



## From Geometric to Wave Optics: A Conceptual Change Strategy for Teaching the Mirage Phenomenon

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### ABSTRACT

#### Keywords:

Mirage; Wave Optics;  
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The mirage is traditionally explained through light refraction in thermally stratified air—a model rooted in geometrical optics. However, this classical framework faces empirical contradictions: field measurements reveal temperature gradients far smaller than required, yet mirages persist in cold, windy, and artificially illuminated conditions. Research by Tavassoly and colleagues resolves these anomalies by demonstrating that mirages are images formed directly on ground surfaces through coherent reflection at grazing angles—a phenomenon explicable only within wave optics. This model uniquely accounts for wavelength-dependent visibility and zero object-image separation, aligning with all observations. This article critically compares both frameworks, highlighting the limitations of geometrical optics and the explanatory power of wave optics in understanding this phenomenon. Furthermore, we propose a three-phase instructional strategy grounded in Conceptual Change Theory, addressing the Pedagogical Content Knowledge required for effective implementation. Through cognitive conflict, hands-on experimentation, and visual representation, students transition from geometric to wave-optics reasoning. By centering instruction on this indigenous scientific achievement, the approach fosters conceptual understanding, critical thinking, and national scientific identity, offering a novel pedagogical approach to optics education.

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## 1. INTRODUCTION

The mirage phenomenon has long captivated both the public and scientific community. For decades, physics textbooks have presented the inferior mirage—observed by drivers on hot highways as illusory water patches—as a quintessential example of geometric optics. The standard explanation attributes it to light refraction and total internal reflection within air layers possessing a vertical temperature gradient [1,2]. According to this classical model, heated ground creates hot, less dense air near the surface, causing light rays to bend upward and reach the observer's eye, creating a virtual image below the horizon. This refractive model has been reproduced in textbooks for over a century [3,4]. Tavassoly and Dashtdar [5,6] conducted field measurements in Iranian deserts (Qarpuzabad), recording temperature variations between ground and air. They attribute the formation of mirages to a strong vertical temperature gradient between the ground surface and the adjacent air layer, sometimes implying a rapid temperature difference of tens of degrees Celsius. However, such a large and highly localized temperature difference (e.g., a 20–30 °C temperature difference confined to a very thin near-surface layer) is physically unrealistic under typical outdoor conditions. As shown in Ref. [5], even a temperature difference as large as  $\Delta T \approx 50^\circ\text{C}$  in air produces a thermal variation spread over several millimeters rather than a sharply confined sub-millimeter layer. Therefore, the classical gradient-based explanation does not match the experimentally reported thermal behavior of near-ground air.

Beyond empirical difficulties, the classical model fails to account for wave-optical properties essential for image formation. Berry's [7] analysis of the "horizontal ray problem" suggests that geometrical optics, by itself, cannot explain continuous ray bending without conflicting with wave principles. A complete treatment requires considering light's wave nature [8], as geometrical optics cannot address coherence requirements for image formation [9,10].

Drawing on wave optics and image formation on rough surfaces, Tavassoly and colleagues developed an alternative model resolving these inconsistencies [2,5,11]. According to this framework, the mirage is not an atmospheric phenomenon but an image formed directly on the ground surface. All surfaces possess microscopic roughness ( $\sigma$ ). At ordinary angles, random phase variations destroy coherence. However, at extremely shallow grazing angles, path length differences become sufficiently small that constructive interference occurs, allowing image formation.

This wave-optics model makes distinctive, experimentally verified predictions. The intensity of coherently reflected light leads to a threshold angle depending on surface roughness and wavelength [11,12]. Consequently, longer wavelengths (red) are expected to remain visible at smaller grazing angles (greater distances) than shorter wavelengths (blue), a trend that is consistent with field observations of bi-colored objects in the desert [2,13]. The model correctly predicts zero vertical separation between object and mirage, consistent with everyday observation. These findings are corroborated by laboratory experiments [2,14] and independent studies [15].

This scientific divergence presents both challenge and opportunity for physics education. Persisting with the classical explanation may reinforce misconceptions about light. Students who internalize the refractive model possess an alternative conceptual framework that interferes with new learning [16,17]. The classical explanation represents what Chi [18] terms a "robust misconception"—resisting modification because it appears consistent with observable phenomena.

From Conceptual Change Theory [19], learning occurs when students become dissatisfied with existing conceptions and find new ones intelligible, plausible, and fruitful [20,21]. Creating cognitive conflict through empirical anomalies is essential for facilitating

change [22]. Thus, shifting from geometric to wave-optics explanation is a strategic pedagogical intervention. By confronting students with limitations of the geometric model—unrealistic temperature requirements, failure to explain wavelength dependence, and the horizontal ray paradox—educators create necessary cognitive conflict.

Despite the wave-optics model's robustness, it remains absent from standard curricula, underscoring the need to reevaluate teachers' Pedagogical Content Knowledge (PCK) [23]. Teachers need strategies to guide students through conceptual transition. Research demonstrates effectiveness of visual representation strategies: drawing-to-learn [24] and "Attentive Teaching" approaches emphasize iterative drawing and discourse in promoting conceptual change [25,26].

Moreover, integrating indigenous scientific research carries profound significance. The work of Tavassoly and colleagues—conducted in Iranian deserts, published in leading journals—demonstrates that significant scientific contributions can emerge from students' own cultural context. By centering instruction on this research, educators foster national scientific identity and challenge narratives positioning scientific progress as exclusively Western [27].

This article builds on our preliminary work [28], extending the educational framework. It aims to bridge advanced optical research and classroom practice through three objectives: (1) critically compare classical and wave-optics models, (2) frame this reconsideration within educational context proposing a Conceptual Change Strategy, and (3) offer practical pedagogical implications and activities enhancing conceptual understanding while promoting critical thinking and scientific identity.

The paper is organized as follows: Section 2 presents theoretical foundations. Section 3 develops the educational framework. Section 4 examines broader implications. Section 5 concludes with recommendations.

By reinterpreting a classical phenomenon through modern physics, educators can transform teaching the mirage from rote memorization into rich exploration of light's true nature, modeling scientific inquiry and preparing students to participate in knowledge creation.

## 2. Theoretical Foundations

This section presents the theoretical foundations of mirage formation, comparing the classical geometric optics model with the wave-optics alternative developed by Tavassoly and colleagues.

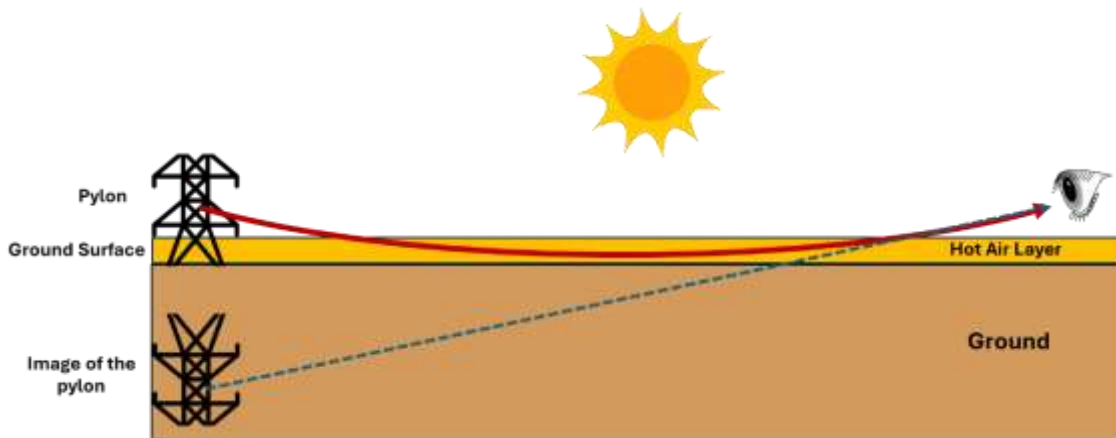
### 2.1 The Classical Geometric Optics Model

The classical explanation attributes inferior mirages to refraction and total internal reflection within thermally stratified air layers [1,3,4]. On sunny days, solar radiation heats the ground, warming adjacent air through conduction. This near-surface air expands, becoming less dense with lower refractive index than cooler air above, creating a vertical gradient decreasing toward the ground [2] (Figure 1).

The refractive index of air depends on temperature, pressure, and wavelength according to the relation [1]:

$$n(T, P, \lambda) = 1 + \left( \frac{0.05792105}{238.0185 - \lambda^{-2}} + \frac{0.00167917}{57.362 - \lambda^{-2}} \right) \times \frac{P}{1 + 0.003661T} \quad (1)$$

where  $T$  is the temperature in degrees Celsius,  $P$  is the pressure in Pascals, and  $\lambda$  is the wavelength in micrometers.



**Figure 1.** Classical explanation of the mirage phenomenon. Light rays from a distant object bend gradually due to the vertical temperature gradient. At the critical angle, total internal reflection occurs, directing rays toward the observer's eye.

When light rays travel from cooler, denser air toward warmer, less dense air, they progressively bend away from the normal—that is, toward the horizontal. If the temperature gradient is sufficiently steep, the curvature of the ray path can become so pronounced that the rays undergo total internal reflection at an imaginary horizontal interface within the air column, as illustrated in Figure 1 [2,4].

For an observer at height  $h$  viewing an object at height  $H$  with horizontal distance  $L$  between them, the angle of incidence  $\theta$  at the point of total internal reflection is given by [5]:

$$\sin \theta = \frac{L}{\sqrt{L^2 + (h + H)^2}} \quad (2)$$

Assuming a linear temperature gradient and applying Snell's law at the critical angle, the required temperature difference  $\Delta T$  between the ground surface and the point of reflection can be derived from [5]:

$$n(T) \sin \theta = n(T + \Delta T) \quad (3)$$

For typical mirage observation conditions—observer height  $h = 1.5$  m, object height  $H = 1.5$  m, and distance  $L = 400$  m—this yields an incident angle  $\theta \approx 89.57^\circ$  and a required temperature gradient of approximately  $\Delta T \approx 28^\circ\text{C}$  over a vertical distance of a few centimeters [5]. Such a steep gradient is physically unrealistic under normal atmospheric conditions.

This classical model rests upon two fundamental assumptions that warrant critical examination:

1. The air layers near the ground are stable, well-defined, and horizontally stratified.
2. The gradual bending of light rays can produce a coherent image despite the highly turbulent nature of near-surface air.

## 2.2 Challenges to the Classical Model

Field measurements report temperature differences significantly smaller than those typically assumed in classical models. Tavassoly and Dashtdar [5,6] recorded only  $\sim 5^\circ\text{C}$  differences between ground and 150 cm height in Iranian deserts—far below the  $28^\circ\text{C}$  often cited [5]. Mirages have been observed under conditions where strong thermal stratification is unlikely: on cold days ( $\sim 10^\circ\text{C}$ ), in windy weather (7 m/s), and at night with artificial illumination [2]. Furthermore, previous observations indicate that mirages

can also occur under cold or weakly stratified atmospheric conditions, including wintertime situations, suggesting that a strong temperature gradient may not always be required for image formation [2].

Previous experimental studies have reported the observation of mirage-like images even under relatively cold environmental conditions. In particular, Tavassoly et al. [2,15] documented the formation of mirage patterns on cold days, during nighttime observations under artificial illumination, and under windy conditions where strong thermal stratification is unlikely.

In the present work, our imaging experiments were performed under laboratory conditions without intentionally creating any temperature difference between the surface and the surrounding air. Under these conditions, mirage-like images were still observed. It should be noted that the present study did not include direct temperature measurements, and therefore the role of thermal gradients cannot be completely excluded.

Taken together, these observations suggest that a strong near-surface temperature gradient may not always be a necessary condition for the formation of such mirage-like images. This also suggests that similar optical effects could potentially occur under cold environmental conditions; however, systematic field measurements would be required for a definitive quantitative assessment.

The “horizontal ray problem” presents a theoretical challenge [7,9]: in a medium with vertically varying refractive index, a horizontal ray should continue horizontally by symmetry. Geometrical optics exhibits a singularity at this point, indicating incompleteness [7,9]. Born and Wolf [8] emphasize that complete image formation treatment requires considering light’s wave nature, including coherence and interference— aspects the classical model neglects.

### 2.3 The Wave-Optics Model: Image Formation on Rough Surfaces

Tavassoly and colleagues developed an alternative model resolving these difficulties [2,5,11]. The mirage forms directly on the ground surface through coherent reflection at grazing angles. At ordinary angles, random phase variations from surface roughness destroy coherence. At grazing angles approaching zero, path length differences become small enough for constructive interference.

All surfaces possess microscopic roughness with height distribution relative to a mean plane. For most surfaces, this distribution is approximately Gaussian [11]:

$$P_N(h) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{h^2}{2\sigma^2}\right) \tag{4}$$

where  $\sigma$  is the root-mean-square height deviation (roughness parameter) and  $h$  is the height relative to the mean plane.

The amplitude of coherently scattered light in the specular direction is given by [6,11]:

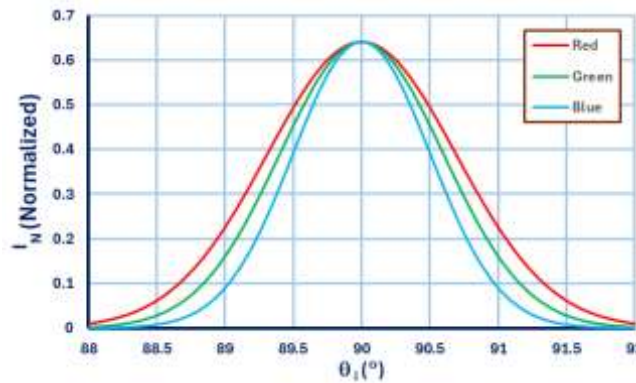
$$E_N(\theta_i) = R \int_{-\infty}^{+\infty} P_N(h) \exp(-2ikh \cos \theta_i) dh \tag{5}$$

where  $\theta_i$  is the angle of incidence measured from the normal,  $R$  is the ratio of the effective area of facets parallel to the mean plane to the total area, and  $k = 2\pi/\lambda$  is the wave number. Substituting the Gaussian height distribution and integrating yields [11]:

$$E_N(\theta_i) = R \exp\left(-\frac{8\pi^2\sigma^2 \cos^2 \theta_i}{\lambda^2}\right) \tag{6}$$

The corresponding intensity is:

$$I_N(\theta_i) = R^2 \exp\left(-\frac{16\pi^2\sigma^2 \cos^2 \theta_i}{\lambda^2}\right) \tag{7}$$



**Figure 2.** Theoretical normalized intensity  $I_N$  of coherently reflected light as a function of incident angle  $\theta$  for different wavelengths, calculated from Equation (7) with parameters  $\sigma = 3.0 \mu\text{m}$  and  $R^2 = 0.64$  (corresponding to reflection coefficient  $R = 0.8$ ). These values represent typical office paper ( $80 \text{ g/m}^2$ ): the roughness parameter  $\sigma = 3.0 \mu\text{m}$  is within the range specified by DIN 53145 [29] for standard paper, and the reflection coefficient  $R = 0.8$  corresponds to a brightness of approximately 80% measured according to GB/T 7973 [30] and ASTM D985 [31]. The curves for red ( $\lambda = 645 \text{ nm}$ ), green ( $\lambda = 560 \text{ nm}$ ), and blue ( $\lambda = 470 \text{ nm}$ ) show that longer wavelengths maintain detectable intensity at larger angles (smaller grazing angles) than shorter wavelengths.

This expression reveals the essential physics: at ordinary angles of incidence ( $\theta_i$  not too close to  $90^\circ$ ), the exponential factor is extremely small, and the coherently reflected intensity is negligible—no image forms. However, as  $\theta_i$  approaches  $90^\circ$  (grazing incidence),  $\cos \theta_i$  approaches zero, the exponential factor approaches unity, and the rough surface behaves increasingly like an imperfect mirror [11,12].

The threshold angle for image observation,  $\theta_T$ , can be defined as the angle at which the coherent intensity becomes detectable. This yields the relation [12,13]:

$$\frac{2 \cos \theta_T}{\lambda} \approx \frac{1}{2\sqrt{2 \ln 2} \sigma} \quad (8)$$

Several important consequences follow from this relationship:

1. **Wavelength dependence:** Longer wavelengths (red light) have smaller threshold angles, meaning they become visible as images at more grazing incidence (greater distances) than shorter wavelengths (blue light). This predicts that in a mirage of a multi-colored object, the red portions should remain visible at greater distances than blue portions [2,13].
2. **Surface roughness dependence:** Rougher surfaces (larger  $\sigma$ ) require more grazing incidence angles for image formation, consistent with the intuitive expectation that highly rough surfaces are poorer reflectors.
3. **Zero vertical separation:** Since the image forms on the ground surface itself, there should be zero vertical separation between an object and its mirage, consistent with everyday observations of road mirages [2,5].

#### 2.4 Experimental Verification of the Wave-Optics Model

Tavassoly and colleagues have conducted extensive laboratory and field experiments that verify the predictions of the wave-optics model [2,5,11,13]. In laboratory settings, they used various rough surfaces including foam board, cardboard, white-painted walls, and stone plates with different roughness characteristics. To verify the model under controlled conditions using simple, readily available materials, we conducted a laboratory experiment with a white paper surface and a colored object.

A white paper surface (standard A4 sheets) was placed horizontally on a table. A colored object consisting of three vertical stripes—blue (left), green (center), and red (right)—each measuring 2 inches in width and 3 inches in height, was positioned vertically at one

end of the table. The object was illuminated by a white LED lamp, and photographs were taken from a distance of 2 m at three different camera heights.

The photographs in Figure 3 dramatically illustrate the wavelength-dependent threshold effect.

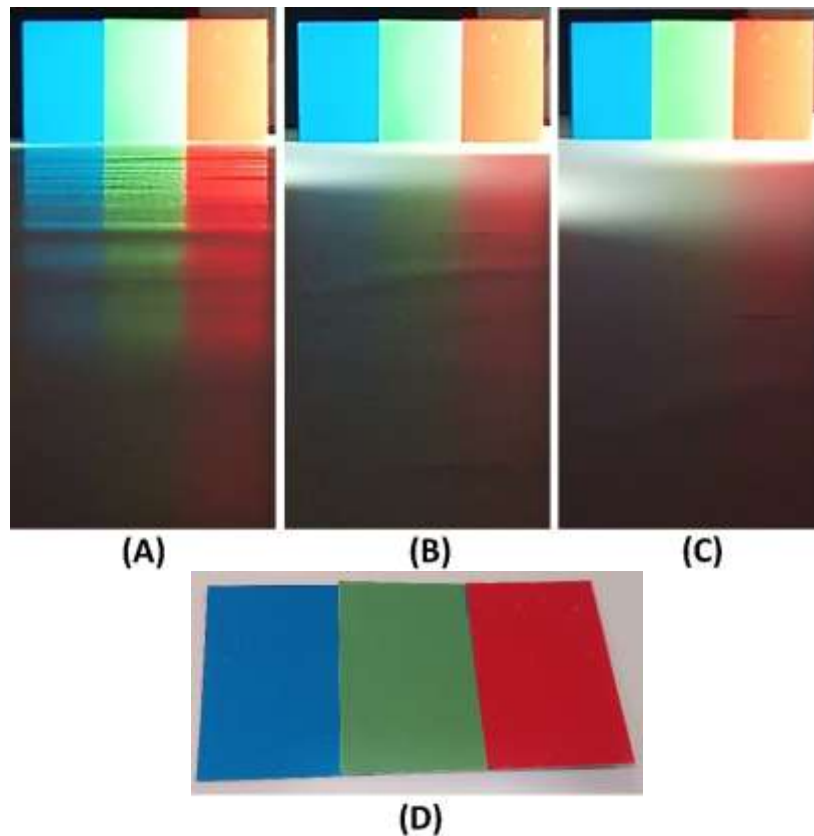
It is important to note that the incident angle  $\theta_i$  (measured from the normal to the surface) and the viewing angle  $\alpha$  (measured from the surface itself) are complementary:  $\theta_i + \alpha = 90^\circ$ . Therefore, the theoretical curves in Figure 2, which predict that the intensity is maximal at  $\theta_i = 90^\circ$  (grazing incidence), correspond to the smallest viewing angles ( $\alpha \rightarrow 0^\circ$ ) in the experimental photographs of Figure 3.

At the smallest angle (Figure 3A), all three colors are clearly visible in the reflected image. At the intermediate angle (Figure 3B), the blue stripe has nearly disappeared and the green stripe is significantly diminished, while the red stripe remains clearly visible. At the largest angle (Figure 3C), only traces of the red stripe remain. This sequence—blue disappearing first, then green, with red persisting longest—precisely matches the wavelength-dependent threshold angle prediction of Equation (7) [2]. These results provide direct experimental support for the wave-optics model using simple, readily available materials.

Field observations reported by Tavassoly et al. [2] provide even more compelling evidence consistent with this interpretation. They photographed mirages of bi-colored objects in the Iranian deserts, including a banner painted half red and half blue, at various distances. In these observations, the red portion's mirage was observed to appear at greater distances than the blue portion—a phenomenon inexplicable within the classical model (which predicts no color dependence) but following directly from the wave-optics framework.

Additional support comes from observations in windy weather, where mirages persist despite atmospheric turbulence that would be expected to destroy any stable thermal stratification [2]. Furthermore, the wave-optics model correctly predicts zero vertical separation between an object and its mirage—the image appears directly on the ground surface at the object's location. This matches everyday observation of road mirages, where a vehicle's reflection appears on the road immediately beneath the actual vehicle [2,5].

Independent studies have provided additional support. Zhou et al. [15] investigated road surface mirages and concluded that temperature-gradient explanations cannot account for their observations. Fakhruddin [14] demonstrated specular reflection from rough surfaces in classroom settings, providing accessible experimental evidence that is consistent with the underlying physics.



**Figure 3.** Laboratory demonstration of image formation on rough surfaces. Images of a colored object (blue, green, and red stripes from left to right) reflected from a white paper surface at camera distances of 2 m and heights of (A) 1.5 cm, (B) 15.5 cm, and (C) 32.5 cm relative to the surface, corresponding to approximate viewing angles of  $0.43^\circ$ ,  $4.43^\circ$ , and  $9.23^\circ$  respectively. The progressive disappearance of shorter wavelengths with increasing angle is evident: blue disappears first, followed by green, while red persists longest. (D) Direct photograph of the object for reference. Photographs by the authors.

### 2.5 Summary: Two Competing Paradigms

Table 1 summarizes the key differences between the classical geometric optics model and the wave-optics model of mirage formation.

The wave-optics model resolves theoretical inconsistencies and provides superior explanatory power—a genuine paradigm shift with profound implications for physics education.

### 3. A Conceptual Change Strategy for Teaching the Mirage Phenomenon

The preceding section established that Tavassoly's wave-optics model provides a more accurate account than classical geometric optics. However, accurate content alone does not guarantee learning. Students with internalized refractive models possess alternative conceptual frameworks that interfere with new learning [16,17]. This section presents a structured instructional framework guiding students from ray-based to wave-based reasoning.

**Table 1:** Comparison of the Classical and Wave-Optics Models of Mirage Formation

Feature	Classical Model	Wave-Optics Model
Location of image	In the air above ground	On the ground surface
Physical mechanism	Refraction and total internal reflection in stratified air	Coherent reflection from rough surface at grazing incidence
Required conditions	Strong temperature gradient (>28°C over few cm)	Grazing incidence angle ( $\theta \rightarrow 90^\circ$ )
Color dependence	None predicted	Strong: red visible at greater distances than blue
Object-image separation	Non-zero (vertical displacement)	Zero (image contiguous with object)
Effect of turbulence	Destroys image formation	No effect (image on solid surface)
Empirical status	Contradicted by field measurements	Consistent with laboratory and field observations

### 3.1 Theoretical Framework: Conceptual Change Theory

Conceptual Change Theory [19] posits that learning occurs when students become dissatisfied with existing conceptions and find new ones intelligible, plausible, and fruitful. The four conditions for conceptual change are [19,20]:

1. **Dissatisfaction:** Learners must become dissatisfied with their existing conceptions. Without this dissatisfaction, students have no motivation to abandon familiar explanations.
2. **Intelligibility:** The new conception must be intelligible—learners must be able to grasp its meaning and see how it applies to phenomena.
3. **Plausibility:** The new conception must appear plausible—it must be consistent with other knowledge and capable of explaining observations that the old conception cannot.
4. **Fruitfulness:** The new conception must prove fruitful—it should open up new avenues of inquiry, solve previously puzzling problems, or suggest novel predictions.

The classical mirage explanation represents a "robust misconception" [18]—an intuitive framework resisting modification. Students believing "mirages are caused by hot air bending light" have constructed a mental model that, while incorrect, explains everyday observations. Simply presenting the correct model is insufficient; students must recognize their existing framework's limitations [21,22]. Creating cognitive conflict through empirical anomalies is essential for initiating conceptual change [16,20].

### 3.2 Learning Objectives

The proposed instructional framework is designed to achieve the following learning objectives:

#### Conceptual Objectives:

- Students will be able to explain the limitations of the geometric optics model in accounting for mirage formation
- Students will describe how coherent reflection from rough surfaces at grazing angles produces images
- Students will explain why red mirages persist at greater distances than blue mirages

- Students will articulate the role of wavelength, surface roughness, and illumination intensity in image formation

**Procedural Objectives:**

- Students will construct simple experimental setups to observe image formation on rough surfaces
- Students will measure threshold angles for different colors and relate measurements to theoretical predictions
- Students will create visual representations (drawings) of their conceptual understanding at multiple stages

**Attitudinal Objectives:**

- Students will develop critical thinking skills by evaluating competing scientific explanations
- Students will appreciate that scientific theories evolve in response to empirical evidence
- Students will recognize that significant scientific contributions can emerge from their own cultural context

**3.3 Overview of the Instructional Framework**

The proposed framework organizes instruction into three interconnected phases, adapted from Even et al.'s [18] "experiment first" model and incorporating visual representation strategies from Attentive Teaching approaches [25,26]:

**Phase 1: Elicitation and Cognitive Conflict (2 class sessions)**

- Students observe mirage phenomena and record initial explanations
- Teacher elicits students' existing conceptions through drawings and discussion
- Students encounter empirical anomalies that challenge the classical model

**Phase 2: Introduction of Wave-Optics Model (2 class sessions)**

- Teacher presents the wave-optics framework through demonstration and guided inquiry
- Students conduct simple experiments with rough surfaces at grazing angles
- Students construct understanding of coherence, interference, and wavelength dependence

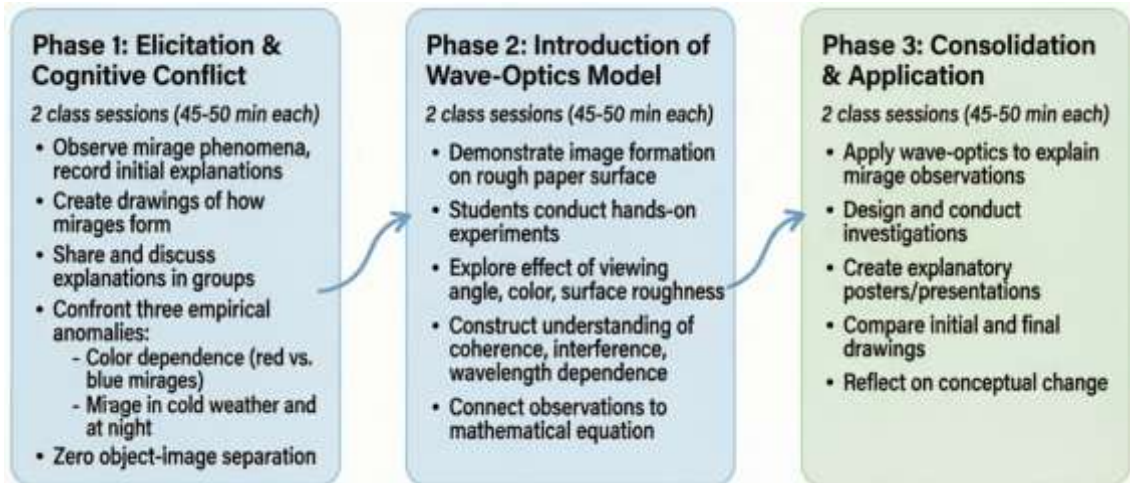
**Phase 3: Consolidation and Application (2 class sessions)**

- Students apply the wave-optics model to explain mirage observations
- Students design and conduct investigations of image formation on various surfaces
- Students reflect on conceptual change and the nature of scientific knowledge

**3.4 Phase 1: Elicitation and Cognitive Conflict**
**Session 1.1: Initial Observations and Drawings**

Students recall seeing apparent water on hot highways and share explanations. Following Attentive Teaching [25,26], students create drawings showing how they think mirages form. This task:

- It forces students to make their implicit conceptualizations explicit
- It provides the teacher with diagnostic information about students' mental models
- It creates a record against which later conceptual development can be assessed



**Figure 4.** Overview of the three-phase instructional framework for teaching the mirage phenomenon through wave optics. Phase 1 (Elicitation and Cognitive Conflict) engages students' initial conceptions through drawing and introduces empirical anomalies to create dissatisfaction. Phase 2 (Introduction of Wave-Optics Model) follows the "experiment first" principle, allowing hands-on discovery of image formation on rough surfaces before formal theory. Phase 3 (Consolidation and Application) returns students to mirage observations, applying wave-optics concepts to explain phenomena, conducting extended investigations, and reflecting on conceptual change through drawing comparisons. Each phase is designed for two 45–50-minute class sessions.

Students present their drawings to small groups and explain their thinking. The teacher facilitates discussion without evaluating correctness, creating a safe environment for students to express their ideas [25].

**Session 1.2: Creating Cognitive Conflict**, the second session introduces empirical anomalies that challenge the classical model. The teacher presents three observations that students cannot explain within their current framework:

**Anomaly 1: Color Dependence** The teacher shows photographs of mirages from bi-colored objects (Figures 3A-C) and asks students to compare them with the direct photograph of the object (Figure 3D). Students observe that in the reflected images, the red portion remains visible at larger angles while the blue portion disappears. They are then asked: "If mirages are caused by hot air bending light, why would red and blue behave differently?"

**Anomaly 2: Mirage in Cold Weather** The teacher presents evidence that mirages occur on cold days (approximately 10°C) and even at night with artificial illumination [2]. Students confront the question: "If hot air is necessary, how can mirages appear when the air is cold?"

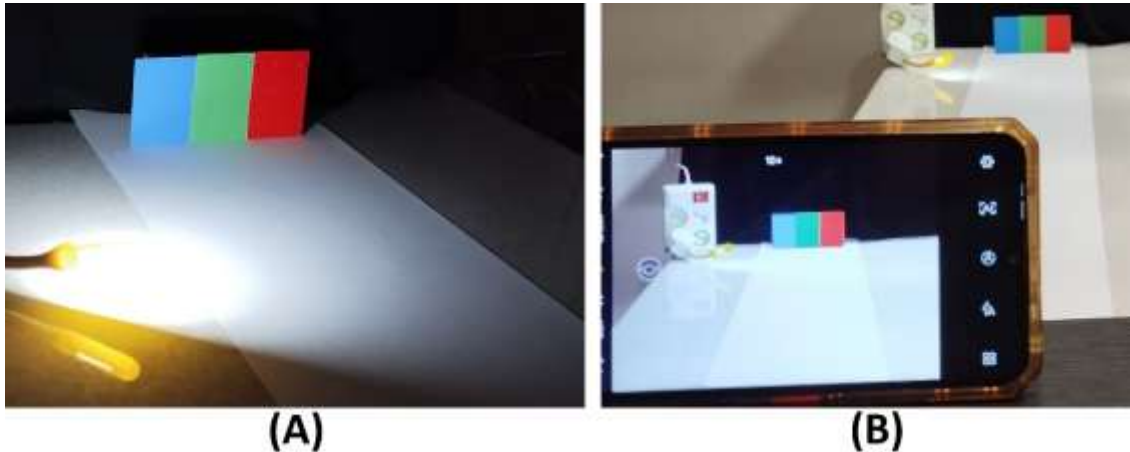
**Anomaly 3: Zero Object-Image Separation** The teacher directs attention to photographs showing that mirages appear directly beneath objects, with no vertical gap. Students consider: "If light is reflecting from layers in the air, why doesn't the image appear above the ground?"

Students discuss these anomalies in small groups, experiencing the dissatisfaction that Posner et al. [19] identify as the first condition for conceptual change. The teacher does not yet provide explanations but ensures that students recognize the limitations of their current conceptions.

### 3.5 Phase 2: Introduction of the Wave-Optics Model

The teacher introduces a simple classroom demonstration based on our laboratory setup described in Section 2.4. A white paper surface (standard A4 sheets) is placed horizontally

on a table. A colored object consisting of three vertical stripes—blue, green, and red—is positioned vertically at one end of the table and illuminated by a white LED lamp. Students observe the reflected image at very shallow angles using their smartphones or cameras.



**Figure 5.** Classroom experimental setup for observing image formation on rough surfaces. (A) Close-up photograph of the colored object illuminated by the white LED lamp, showing the three vertical stripes (blue left, green center, red right) clearly visible. (B) Overall view showing the smartphone camera mounted at an elevated position, the white paper surface (A4 sheets), the colored object (blue, green, and red stripes), and the white LED lamp. The smartphone screen displays the live image being captured at a shallow angle. Photographs by the authors.

Students work in small groups with their own setups, exploring how the image changes as they vary:

- The viewing angle (moving the camera closer to or farther from the surface)
- The color of the object (using different colored papers or filters)
- The roughness of the surface (comparing different materials such as cardboard, sandpaper, or fabric)

This hands-on exploration embodies Even et al.'s [18] "experiment first" principle: students discover the phenomenon qualitatively before encountering formal theory.

### Session 2.2: Constructing the Wave-Optics Explanation

Through Socratic questioning, the teacher guides students to develop qualitative understanding of:

- **Coherence:** Light waves must maintain consistent phase relationships to form images
- **Surface roughness:** Random height variations destroy coherence at ordinary angles
- **Grazing angles:** At very shallow angles, path length differences become small enough that waves remain approximately in phase
- **Wavelength dependence:** Longer wavelengths (red) can tolerate larger path differences, explaining why red images persist at larger angles

The teacher introduces Equation (7) as a quantitative summary, with students appreciating the key dependencies without mastering the mathematics.

### 3.6 Phase 3: Consolidation and Application

#### Session 3.1: Applying the Model to Mirage Phenomena

Students now return to the mirage photographs that created cognitive conflict in Phase 1 and apply their new understanding to explain them:

- **Color dependence:** The red portion remains visible at greater distances because red light has a longer wavelength, making its threshold angle smaller (Equation 7 from Section 2). As the observer approaches, the grazing angle increases, exceeding the threshold for blue while remaining below the threshold for red.
- **Cold weather mirages:** Since mirages form on the ground surface itself through coherent reflection, atmospheric temperature is irrelevant. The phenomenon depends only on surface roughness and illumination, explaining persistence in cold and windy conditions.
- **Zero separation:** Because the image forms on the ground surface, it necessarily appears directly beneath the object, with no vertical displacement.

Students work in groups to create explanatory posters or presentations that integrate these insights, practicing scientific communication.

#### Session 3.2: Extended Investigation and Reflection

Students design and conduct simple investigations exploring questions that arise from the wave-optics model:

- How does the threshold angle vary for different colors? (Quantitative measurement using protractors and colored filters)
- How does surface material affect image formation? (Comparing cardboard, sandpaper, fabric, etc.)
- Does illumination intensity affect the visibility of the image? (Varying light source brightness)

The final session includes meta-cognitive reflection. Students compare their initial drawings (from Session 1.1) with their current understanding, articulating how their thinking has changed. This reflection reinforces the conceptual change process and helps students appreciate the nature of scientific learning [16].

### 3.7 Assessment Strategies

The instructional framework incorporates multiple assessment approaches aligned with the learning objectives:

**Table 2:** Formative Assessment Strategies

Assessment Type	Description	Timing
Initial drawings	Reveal baseline conceptions	Session 1.1
Group discussion observations	Teacher notes contributions and questions	All sessions
Intermediate drawings	Updated drawings after Phase 2	Session 2.2
Lab notebooks	Record observations and interpretations	All sessions

**Table 3:** Summative Assessment Strategies

Assessment Type	Description	Alignment
Conceptual explanation task	Explain mirage photographs using wave-optics	Conceptual objectives
Experimental design task	Design investigation testing wave-optics predictions	Procedural objectives
Reflective essay	Reflect on how and why understanding changed	Attitudinal objectives
Final drawing	Comprehensive drawings showing wave-optics model	All objectives

Drawing-based assessments build on Ainsworth and Tytler's [24] framework, enabling teachers and students to track conceptual development.

**Table 4:** Summary of the Three-Phase Instructional Framework

Phase	Activities	Learning Objectives	Assessment
Phase 1: Elicitation & Cognitive Conflict	<ul style="list-style-type: none"> <li>Recall mirage experiences</li> <li>Create initial drawings</li> <li>Share and discuss explanations</li> <li>Confront empirical anomalies</li> </ul>	<ul style="list-style-type: none"> <li>Articulate initial conceptions</li> <li>Recognize limitations of classical model</li> <li>Experience dissatisfaction</li> </ul>	<ul style="list-style-type: none"> <li>Initial drawings</li> <li>Discussion contributions</li> <li>Written responses to anomalies</li> </ul>
Phase 2: Wave-Optics Introduction	<ul style="list-style-type: none"> <li>Observe image formation on rough surfaces</li> <li>Conduct hands-on exploration</li> <li>Construct qualitative understanding</li> <li>Connect to mathematical formulation</li> </ul>	<ul style="list-style-type: none"> <li>Describe role of coherence</li> <li>Explain wavelength dependence</li> <li>Relate grazing angle to image formation</li> </ul>	<ul style="list-style-type: none"> <li>Lab notebook entries</li> <li>Intermediate drawings</li> <li>Group discussion</li> </ul>
Phase 3: Consolidation & Application	<ul style="list-style-type: none"> <li>Apply model to explain mirage observations</li> <li>Design and conduct investigations</li> <li>Create explanatory presentations</li> <li>Reflect on conceptual change</li> </ul>	<ul style="list-style-type: none"> <li>Apply wave-optics to explain phenomena</li> <li>Design simple experiments</li> <li>Articulate personal conceptual change</li> </ul>	<ul style="list-style-type: none"> <li>Final drawings</li> <li>Investigation reports</li> <li>Reflective essays</li> <li>Explanatory presentations</li> </ul>

### 3.8 Teacher Preparation and Pedagogical Content Knowledge

Implementing this instructional framework requires that teachers possess appropriate Pedagogical Content Knowledge (PCK) [23]. Beyond understanding the physics, teachers need:

- **Knowledge of student conceptions:** Teachers must be familiar with common alternative conceptions about mirages and light, including the robust misconception that "mirages are caused by hot air."
- **Knowledge of instructional strategies:** Teachers need strategies for creating cognitive conflict, facilitating discussion without premature evaluation, and guiding students through conceptual change.

- **Knowledge of representations:** Teachers must be able to use multiple representations—demonstrations, diagrams, photographs, equations—and help students connect them.
- **Knowledge of assessment:** Teachers need skills in interpreting student drawings and explanations to diagnose conceptual understanding.

Professional development programs should address these PCK components, providing teachers with opportunities to experience the conceptual change process themselves and practice the instructional strategies [20].

### 3.9 Summary of the Instructional Framework

Table 4 summarizes the three-phase instructional framework, including the activities, learning objectives, and assessment strategies for each phase.

## 4. Discussion: Implications for Physics Education

This section examines the broader implications of the wave-optics approach for physics education, addressing its potential to enhance conceptual understanding, foster critical thinking, promote scientific literacy, and cultivate national scientific identity.

### 4.1 Deepening Conceptual Understanding of Light

The wave-optics model offers a unique opportunity to introduce fundamental concepts typically deferred to advanced courses. Table 5 summarizes key concepts embedded in the mirage phenomenon.

**Table 5:** Key Wave-Optics Concepts Embedded in the Mirage Phenomenon

Concept	Relevance to Mirage Formation	Educational Significance
Coherence	Image formation requires consistent phase relationships	Introduces coherent vs. incoherent light; foundational for lasers and interference
Interference	Constructive interference at grazing angles enables image formation	Connects to double-slit experiment, thin films, and wave nature of light
Surface roughness	Random height variations ( $\sigma$ ) determine threshold angle	Links optics to materials science; introduces statistical surface description
Wavelength dependence	Threshold angle varies with $\lambda$ ; red visible at smaller angles	Demonstrates color-dependent optical phenomena; connects to dispersion and spectra
Grazing incidence	At $\theta \rightarrow 90^\circ$ , rough surfaces behave as imperfect mirrors	Illustrates boundary condition effects; connects to total internal reflection
Scattering	Light scatters from rough surfaces; only coherent component forms images	Introduces specular vs. diffuse reflection

Unlike abstract phenomena like double-slit interference, mirages are personally observable, providing an accessible entry point into wave-optical thinking [2,14]. Students learn that geometric optics is an approximation that breaks down when coherence and interference become important, preparing them for advanced study while preventing misconceptions [8,9].

## 4.2 Fostering Critical Thinking and Scientific Literacy

The framework promotes critical thinking and scientific literacy through:

**Evaluating Competing Explanations:** Students confront two explanations for the same phenomenon and evaluate them against empirical evidence, developing skills in:

- Identifying the assumptions underlying each model
- Comparing predictions with observations
- Recognizing when evidence contradicts a theory
- Assessing explanatory power of competing frameworks [20]

**Understanding the Nature of Science:** The history of mirage explanation provides a case study in how scientific understanding evolves. Students learn that:

- Scientific theories are not fixed truths but working models subject to revision
- Empirical evidence can challenge long-held explanations
- Scientific progress often requires reconceptualizing familiar phenomena
- Even textbook explanations may be incomplete [16]

**Developing Meta-Cognitive Awareness:** Drawing and reflection (Sessions 1.1, 2.2, 3.2) promote meta-cognitive awareness. Comparing initial drawings with final understanding helps students recognize conceptual change, reinforcing learning and building confidence [17,21].

## 4.3 Cultivating National Scientific Identity

The framework emphasizes indigenous scientific achievement. Tavassoly's wave-optics model was developed by Iranian scientists in Iranian deserts, published in leading journals, and validated through rigorous methods in their home country [2,5,11].

**Challenging Narratives of Scientific Exclusion:** Students often internalize the message that significant scientific contributions come primarily from Western Europe and North America [27]. Centering instruction on Tavassoly's work challenges this narrative. Students learn that:

- Cutting-edge scientific research occurs in their own country
- Iranian scientists have challenged and refined internationally accepted theories
- Local knowledge—such as familiarity with desert environments—can contribute to scientific discovery
- Scientific progress is a global endeavor with diverse contributions

**Fostering Scientific Confidence and Aspiration:** Seeing scientists from their own context making significant contributions helps students imagine themselves as potential scientists. The Tavassoly model provides role models, cultural relevance, local pride, and aspiration [27].

**Connecting Science to Place:** The model developed through fieldwork in Iranian deserts (Dagh and Qarpuzabad) connects science to familiar landscapes, making it more concrete and meaningful. This place-based approach increases engagement and deepens understanding [24].

#### 4.4 Addressing Challenges and Limitations

**Teacher Preparation:** Most teachers learned the classical model and may be unfamiliar with wave optics. Professional development should introduce the model, engage teachers in conceptual change, provide practice with strategies, and build confidence in facilitating discussion about competing explanations [23].

**Curriculum Constraints:** The framework reconceptualizes an existing topic rather than adding new content. Time allocated to teaching mirages remains the same, with content shifting from geometric to wave optics. Strong empirical evidence supports updating standards where needed [2,5,15].

The intention of this proposal is not necessarily to replace the current textbook explanation, but rather to introduce a complementary discussion that allows students to examine the limitations of the classical model and explore alternative interpretations based on wave optics

**Assessment Alignment:** Standardized assessments often reflect the classical model. Addressing this requires working with assessment developers, developing local assessments aligned with the framework, and teaching students to understand both models while recognizing the wave-optics account's superiority. Emphasis on conceptual understanding prepares students for novel situations [20].

**Resource Availability:** Demonstrations require simple, widely available materials (foam board, colored paper, projectors). Teachers may need support in assembling materials, adapting activities, and troubleshooting. Sharing resources through teacher networks can help.

#### 4.5 Connections to Broader Educational Goals

The framework aligns with contemporary science education goals:

**STEM Integration:** Integrates physics (optics, wave theory) with mathematics (exponential functions, statistical roughness description) and engineering (surface properties, materials).

**Inquiry-Based Learning:** The three-phase structure embodies inquiry-based principles—from open-ended exploration to guided investigation to student-designed inquiries [18].

**Culturally Responsive Pedagogy:** Centering instruction on research from students' cultural context validates backgrounds while maintaining rigorous scientific standards, demonstrating science can be advanced from diverse contexts [27].

**Education for Sustainable Development:** Understanding reflection and absorption relates to building design, energy efficiency, and urban heat island effects. Surface property emphasis opens connections to applied topics.

#### 4.6 Recommendations for Research

The framework requires empirical validation in classroom contexts. Future research should address:

**Effectiveness Studies**

- Does the framework produce greater conceptual understanding than traditional instruction?
- Do students retain understanding over time?
- Does the framework successfully induce conceptual change from geometric to wave-optics reasoning?

**Implementation Studies**

- How do teachers adapt the framework to different classroom contexts?
- What challenges arise in implementation, and how can they be addressed?
- What professional development models best support teacher learning?

**Comparative Studies**

- How does student learning compare across different instructional sequences?
- What is the optimal balance between qualitative exploration and quantitative analysis?
- Does the emphasis on indigenous scientific achievement affect student engagement and identity?

**Longitudinal Studies**

- Do students who learn through this framework demonstrate different trajectories in subsequent physics learning?
- Does exposure to the framework influence career aspirations in science?

Collaboration between physics educators, optical physicists, and educational researchers will be essential for addressing these questions.

**4.7 Summary of Implications**

Table 6 summarizes the key implications of the proposed framework for physics education.

**5. CONCLUSION**

This article has presented a comprehensive reconceptualization of the mirage phenomenon for physics education, grounded in Tavassoly's wave-optics model. The journey from geometric to wave optics represents a genuine paradigm shift with profound implications for teaching light and vision.

**5.1 Summary of Key Arguments**

The classical model attributes mirages to refraction in thermally stratified air [1,3,4] but faces insurmountable difficulties:

- Empirical inconsistencies: Field measurements suggest that near-surface temperature gradients are only  $\sim 5^{\circ}\text{C}$ , far below the  $28^{\circ}\text{C}$  required by the classical model [5]; mirages nonetheless persist in cold, windy, and artificially lit conditions [2], mirages persist in cold, windy, and artificially lit conditions [2], and mirage-like images were also observed in our laboratory experiments without any intentionally imposed temperature difference (see Section 2.2).

**Table 6:** Summary of Educational Implications

Domain	Implications
Conceptual understanding	Introduces coherence, interference, surface roughness, and wavelength dependence through accessible phenomenon; connects abstract wave optics to everyday experience
Critical thinking	Develops skills in evaluating competing explanations, assessing evidence, and recognizing theory change
Nature of science	Models scientific progress as theory revision in response to evidence; counters view of science as fixed facts
Meta-cognition	Promotes awareness of conceptual change through drawing and reflection
National scientific identity	Challenges narratives of scientific exclusion; provides role models; connects science to place
Teacher preparation	Requires professional development in wave optics, conceptual change strategies, and PCK
Curriculum development	Curriculum development – Reconceptualizes an existing topic rather than adding content; may require advocacy for standards update; emphasizes using the new model as a complementary discussion rather than an immediate replacement of current textbook explanations.
Assessment	Requires alignment between instruction and assessment; emphasizes conceptual understanding
Broader educational goals	Supports STEM integration, inquiry-based learning, culturally responsive pedagogy

- Theoretical inadequacies: The "horizontal ray problem" reveals that geometrical optics cannot explain continuous ray bending in gradient-index media [7,9].
- Explanatory failures: The classical model cannot account for color-dependent visibility [2,13] or zero object-image separation.

In contrast, the wave-optics model [2,5,11] reconceptualizes mirages as images formed directly on ground surfaces through coherent reflection at grazing angles. This model explains wavelength-dependent threshold angles, predicts zero separation, accounts for persistence under non-thermal conditions, and is verified by extensive experiments [2,11,14,15].

## 5.2 The Proposed Educational Framework

Building on Conceptual Change Theory [19,20] and physics education research [16,18,24,25], we developed a three-phase framework:

**Phase 1:** Elicitation and Cognitive Conflict—engages initial conceptions through drawings and introduces empirical anomalies to create dissatisfaction [19].

**Phase 2:** Introduction of Wave-Optics Model—follows "experiment first" principle [18], allowing hands-on discovery before formal theory.

**Phase 3:** Consolidation and Application—students apply wave-optics concepts to explain mirage observations, conduct investigations, and reflect on conceptual change [24,25].

## 5.3 Key Contributions

- Scientific contribution: Synthesized Tavassoly's research [2,5,6,11–13] into an accessible account for educators.
- Pedagogical contribution: Operationalized Conceptual Change Theory through a detailed, classroom-ready framework.

- Cultural contribution: Centered instruction on Iranian scientific achievement, challenging Western-centric narratives [27] and fostering national scientific identity.
- Curricular contribution: Demonstrated how a common textbook topic can introduce wave optics without adding new content.

### 5.4 Recommendations

#### For Curriculum Developers:

- Revise textbook presentations to include both classical and wave-optics models with empirical evidence.
- Integrate wave-optics concepts earlier using accessible phenomena like mirages.
- Include indigenous scientific contributions in curriculum materials.
- Develop assessment items that evaluate conceptual understanding rather than memorization.

#### For Teacher Educators:

- Provide professional development that engages teachers in conceptual change [23].
- Prepare teachers to use drawing-based assessment formatively.
- Equip teachers with demonstration skills for simple experiments.
- Foster awareness of the cultural significance of indigenous scientific achievement.

#### For Classroom Teachers:

- Begin with students' experiences before introducing formal models.
- Create cognitive conflict through empirical anomalies.
- Let students discover through hands-on exploration before theory.
- Use drawings as tools for thinking, communication, and assessment.
- Connect to cultural context, especially for Iranian students.
- Facilitate reflection on conceptual change.

### 5.5 Limitations and Future Research

The framework requires empirical validation in classroom settings. Future research should address:

- Effectiveness studies: Does the framework produce greater conceptual understanding and successful conceptual change?
- Implementation studies: How do teachers adapt the framework? What challenges arise?
- Comparative studies: How does this approach compare to alternative instructional sequences?
- Longitudinal studies: Do students retain understanding? Does it influence subsequent learning?
- Cultural impact studies: Does centering indigenous science affect engagement and identity?

Collaboration between physics educators, optical physicists, and educational researchers is essential.

### 5.6 Final Remarks

The mirage, once taught through simplified geometric models, becomes through wave optics a rich opportunity to explore coherence, interference, and scientific inquiry. Students who understand why red mirages persist at greater distances, why images appear directly beneath objects, and why mirages occur on cold days have grasped fundamental principles of light and the nature of scientific progress. By centering this instruction on Iranian research, we offer students the knowledge that significant scientific contributions can emerge from their own cultural context. The journey from geometric to wave optics

mirrors the journey of science itself—and guiding students through this journey initiates them into the practice of scientific thinking, the ultimate goal of physics education.

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