failure, a specific conceptual and empirical gap remains. In physics education, anomalous data generally refer to observations that conflict with learners' prior conceptions and are often introduced within deliberately designed experiments. Cognitive conflict similarly describes the psychological and conceptual tension produced when evidence challenges an existing belief. In both cases, the phenomenon is normally embedded in an instructional setting in which the apparatus has already been designated as an object of scientific investigation and the teacher has anticipated, at least broadly, the conceptual direction of the activity.

Technological failure, as conceptualized in the present study, differs from these instructional anomalies in three respects. First, it originates unintentionally within an artifact that ordinarily functions as an instructional tool rather than as an object of inquiry. Second, it interrupts an established practice of use and thereby exposes components, dependencies, and material constraints that normally remain hidden from learners. Third, it challenges not only a specific physical conception but also a broader epistemological assumption that digital technologies are seamless, immaterial, or scientifically opaque. The failure therefore creates an opportunity to investigate both the physical mechanism responsible for the malfunction and the nature of technological systems as material constructions governed by physical laws.

This perspective also differs from conventional troubleshooting. Troubleshooting is primarily directed toward locating a fault and restoring the intended operation of a device. Its success is generally evaluated in practical terms: whether the system can be repaired, reset, or replaced. The pedagogical use of technological failure proposed here does not require the device to be repaired. Instead, the malfunction is temporarily stabilized as an epistemic object and examined for what it reveals about the device's physical architecture, causal mechanisms, and material limitations. The emphasis consequently shifts from restoring functionality to constructing an explanation.

The approach is related to engineering analyses of failure, which use breakdowns to understand design assumptions, material limitations, and system vulnerabilities. However, the present study extends this reasoning into physics education by examining how learners, rather than professional engineers, interpret an unplanned failure in a familiar classroom technology. It also extends authentic inquiry by suggesting that authenticity can emerge not only from intentionally selected real-world problems but also from unscripted events whose causes are initially unknown to both the learners and, in some cases, the instructional sequence itself. Technological failure is therefore not presented as an entirely separate learning theory. Rather, it is proposed as a distinctive pedagogical category that brings together authentic inquiry, attention to technological materiality, and mechanistic reasoning within an unplanned classroom event.

Against this conceptual background, the study examines a visually distinctive failure mode of a digital light processing (DLP) projector: the appearance of persistent white dots associated with micromirrors immobilized in the "on" position. The phenomenon establishes a direct explanatory relationship between a macroscopic image artifact and microscopic processes within a microelectromechanical system (MEMS). Each persistent point of light can be related to the loss of controlled motion in an individual micromirror and, more broadly, to optical directionality, electrostatic actuation, adhesion, fatigue, or material degradation. The phenomenon therefore affords reasoning across several levels of description, linking visible optical effects with microscale mechanical and material processes.

In this study, technological failure is defined as a stable and perceptible malfunction of a material system that interrupts habitual use and renders previously concealed structures, processes, or constraints available for investigation. When pedagogically reframed as an object of inquiry, such a failure may function as an epistemic resource by supporting observation, hypothesis formation, model construction, causal explanation, and reflection on the material nature of technology.

The contribution of the study is threefold. Theoretically, it examines technological failure as an authentic phenomenon that can support mechanistic reasoning when learners are required to connect observable effects with underlying physical processes. Empirically, it provides an exploratory qualitative account of how pre-service primary teachers initially explained a genuine DLP projector malfunction and how their explanations developed during a short inquiry- and model-based instructional sequence. Pedagogically, it illustrates how a stable technological malfunction can be structured as an explanatory problem involving observation, hypothesis generation, evaluation of competing explanations, model construction, and revision of explanations. The study does not claim that technological failure constitutes a universally effective instructional strategy. Rather, it examines how one authentic malfunction provided a context for evidence-based inquiry and model-supported causal explanation, thereby identifying processes that may be investigated in future research across other technological phenomena and educational settings.

Accordingly, the study was guided by the following two research questions (RQs):

RQ1: How do pre-service primary teachers explain the persistent white dots observed in the projected image of a malfunctioning DLP projector?

RQ2: How does an inquiry- and model-based instructional sequence influence pre-service primary teachers' explanations of the persistent white-dot phenomenon?

THEORETICAL FRAMEWORK

This study draws on three interconnected perspectives: relational authenticity, the materiality of technology, and mechanistic and model-based reasoning. Together, they provide an analytic framework for examining how an unintended technological failure can be transformed from a disruption of routine classroom practice into an object of scientific explanation.

Authenticity is not treated here as an inherent property of a real-world object or situation. Rather, it emerges through the relationship among learners, the phenomenon, the task, and the disciplinary practices in which they participate (Herrington et al., 2014; Nachtigall et al., 2024). A familiar technological artifact becomes epistemically authentic when learners are invited to observe it closely, pose questions, evaluate competing explanations, and construct an account of an initially unresolved phenomenon.

The educational value of the malfunction therefore lies not simply in its occurrence in a real classroom but in the opportunities for sense-making created through its pedagogical framing (Yonai et al., 2024).

The second perspective concerns the materiality of technology. Technological devices embody physical principles, design choices, materials, and constraints, even when their mechanisms remain concealed during normal operation (de Vries, 2005; Vincenti, 1990). Treating classroom technologies solely as content-delivery instruments may reinforce black-box interpretations in which their outputs are familiar but their internal structures are viewed as inaccessible. Examining operation and failure can make these structures more visible and can direct attention to the physical and engineering compromises underlying technological systems (Hew & Brush, 2007; Petroski, 2012).

The third perspective concerns mechanistic and model-based reasoning. Learners frequently find it difficult to connect observable phenomena with underlying entities and processes, especially when these operate at scales beyond direct perception (Chi, 2005; Vosniadou, 2013). Mechanistic explanations identify the entities involved, the activities in which they participate, and the causal relationships through which an observed effect is produced (diSessa, 2007). Model-based inquiry can support this process by providing representations that learners can use to generate, evaluate, and revise explanations (Tytler et al., 2013; Windschitl et al., 2008).

The DLP white-dot phenomenon brings these perspectives together. It is an authentic, unplanned event involving a material technological system, and its explanation requires coordination between a visible macroscopic effect and microscopic mechanisms. Simplified representations of the optical pathway and micromirror array may assist learners in connecting the stable luminous dots with the loss of controlled micromirror motion and the directional reflection of light. This type of micro-macro coordination is an important challenge in physics learning (Ainsworth, 2006; Müller et al., 2017).

In the present analysis, these perspectives guide attention to two related aspects of participants' reasoning: how they initially explained the persistent white-dot phenomenon and how their explanations developed during the inquiry- and model-based instructional sequence. Particular attention is given to the ways participants evaluated competing explanations against observational evidence and used simplified models to construct increasingly explicit causal accounts linking the visible white dots with the behavior of individual micromirrors. Epistemic engagement is therefore interpreted through participants' efforts to construct, compare, evaluate, and revise explanations during the activity (Chinn et al., 2011).

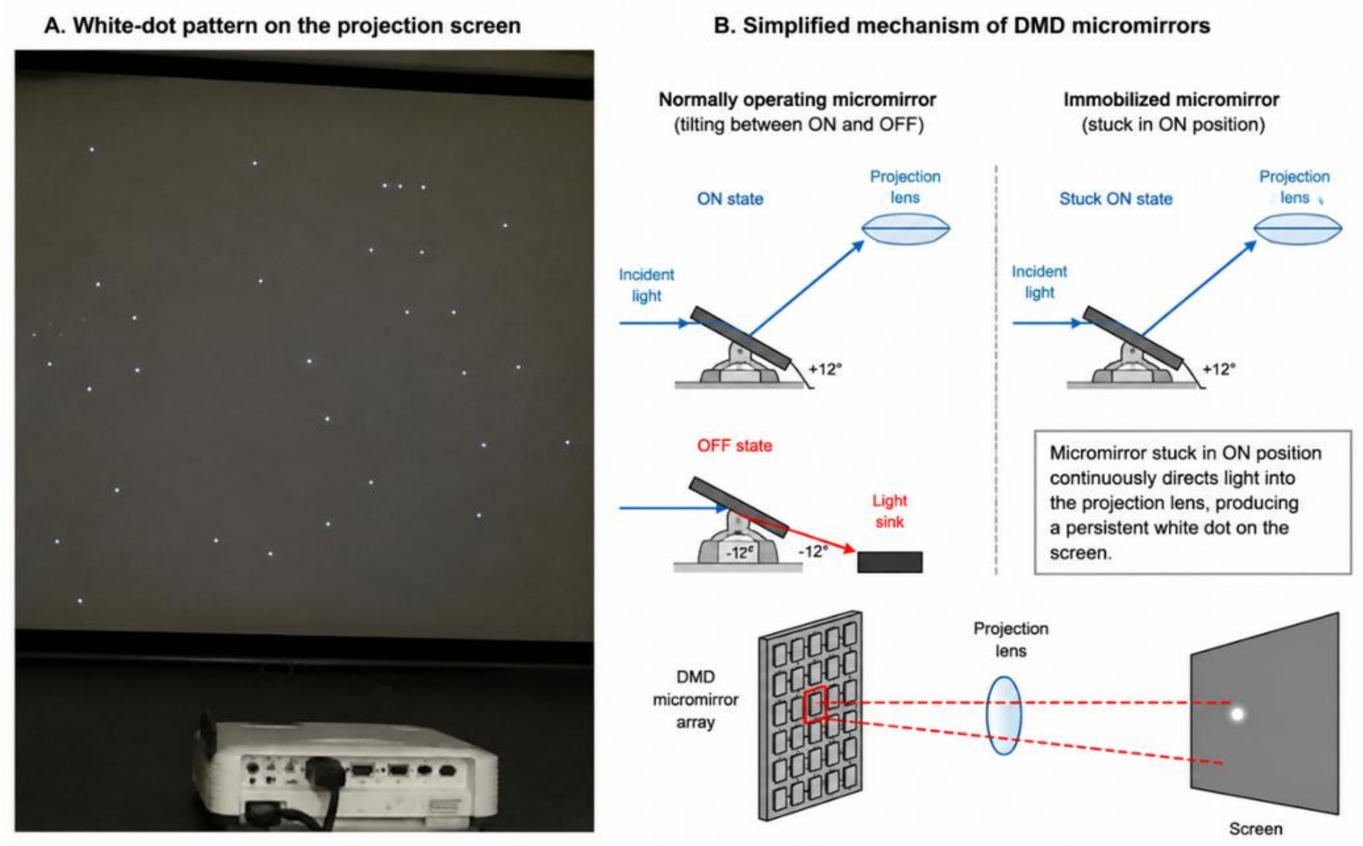

Figure 1. Observable manifestation and physical mechanism of DLP white-dot failure (the schematics are simplified for educational purposes and are not drawn to scale) (the photograph was taken by the author and the schematic was created by the author)

THE PHENOMENON: DLP WHITE-DOT FAILURE

This study's empirical and conceptual work is based on a prevalent technological phenomenon: the emergence of many stable white dots in the projected image of a DLP projector. The dots are observable across all input sources and are there even in the projector's internal menu interface, suggesting that their source is within the device's imaging core rather than the signal chain, computer output, or external optics. In educational environments, such artifacts are generally seen as indicators of obsolete equipment and are managed through maintenance or replacement. From a physics standpoint, they represent direct optical indicators of micro-scale mechanical and material processes within an actual technological system.

Figure 1 presents the observable white-dot pattern and a simplified representation of how an immobilized micromirror in the "on" position continuously directs light into the projection pathway.

Insert a two-panel figure immediately after the paragraph explaining that immobilized micromirrors produce stable illuminated points.

Panel A: Photograph of the projected image showing the persistent white dots in fixed screen positions.

Panel B: Simplified schematic of a DLP micromirror array illustrating a normally operating mirror that alternates between the projection lens and light sink, and an immobilized mirror in the "on" position that continuously reflects light toward the screen.

As illustrated in **Figure 1**, a micromirror immobilized in the "on" position continuously directs light into the projection lens, producing a stable luminous point whose screen position does not change with the digital content.

DLP projection relies on a digital micromirror device (DMD), a MEMS composed of an array of hundreds of thousands to millions of micrometer-scale mirrors produced by semiconductor fabrication methods. Each micromirror represents an individual pixel in the projected image and can oscillate between two stable orientations, directing incoming light either into the projection lens or towards a light sink. The technology utilizes temporal integration in human vision to generate grayscale and color images by swiftly toggling these mirrors on and off (Dudley et al., 2003; Hornbeck, 1996). The DMD operates as a spatial light modulator within a certain illumination geometry, characterized by exact angular relationships among the light source, the micromirror surface, and the projection optics (Zhu et al., 2015). The clarity and contrast of DLP pictures are fundamentally reliant on the capacity of each mirror to maneuver freely and to consistently stabilize in its designated position.

When a micromirror is mechanically or electrostatically fixed in the "on" position, it perpetually channels light into the optical path, resulting in a consistently illuminated point on the screen irrespective of the digital image content. Each mirror corresponds directly to a pixel point, resulting in such failures manifesting as distinctly defined white dots. When several mirrors malfunction in this manner, the resultant pattern may resemble a constellation of luminous dots dispersed throughout the image. Significantly, these artifacts are not ephemeral noise but enduring characteristics, indicating the permanent condition of particular micro-scale elements. Their stability is a crucial diagnostic characteristic, differentiating them from dust contamination, which generally results in diffuse shadows, or from signal artifacts, which fluctuate with content.

From a physical and technical perspective, micromirrors may become immobilized in the activated state due to a combination of microscale mechanical, material, and electrostatic processes. At small length scales, surface forces such as adhesion and stiction can inhibit mirror release, particularly as coatings degrade and surface chemistry changes under prolonged thermal cycling (Huang et al., 2012; Maboudian & Howe, 1997). In addition, each micromirror undergoes billions of actuation cycles during normal operation, making hinge fatigue a plausible long-term failure mechanism that can bias mirrors toward a single orientation (Bagdahn & Sharpe, 2003; Calegaro et al., 2024). Electrostatic actuation further introduces vulnerability to charge trapping and dielectric aging, processes that are accelerated by elevated operating temperatures common in projector systems (Huang et al., 2012; Xu et al., 2024).

For the purposes of physics education, the importance of these mechanisms lies not in their precise technical distinction but in their shared consequence: the permanent loss of controlled micromirror motion. This loss transforms each affected micromirror into a stable optical element that continuously directs light into the projection path, thereby producing a persistent white dot on the screen. The underlying failure may involve mechanical, material, or electrostatic degradation that results in localized loss of function.

The irreversibility of the white-dot phenomenon is a direct consequence of these microphysical mechanisms. The failure, usually due to structural fatigue, surface adhesion, or dielectric degradation, cannot be resolved through external cleaning, software resets, or light replacement. Disassembling and cleaning the optical path will not restore functionality to a shattered hinge or a mirror that has been irreversibly affixed to its landing pad. From an engineering standpoint, the sole conclusive solution is the replacement of the DMD chip or the entire light engine, a process that is financially unfeasible for several educational institutions. The statistical characteristics of MEMS failure indicate that flaws typically manifest progressively, with isolated instances arising and subsequently multiplying over time as cumulative pressures exert their influence (Xu et al., 2024).

The importance of this phenomenon in physics education resides not in its technical diagnosis but in its capacity for explanation. The white dots on the screen are not random artifacts but direct optical representations of the mechanical and material constraints of a genuine micro-scale system. They offer a unique and tangible connection between a macroscopic, perceptually prominent effect and microscopic physical phenomena. Each luminous point can be attributed, in theory, to the movement or stillness of a particular mirror, the pressures exerted upon it, and the characteristics of the materials from which it is constructed. This hierarchical chain of causality renders the phenomenon particularly conducive to mechanistic reasoning and facilitates the coordination of microscopic and macroscopic descriptions, a challenge long acknowledged in physics education (Chi, 2005; Vosniadou, 2013). This failure pattern was the central phenomenon guiding students' observations, ideas, and models, facilitating the investigation of optics, micro-mechanics, and material behavior within a unified environment.

METHODOLOGY

This study employed a qualitative case study design to investigate how a conspicuous technological failure in a classroom context can serve as an epistemic resource for physics education. The case study methodology is especially effective for examining intricate, context-dependent phenomena where the distinctions between the phenomenon and its environment are not distinctly defined (Yin, 2018). The phenomenon of interest in this case was inextricably linked to the classroom's material environment and the instructional choices that influenced the framing and examination of the malfunction. The objective was not to generate statistically generalizable assertions, but to construct a comprehensive, theoretically grounded narrative regarding learners' interactions with a genuine technology failure and the evolution of their reasoning in response.

The research was carried out at a university course focused on physics teaching for pre-service primary educators. The subject is integral to a teacher preparation program, emphasizing conceptual comprehension of physical processes and pedagogical strategies appropriate for primary schools. The participants were 34 third-year pre-service primary teachers, most of whom had limited prior experience with microtechnology, advanced optics, or the internal mechanisms of digital devices. The educational environment was a conventional lecture room featuring a ceiling-mounted DLP projector that exhibited a distinct pattern of persistent white dots observable on all projected material and within the projector's internal menu. The instructor intentionally integrated the device's malfunction into the lecture sequence as a central phenomenon for investigation. This conclusion was conveyed clearly to the students, framing the projector not as a flawed instrument to be disregarded but as a subject for examination. Ethical approval was secured from the appropriate institutional committee, and all participants granted informed consent for the collection and utilization of data for study purposes.

The instructional intervention took place during two consecutive 90-minute sessions. Its sequence was informed by inquiry-oriented and model-based approaches emphasizing observation, hypothesis generation, comparison of alternative explanations, model construction, and revision of explanations (Hmelo-Silver et al., 2007; Windschitl et al., 2008). Five complementary qualitative data-collection instruments were used:

(a) a structured observation sheet,

(b) a written hypothesis-generation prompt,

(c) a model-construction sheet incorporating simplified representations of the DLP optical pathway and micromirror array,

(d) a final written explanation and reflection form, and

(e) an instructor observation protocol used for field notes.

In addition, whole-class discourse was audio-recorded and transcribed to provide a record of participants' verbal reasoning during the inquiry. These instruments were developed specifically for the present study rather than adapted from standardized scales. Their design followed the successive stages of the instructional sequence so that participants' reasoning could be documented before, during, and after the model-based inquiry. The observation sheet focused on describing the visible phenomenon and identifying empirical regularities; the hypothesis prompt elicited initial causal explanations and predictions; the model-construction task examined how participants connected micromirror behavior with the observed white dots; and the final written task elicited their revised explanation after the inquiry. The instruments were therefore designed as qualitative elicitation tools for tracing changes in participants' explanations, rather than as psychometric measures intended to generate numerical scores.

The instructional sequence was organized as a guided inquiry progressing through observation, hypothesis generation, testing of explanations against evidence, model construction, and revision of explanations. During the first session, the inquiry began with direct observation of the malfunctioning projector, before participants received any information about its internal operation. Using the structured observation sheet, participants examined the color, shape, apparent size, location, and stability of the white dots and investigated whether the pattern changed when the projected background, image content, computer input, or projector menu was altered. This first phase established the empirical evidence that subsequent explanations had to account for.

In the second phase of the inquiry, participants generated possible explanations for the phenomenon. They proposed one or more causes and identified observations that could support or challenge each hypothesis. Participants initially worked individually and subsequently compared competing explanations in small groups and whole-class discussion. The instructor facilitated the inquiry through questions such as "What remains unchanged?", "Where in the system could the cause be located?", and "What would this explanation predict if the input source changed?" Rather than providing the correct explanation, these prompts encouraged participants to evaluate their hypotheses against the available evidence and progressively eliminate explanations that were inconsistent with the observations.

The second session introduced the model-based phase of the inquiry. Participants were provided with simplified representations of the projector's optical pathway and DLP micromirror array and were asked to use these representations as explanatory models. They identified relevant components, traced the direction of light, and constructed a causal sequence linking the condition of an individual micromirror to the persistent white dot observed on the screen. Finally, participants reconsidered their initial hypotheses and produced revised explanations based on the observational evidence and the model. Thus, inquiry and modeling were not separate activities: the model was introduced as a resource for resolving the explanatory problem generated during the preceding inquiry. Throughout the sequence, the instructor deliberately withheld the complete explanation and supported participants through questioning, comparison of alternatives, and evidence-based revision.

At the end of the activity, participants completed a final written explanation in which they were asked to account for the persistent white-dot phenomenon in their own words and to revise their initial explanation in light of the observational evidence and the DLP model. This task provided a post-inquiry record of the causal explanations participants constructed after completing the inquiry- and model-based sequence.

Multiple qualitative data sources were collected. The observation sheets documented participants' initial descriptions and hypotheses. The hypothesis-generation responses captured the alternative explanations proposed during the inquiry phase. The model-construction sheets and diagrams documented how participants represented the relationships among micromirrors, light direction, and the projected image. The final written explanations recorded the causal accounts produced after participants had evaluated the observational evidence and used the simplified DLP representations.

Classroom discourse was audio-recorded and transcribed to capture the explanations proposed during whole-class discussion, the questions participants asked, the ways competing hypotheses were compared, and the language used to connect observable effects with internal mechanisms. The recording was used as a record of verbal sense-making rather than as a measure of participation frequency. Quotations reported in the results were drawn from this transcript and were labeled as classroom discourse.

The instructor's field notes focused on observable features that were not fully represented in the written artifacts or audio transcript. These included sustained visual attention to the projected pattern, expressions of surprise or uncertainty, spontaneous questioning, peer-to-peer explanation, and moments when a new observation or representation appeared to redirect the discussion. The field notes were interpretive records and were therefore considered alongside, rather than independently of, the classroom transcript and participant artifacts. Triangulation across discourse, written work, diagrams, reflections, and field notes was used to strengthen the credibility of the interpretations (Denzin, 2009).

The data were examined through an iterative thematic analysis informed by established principles of qualitative educational research (Braun & Clarke, 2006; diSessa, 2007). The initial coding cycle focused on the form and explanatory scope of participants' accounts. Codes distinguished external causes, unspecified internal damage, internal components without causal processes, partial mechanistic explanations, and mechanistic explanations linking identifiable entities, activities, and optical consequences.

A second coding cycle focused on changes in the causal structure and specificity of participants' explanations across the instructional sequence. Particular attention was given to whether participants moved from external or generic fault descriptions toward explanations that identified an internal component, specified its behavior, and linked that behavior causally to the persistent white-dot pattern. The analysis also examined how participants used observational evidence to reject or revise earlier hypotheses and how the simplified DLP model contributed to the construction of more mechanistic explanations.

Evidence from the different data sources was compared across the successive phases of the instructional sequence in order to trace changes in participants' explanations from initial hypothesis generation through inquiry-based evaluation and model-supported revision.

Throughout the analysis, evidence from the different sources was compared to trace the development of reasoning across the instructional sequence. Initial observation sheets and hypotheses were contrasted with later diagrams, explanations, discourse excerpts, and reflections. Codes were revised and combined through constant comparison as the distinctions among phenomenological, transitional, partial mechanistic, and mechanistic explanations became clearer.

The analysis, aligned with the interpretive orientation of the study, focused not on measuring code frequencies but on constructing a coherent narrative of the evolution of students' thinking throughout the intervention. Analytic attention centered on identifying shifts in the explanatory resources students employed, particularly transitions from phenomenological descriptions to explanations that invoked internal structures, causal mechanisms, and physical constraints. For example, early references to external causes such as "dust" or "signal problems" were contrasted with later explanations that explicitly linked the stability of the white dots to the persistent orientation of individual micromirrors and the directional control of light.

Selected excerpts from transcripts and written artifacts were used to illustrate typical and theoretically salient forms of reasoning rather than to establish representativeness through frequency. To enhance credibility, emerging interpretations were documented through analytic memos and discussed with a colleague experienced in physics education research who was not involved in the intervention, providing a form of peer debriefing. The analytic focus remained on tracing the sense-making process as it unfolded through discourse and artifacts, rather than on evaluating instructional effectiveness against predefined learning outcomes.

This methodological approach reflects the study's interpretive orientation by treating learning as a contextually situated and socially mediated process. The analysis focused on classroom discourse and participant artifacts to examine both the understandings that participants developed and the processes through which those understandings emerged. This methodological orientation is well established in physics education research, particularly in detailed studies of classroom interaction and reasoning concerned with conceptual change, epistemic framing, and the development of mechanistic understanding (diSessa, 2007; Hammer & Berland, 2014). This setting facilitates a thorough analysis of how a genuine technological failure was embraced by learners and reconstituted as an explanatory object.

RESULTS

The analysis was organized around the two RQss and focused specifically on participants' explanations of the persistent white-dot phenomenon and on how these explanations developed during the inquiry- and model-based instructional sequence. For **RQ1**, the analysis examined the explanations proposed before participants received information about the internal operation of the DLP projector. For **RQ2**, these initial explanations were compared with the explanations produced as participants examined observational evidence, evaluated competing hypotheses, used simplified models of the optical pathway and micromirror array, and revised their accounts. Evidence was drawn from observation sheets, hypothesis-generation responses, classroom discourse, model-construction tasks, and final written explanations. The purpose was not to quantify learning gains, but to trace qualitative changes in the structure and causal specificity of participants' explanations across the instructional sequence.

Table 1. Development of explanatory reasoning across the instructional sequence

Phase of reasoning	Analytic characteristics	Illustrative evidence	Data source
Initial phenomenological reasoning	Explanations referred mainly to visible effects, familiar technical faults, or external causes, without identifying internal entities or causal processes.	"Dust"; "dead pixels"; "a signal problem"; "something broken."	Initial observation sheets and small-group discussion, WA/CD
Intermediate internal-cause reasoning	Participants rejected some external explanations and located the cause inside the projector, although the internal mechanism remained undifferentiated.	"It must be something in the projector itself"; "a stationary component"; "an obstruction."	Whole-class discussion, CD
Partial mechanistic reasoning	Participants identified an internal component but did not fully explain the role of light direction.	"Stuck switches"; "broken pixels."	Written explanations and group discussion, WA/CD
Emerging mechanistic reasoning	Explanations identified an internal entity, its activity or loss of activity, and the resulting optical effect.	"If the mirror cannot move, then the light consistently travels there, thus the dot is perpetually bright."	Post-model written explanation, WA

For transparency, the evidence is presented across three broad stages of reasoning: initial phenomenological reasoning, intermediate internal-cause reasoning, and post-model reasoning; the latter included both partial and more fully developed mechanistic explanations. Quotations from classroom discourse are identified as CD, while statements from observation sheets, hypothesis-generation tasks, model-construction activities, and final written explanations are identified as WA. **Table 1** shows the development of explanatory reasoning across the instructional sequence.

Initial Explanations of the Persistent White Dots

In response to **RQ1**, the participants initially explained the persistent white dots mainly in terms of familiar external or generic technological faults. Before receiving information about the internal operation of the DLP projector, common explanations included "dust," "dead pixels," "a signal problem," and "something broken." These accounts were predominantly phenomenological because they named possible faults without specifying the physical entities, processes, or causal relationships responsible for producing stable luminous points.

Several participants attributed the phenomenon to dust on the lens or another form of optical contamination, while others proposed defective pixels, corrupted image files, or problems with the HDMI connection or computer signal. Although these explanations differed in their proposed source, they shared a common characteristic: they treated the projector largely as a functional whole and did not refer to its internal micromechanical structure.

The initial explanations therefore showed limited mechanistic reasoning. Participants generally identified possible categories of malfunction rather than explaining how a particular internal process could produce white dots that remained fixed in the same positions on the projected image. At this stage, the relationship between the visible optical effect and the internal physical operation of the projector had not yet been established.

Influence of the Inquiry- And Model-Based Sequence on Participants' Explanations

In response to **RQ2**, participants' explanations changed progressively during the inquiry- and model-based instructional sequence. The inquiry phase first required participants to evaluate their initial explanations against observational evidence. They examined whether the white dots changed when the projected background, image content, connected computer, and input source were altered. The persistence of the dots under these changes, and particularly their appearance in the projector's internal menu, weakened explanations based on dust, image files, the computer, or the external signal. Participants consequently began to locate the cause within the projector itself. Statements such as "it must be something in the projector itself," "a stationary component," and "an obstruction" represented an intermediate stage of reasoning: the proposed cause had shifted from an external source to an internal one, although the mechanism remained unspecified.

The model-based phase supported a further development in participants' explanations. After examining simplified representations of the DLP optical pathway and micromirror array, participants began to identify the micromirror as the relevant entity, its movement or failure to move as the relevant physical process, and the direction of reflected light as the causal connection between the internal mechanism and the visible white dot. One written explanation stated: "If the mirror cannot move, then the light consistently travels there, thus the dot is perpetually bright" (WA). Another participant explained that an immobilized mirror would "consistently direct light to the screen" (WA). In contrast to the initial references to generic faults, these explanations connected a specific internal physical condition with the observed optical effect.

The two phases played complementary roles in the development of the explanations. Inquiry enabled participants to test competing hypotheses against observable evidence and progressively reject explanations that were inconsistent with the behavior of the white dots. The model-based phase then provided the representational resources needed to construct a causal account connecting micromirror behavior with the direction of light. Thus, participants' explanations generally progressed from external or generic fault descriptions, through recognition of an unspecified internal cause, toward more explicit mechanistic explanations.

This progression was not uniform among all participants. Some continued to use partially specified expressions such as “stuck switches” or “broken pixels” without fully explaining how micromirror orientation controlled the direction of reflected light. The findings therefore indicate that the inquiry- and model-based sequence supported movement toward more mechanistic explanations but did not produce equally elaborated causal accounts among all participants.

Overall, the findings show that participants’ explanations developed from external or generic accounts of the white-dot phenomenon toward more specific explanations involving micromirror motion and the directional control of light. The inquiry phase supported the evaluation and rejection of explanations that were inconsistent with the observational evidence, while the model-based phase provided representational resources for constructing more explicit causal accounts. These developments were not uniform across all participants and should be interpreted as context-dependent qualitative changes observed during the two-session instructional sequence rather than as evidence of general instructional effectiveness.

DISCUSSION

The findings of this exploratory case show how pre-service primary teachers explained an initially unfamiliar technological phenomenon and how those explanations developed during an inquiry- and model-based instructional sequence. Participants initially proposed predominantly external or generic causes, including dust, defective pixels, and signal-related problems. As the inquiry progressed, observations concerning the persistence of the white dots across different images, inputs, and the projector’s internal menu constrained these initial hypotheses and directed attention toward an internal cause. The subsequent introduction of simplified models of the DLP optical pathway and micromirror array supported the construction of more explicit explanations connecting micromirror immobilization with the continuous direction of light toward the projection screen.

These findings suggest that the contribution of the instructional sequence was not simply the provision of the correct technical explanation. Rather, the inquiry phase enabled participants to evaluate competing explanations against observable evidence, while the model-based phase provided representational resources for constructing a causal account of the phenomenon. The progression from external or generic fault descriptions toward more mechanistic explanations therefore emerged through the combination of evidence-based inquiry and model-supported reasoning. However, this development was not uniform across all participants, and the findings should not be interpreted as evidence of general instructional effectiveness beyond the specific case examined here.

The findings are consistent with relational perspectives on authenticity, which emphasize learners’ epistemic engagement with a phenomenon rather than the mere presence of a real-world context or artifact (Herrington et al., 2014; Nachtigall et al., 2024; Yonai et al., 2024). The white-dot phenomenon created an authentic problem space because participants did not initially know its cause, the instructor did not immediately provide an explanation, and the activity required the coordination of observations, representations, and physical concepts. Within this particular instructional context, the disruption of habitual technology use appeared to support curiosity and sustained sense-making (Palmer, 2009). This interpretation does not imply that technological failure is inherently authentic or engaging; rather, authenticity emerged through the way the malfunction was pedagogically framed and investigated. The progression from superficial explanations toward more mechanistic accounts observed in the data is relevant to enduring challenges in physics education concerning micro-macro coordination. Research has shown that learners frequently experience difficulty connecting visible phenomena with underlying structures and processes, particularly when these involve scales beyond direct observation (Chi, 2005; Vosniadou, 2013). In the present case, the stability and visibility of the white dots provided a perceptual anchor for developing such connections.

Several participants related each luminous point to the movement or immobilization of an individual micromirror and to the resulting direction of reflected light. These explanations suggest emerging coordination between the macroscopic image artifact and the microscopic mechanism represented in the instructional model. They also contain central features of mechanistic reasoning by identifying relevant entities, activities, and causal interactions (diSessa, 2007). The statement that “if the mirror cannot move, then the light consistently travels there, thus the dot is perpetually bright” exemplifies an emerging causal chain connecting the internal condition of the device with the observed optical effect.

However, this development was not uniform across participants. Some continued to use partial analogies, such as “stuck switches” or “broken pixels,” without fully explaining how mirror orientation controlled the direction of reflected light. The findings therefore indicate the emergence of mechanistic and model-based reasoning within the activity rather than complete or consistent mastery across the participant group (Windschitl et al., 2008).

The case also contributes to discussions about the use of technological phenomena as contexts for physics explanation. Classroom technologies are usually employed as instructional tools, while the physical mechanisms underlying their operation remain largely outside the scope of instruction. In the present case, the projector malfunction provided an observable phenomenon that required participants to connect a visible optical effect with an internal physical mechanism.

The findings suggest that the educational value of the malfunction lay primarily in the explanatory problem it created. The persistence of the white dots across different inputs provided evidence that constrained initial hypotheses, while the simplified DLP model enabled participants to relate the observed pattern to micromirror motion and the directional reflection of light. The technological artifact therefore functioned as a context for coordinating observation, evidence, and causal explanation.

This interpretation should remain limited to the present case. The findings do not establish that technological malfunctions are generally effective learning contexts. Rather, they suggest that a stable and observable malfunction may support physics reasoning when learners can investigate its behavior, compare alternative explanations, and use an appropriate model to account for the observed effect.

The findings must be interpreted in light of several limitations. First, the study examined a single technological failure within one university teacher-education course and involved 34 pre-service primary teachers. The findings are therefore context-dependent and cannot be assumed to generalize to other populations, educational levels, technological systems, or instructional settings.

Second, the inquiry- and model-based sequence consisted of only two 90-minute sessions. The study therefore documents changes in participants' explanations within a short instructional sequence but cannot determine whether the resulting mechanistic explanations were retained over time or transferred to other physical or technological phenomena.

Third, the study employed an interpretive qualitative case-study design. The analysis focused on the structure, causal specificity, and development of participants' explanations rather than on numerical learning gains. No control group, standardized conceptual measure, or delayed assessment was used; consequently, the findings should not be interpreted as evidence of the comparative effectiveness of inquiry- and model-based instruction.

Future research could examine similar phenomena using larger and more diverse participant groups, pre- and post-intervention measures, delayed assessments, or comparative designs. Such studies could determine whether the explanatory progression identified here—from external or generic explanations toward more mechanistic accounts—also occurs across other technological failures and instructional contexts.

The convergence of evidence from classroom discourse, written explanations, observation sheets, and model-construction tasks supports the credibility of the interpretations developed within this case. The findings are not statistically generalizable and should not be assumed to transfer directly to other technologies, age groups, or educational settings. Their value lies instead in illustrating how participants' explanations developed as they evaluated observational evidence, reconsidered initial hypotheses, and used simplified models to construct more explicit causal accounts of the white-dot phenomenon.

In this case, the malfunction functioned as a stable and observable phenomenon around which inquiry and modeling could be organized. Whether similar technological failures can support comparable explanatory development will depend on the characteristics of the phenomenon, learners' prior knowledge, the availability of appropriate representations, and the nature of instructional guidance. Comparative research into different technological failures and educational settings is therefore needed before broader claims can be made. This context-dependent interpretation is consistent with qualitative case-study methodology, in which theoretical insight and transferability are prioritized over statistical generalization (Yin, 2018).

IMPLICATIONS FOR PHYSICS EDUCATION

The findings suggest that technological malfunctions may provide useful contexts for physics learning when they present stable, observable phenomena that can be investigated through evidence and explained through appropriate models. In the present case, the persistence of the white dots across different images, inputs, and the projector's internal menu provided participants with empirical constraints against which competing explanations could be evaluated.

The DLP case also illustrates the potential value of inquiry- and model-based learning for supporting mechanistic reasoning. The visible white dots served as a perceptual anchor for connecting a macroscopic optical effect with the microscopic behavior of individual micromirrors. The inquiry phase encouraged participants to compare alternative explanations with observational evidence, while the model-based phase provided a representation through which they could connect micromirror immobilization with the directional reflection of light. This coordination between observable effects and underlying mechanisms is an important challenge in physics learning (Chi, 2005; Vosniadou, 2013).

The findings therefore suggest that the instructional value of a technological malfunction lies not simply in its novelty or authenticity, but in whether it supports a sequence of observation, hypothesis generation, evidence-based evaluation, modeling, and explanation revision. Similar instructional possibilities may exist with other technological phenomena, although their educational value should be established empirically rather than assumed. Future studies should examine whether comparable inquiry- and model-based sequences support explanatory development across different technological failures, learner populations, and physics contexts.

CONCLUSION

This exploratory qualitative case study examined how pre-service primary teachers explained the persistent white dots produced by a malfunctioning DLP projector and how their explanations developed during an inquiry- and model-based instructional sequence. Initially, participants relied mainly on external or generic explanations, such as dust, defective pixels, or signal problems. As they tested these explanations against observational evidence, they progressively located the cause within the projector. The subsequent use of simplified representations of the DLP optical pathway and micromirror array supported the construction of more explicit causal explanations linking micromirror immobilization with the continuous direction of light toward the screen.

The findings therefore suggest that the instructional sequence supported explanatory development through two complementary processes. Inquiry enabled participants to evaluate competing hypotheses against observable evidence, while model-based learning provided the representational resources needed to connect the visible white-dot pattern with an underlying physical mechanism. The resulting progression was from external or generic fault descriptions toward more mechanistic accounts, although the level of explanatory development varied among participants.

The study does not establish the general effectiveness of inquiry- and model-based instruction, nor does it claim that technological malfunctions are inherently productive learning contexts. The findings derive from one technological failure, one group of 34 pre-service primary teachers, and a short two-session intervention. Their significance lies instead in illustrating how a stable and observable technological phenomenon can be used to support evidence-based hypothesis evaluation and causal model construction in physics learning.

Future research should examine whether similar explanatory progressions occur with other learner populations, technological phenomena, and instructional settings, and whether the resulting mechanistic explanations are retained over time. Comparative and longitudinal studies would also help clarify the conditions under which inquiry- and model-based approaches most effectively support the development of causal explanations in physics.

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REFERENCES

Ainsworth, S. (2006). DeFT: A conceptual framework for considering learning with multiple representations. *Learning and Instruction*, 16(3), 183-198. https://doi.org/10.1016/j.learninstruc.2006.03.001

Bagdahn, J., & Sharpe Jr, W. N. (2003). Fatigue of polycrystalline silicon under long-term cyclic loading. *Sensors and Actuators A: Physical*, 103(1-2), 9-15. https://doi.org/10.1016/S0924-4247(02)00328-X

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, 3(2), 77-101. https://doi.org/10.1191/1478088706qp063oa

Calegaro, D., Merli, M., Ferrari, G., & Mariani, S. (2024). Fatigue-induced failure of polysilicon MEMS: Nonlinear reduced-order modeling and geometry optimization of on-chip testing device. *Micromachines*, 15(12), Article 1480. https://doi.org/10.3390/mi15121480

Chi, M. T. H. (2005). Commonsense conceptions of emergent processes: Why some misconceptions are robust. *Journal of the Learning Sciences*, 14(2), 161-199. https://doi.org/10.1207/s15327809jls1402_1

Chinn, C. A., Buckland, L. A., & Samarapungavan, A. (2011). Expanding the dimensions of epistemic cognition: Arguments from philosophy and psychology. *Educational Psychologist*, 46(3), 141-167. https://doi.org/10.1080/00461520.2011.587722

de Vries, M. J. (2005). *Teaching about technology: An introduction to the philosophy of technology for non-philosophers*. Springer. https://doi.org/10.1007/1-4020-3410-5

Denzin, N. K. (2009). *The research act: A theoretical introduction to sociological methods* (2nd ed.). Routledge. https://doi.org/10.4324/9781315134543

diSessa, A. A. (2007). An interactional analysis of clinical interviewing. *Cognition and Instruction*, 25(4), 523-565. https://doi.org/10.1080/07370000701632413

Dudley, D., Duncan, W. M., & Slaughter, J. (2003). Emerging digital micromirror device (DMD) applications. In H. Urey (Ed.), *Proceedings of SPIE 4985: MOEMS display and imaging systems* (pp. 14-25). SPIE. https://doi.org/10.1117/12.480761

Gilbert, J. K. (2006). On the nature of "context" in chemical education. *International Journal of Science Education*, 28(9), 957-976. https://doi.org/10.1080/09500690600702470

Hammer, D., & Berland, L. K. (2014). Confusing claims for data: A critique of common practices for presenting qualitative research on learning. *Journal of the Learning Sciences*, 23(1), 37-46. https://doi.org/10.1080/10508406.2013.802652

Herrington, J., Reeves, T. C., & Oliver, R. (2014). Authentic learning environments. In J. M. Spector, M. D. Merrill, J. Elen, & M. J. Bishop (Eds.), *Handbook of research on educational communications and technology* (pp. 401-412). Springer. https://doi.org/10.1007/978-1-4614-3185-5_32

Hew, K. F., & Brush, T. (2007). Integrating technology into K-12 teaching and learning: Current knowledge gaps and recommendations for future research. *Educational Technology Research and Development*, 55(3), 223-252. https://doi.org/10.1007/s11423-006-9022-5

Hmelo-Silver, C. E., Duncan, R. G., & Chinn, C. A. (2007). Scaffolding and achievement in problem-based and inquiry learning: A response to Kirschner, Sweller, and Clark (2006). *Educational Psychologist*, 42(2), 99-107. https://doi.org/10.1080/00461520701263368

Hornbeck, L. J. (1996). Digital light processing and MEMS: Reflecting the digital display needs of the networked society. In *Proceedings of SPIE* (vol. 2783). SPIE. https://doi.org/10.1117/12.248477

Huang, Y., Vasan, A. S. S., Doraiswami, R., Osterman, M., & Pecht, M. (2012). MEMS reliability review. *IEEE Transactions on Device and Materials Reliability*, 12(2), 482-493. https://doi.org/10.1109/TDMR.2012.2191291

Maboudian, R., & Howe, R. T. (1997). Critical review: Adhesion in surface micromechanical structures. *Journal of Vacuum Science & Technology B*, 15(1), 1-20. https://doi.org/10.1116/1.589247

Müller, A., Hettmannsperger, R., Scheid, J., & Schnotz, W. (2017). Representational competence, understanding of experiments, phenomena and basic concepts in geometrical optics: A representational approach. In D. F. Treagust, R. Duit, & H. E. Fischer (Eds.), *Multiple representations in physics education* (pp. 209-229). Springer. https://doi.org/10.1007/978-3-319-58914-5_10

Nachtigall, V., Shaffer, D. W., & Rummel, N. (2024). The authenticity dilemma: Towards a theory on the conditions and effects of authentic learning. *European Journal of Psychology of Education*, 39(4), 3483-3509. https://doi.org/10.1007/s10212-024-00892-9

Palmer, D. H. (2009). Student interest generated during an inquiry skills lesson. *Journal of Research in Science Teaching*, 46(2), 147-165. https://doi.org/10.1002/tea.20263

Petroski, H. (2012). *To forgive design: Understanding failure*. Harvard University Press. https://doi.org/10.4159/harvard.9780674065437

Staneviciene, E., & Žekienė, G. (2025). The use of multimedia in the teaching and learning process of higher education: A systematic review. *Sustainability*, 17(19), Article 8859. https://doi.org/10.3390/su17198859

Tytler, R., Prain, V., Hubber, P., & Waldrip, B. (Eds.). (2013). *Constructing representations to learn in science*. Sense Publishers. https://doi.org/10.1007/978-94-6209-203-7

Vincenti, W. G. (1990). *What engineers know and how they know it: Analytical studies from aeronautical history*. Johns Hopkins University Press.

Vosniadou, S. (Ed.). (2013). *International handbook of research on conceptual change* (2nd ed.). Routledge. https://doi.org/10.4324/9780203154472

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education*, 92(5), 941-967. https://doi.org/10.1002/sce.20259

Xu, Y., Liu, S., He, C., Wu, H., Cheng, L., Yan, G., & Huang, Q. (2024). Reliability of MEMS inertial devices in mechanical and thermal environments: A review. *Heliyon*, 10(5), Article e27481. https://doi.org/10.1016/j.heliyon.2024.e27481

Yin, R. K. (2018). *Case study research and applications: Design and methods* (6th ed.). SAGE.

Yonai, E., Blonder, R., & Hofstein, A. (2024). The SEMinal impact of contemporary science: Integrated authentic science design and students' self-efficacy and career aspirations. *International Journal of Science Education*, 48(3), 315-341. https://doi.org/10.1080/09500693.2024.2411466

Zhu, X., Wang, C., Hao, W., Tian, L., & Wang, R. (2015). Optical design of a micro DLP projection system based on LEDs and an innovative light pipe. In *Proceedings of the 1st International Conference on Information Sciences, Machinery, Materials and Energy* (pp. 1188-1192). Atlantis Press. https://doi.org/10.2991/icismme-15.2015.253