Teaching Paradigm Innovation in Geometrical Optics for Cultivating Outstanding Engineers

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Abstract. In order to cultivate outstanding engineers in the Paris Curie Engineering School of Beijing University of Chemical Technology (Chimie Pékin), we made a reform in the teaching paradigm of *Geometrical Optics*. The motivation of this reform mainly stems from three aspects: (1) the regulations of the French Ministry of Education's preparatory education on the physics syllabus. (2) The mathematical and physical foundation of Chimie Pékin's students. (3) The inadequacies of existing textbooks. Our reform includes two innovations. First, we established a mathematical sign rules based on Cartesian coordinates, integrating the physics concepts, optical processes, and mathematical formulas into a systematic and comprehensive mathematical framework. Then, we incorporated all reflective and refractive imaging situations into a unified object-image relation model, further revealing the internal connections between plane mirrors, spherical/curved mirrors, and lenses. Comparative evaluation fully demonstrated that the proposed teaching paradigm innovation can significantly enhance students' six skills and improve the achievement of outstanding engineers' training goals.

Keywords: Sign rules; Object-image relation; Geometrical optics; Outstanding engineers

1. Introduction

The Paris Curie Engineering School of Beijing University of Chemical Technology (Chimie Pékin) is a Sino-French cooperatively-run institution, which was co-established by Beijing University of Chemical Technology (BUCT) and the École Nationale Supérieure de Chimie de Paris (Chimie Paristech) in February 2017 and began enrollment in September 2017, with the approval of both Chinese and French Ministry of Education. By introducing the elite engineering education model of France for the training of outstanding engineers, Chimie Pékin cultivates future engineers via a two-stage training model. The curriculum begins with a three-year preparatory cycle, emphasizing the cultivation of students' solid scientific knowledge (mathematics, physics, chemistry, computer, etc.) and foreign language abilities (French, English). In the following three to four years, selected students enter the engineer stage, which focuses on the cultivation of professional skills and engineering theory.

Geometrical Optics is the first course in a series of *Physics* curriculum in the preparatory cycle of Chimie Pékin, which is taught in the second semester of the first year. In the teaching process of *Geometrical Optics*, teachers should help students complete a critical ideological shift, that is, the purpose of learning is not simply to accumulate knowledge, but to learn to proactively discover and solve problems, which is one of the core skills required for engineers. This paper introduces two major innovations we have made in the teaching paradigm of *Geometrical Optics*. Both two innovations not only comply with the regulations of preparatory education of the French Ministry of Education, but also fully take into account the mathematical and physical foundation of Chinese students. Our teaching practice (2018-2023) has shown that these innovations improve the achievement of outstanding engineers' training goals.

https://doi.org/10.61957/joerai-20230306

2. Motivation

2.1 Training Goals of Preparatory Cycle. According to basic requirements for engineer training of Commission des titres d'ingénieur (CTI) [1], and the regulations of the French Ministry of Education's preparatory education on the *Physic* syllabus [2], all training during the preparatory cycle is based on the idea that the aspiring engineer needs to have both solid theoretical knowledge and practical skills. These goals can be encompassed in six main skills (Table 1) that are likely to extend to the whole scientific training. The teachers in charge of a course are given the authority to organize the content and order of the course to achieve these training goals.

Table 1. Six skills to be achieved through scientific training

Skills	Contents
Investigate and apply a strategy	Spot, analyse, transform or simplify a problem, test on examples, formulate a hypothesis, identify some features or analogies
Model	Transform a real-life problem into scientific language, compare a model to the reality, validate a model and review it
Represent	Choose the best framework to solve a problem or represent a physical object, switch from one representation to another one
Ratiocinate and argue	Construct inductive or deductive reasoning, prove, confirm or invalidate a conjecture
Calculate, use a symbolic language	Using expressions that contain symbols, build the steps of a complex calculus, compute or automate, control the results
Communicate orally or by writing	Understand scientific texts, write out a clear and accurate solution, present and defend a scientific work.

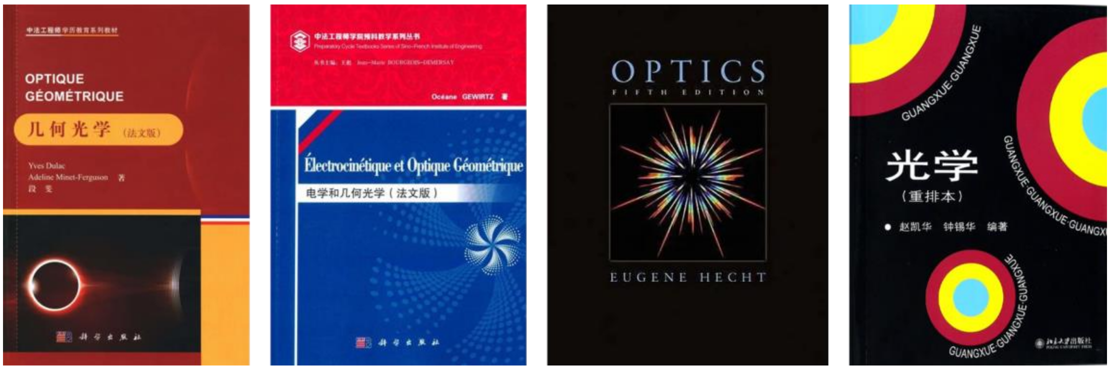

Figure 1. Four textbooks we referred to during our lecture notes compilation process

2.2 Reference Textbooks. Due to the absence of direct available textbooks, we decided to adopt self-compiled lecture notes for Chimie Pékin teaching. The first edition of our lecture notes was completed in the summer of 2017, and it has been continuously updated in recent years to meet the needs of engineering talent cultivation. During the compilation process, we referred to four excellent textbooks as shown in Fig.1, namely: (1) *Optique Géométrique (French Edition)* by Yves Dulac, *et al.*[3], (2) *Électrocinétique et Optique Géométrique (French Edition)* by Océane GEWIRTZ.[4], (3) *Optics* by Eugene Hecht [5], (4) *Optics* by Kaihua Zhao and Xihua Zhong [6]. Among these textbooks, [3] and [4] are the "Preparatory Cycle Textbooks Series of Sino-French Institute of Engineering", written in French and dedicated to textbooks of Sino-French Engineer School of Beihang University (Centrale Pékin) and Institut franco-chinois de I'énergie nucléaire université Sun Yat-sen (IFCEN), respectively. [5] is an internationally renowned optics textbook, written in English. [6] is a classical optics textbook widely used by Chinese universities, written in Chinese.

We conducted a detailed comparison of the teaching content and structure of these textbooks related to *Geometrical Optics*. There are two discoveries that inspired us to revolutionize our lecture notes and change the existing teaching paradigm.

2.3 Sign Rules. We noticed that the textbooks [3] and [4] used for preparatory cycle adopt completely different mathematical sign rules compared to those in [5] and [6], which widely used in Anglo-American and Chinese language countries. Taking the refraction of a light ray at a spherical interface as an example (Fig.2), we summarize this difference of sign rules in Table 2. Understanding this difference is important for teaching *Geometrical Optics*, as Chinese students learn and train with sign rules in [5] and [6] during their high school, while, to meet the training requirements of French engineers, they must quickly transition and adapt to the sign rules shown in [3] and [4] during their preparatory cycle, and use them consistently throughout their future learning and practice.

2.4 Imaging. The imaging process of an object passing through an optical system (simple or complex) to form an image, is not only an interesting physical process, but also crucial for inspiring students to understand the characteristics of optical systems and develop optical design. Most existing optical textbooks [3-6] contain the imaging process of typical optical elements, such as plane mirrors, spherical/curved mirrors, lenses, etc. However, they regard these elements as independent entities, describing their imaging characteristics and object-image relationships individually. Few books discuss the connections between them from a systematic perspective. In fact, the imaging process of all these optical elements can be standardized within a unified mathematical model.

Based on these observations and thinking, we decided to revolutionize the existing teaching paradigm in *Geometrical Optics* from two aspects.

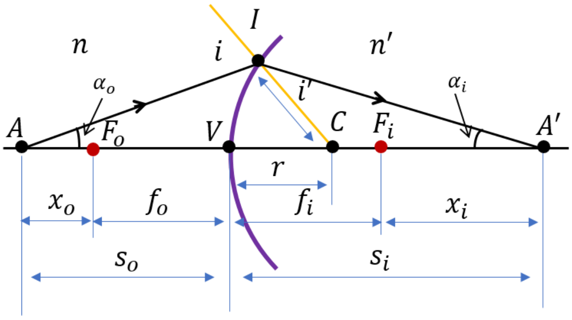

Figure 2. Refraction at a spherical interface

Table 2. Sign convention for spherical refracting surfaces

	Textbook [3] & [4]	Textbook [5] & [6]
s_o, f_o	- left of V	+ left of V
x_o	- left of F_o	+ left of F_o
s_i, f_i	+ right of V	+ right of V
x_i	+ right of F_i	+ right of F_i
r	+ C is right of V	+ C is right of V

3. Innovation

3.1 Cartesian Coordinate based Sign Rules. This set of sign rules uses the Cartesian coordinate system as the basis for distance and angle measurements. Distance measurement starts from the origin O of Cartesian coordinates, with right and upward being positive and left and downward being negative. The angle between the light ray and the x-axis (optical axis) is measured by the acute angle from the optical axis to the light ray. An angle is positive, when it is counterclockwise. Otherwise, the angle is negative. Following this sign rules, we integrate the physics concepts, optical processes, and mathematical formulas of *Geometrical Optics* into a systematic and comprehensive mathematical framework. Several examples are shown in Fig.3. The impact of this innovation is significant. After a semester of training, it directly helps students improve their skills such as Modeling, Representation, Calculation and Communication as listed in Table 1.

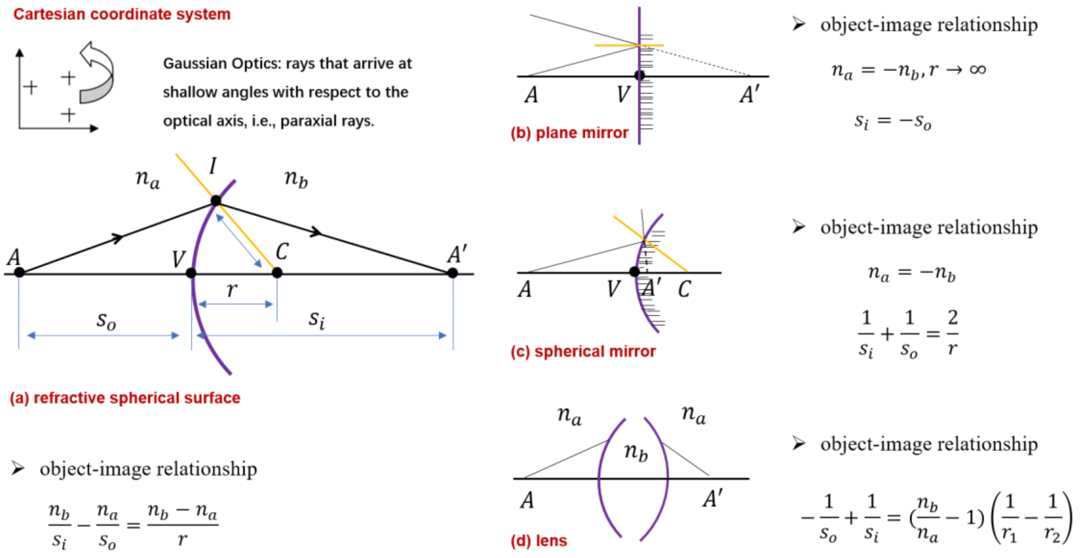

Figure 3. Object-image relationship under a unified mathematical model

3.2 Unified Object-Image Relation Model. Based on the mathematical symbols system we build, we investigated the internal connections between the object-image relation of several typical optical elements, including plane mirrors, spherical/curved mirrors, and lenses.

We did not attempt to directly seek the connection among these optical elements, but started with spherical refraction and first derived the object-image relationship of light ray through a spherical surface, as shown in Fig.3 (a). During the derivation, we adopted Cartesian coordinates and sign rules as described in Section 3.1, following the paraxial ray assumption of the Gaussian optics [5, 6]. We have discovered that, with just two mathematical tricks, we can generalize the object-image relation of spherical refraction to those of plane mirrors, spherical mirrors, and thin lenses. In mathematics, we regard refraction as light entering a medium with refractive index n_b from a medium with refractive index n_a, and reflection as light entering a medium with refractive index $-n_a$ from a medium with refractive index n_a. It should be noted that for reflection, the light returns to its original medium, so we define $n_b=-n_a$. On the other hand, we consider the plane to be the limiting case of the spherical surface, i.e., $r \to \infty$. According to the two conditions mentioned above, it is easy for readers to transform the object-image relation in Fig.3 (a) into that of a plane mirror as shown in Fig.3 (b) and a spherical mirror as shown in Fig.3 (c). As for thin lenses, we consider that light first enters the medium with refractive index n_b from the medium with refractive index n_a, and then passes forward into the medium with refractive index n_a (i.e., the other side of the thin lens). By applying twice object-image relationship of spherical refraction and paying attention to the change in medium and symbol, the transformation from Fig.3 (a) to Fig.3 (d) can be obtained. Even though in physics, we cannot consider the imaging of plane mirrors, spherical mirrors, and lenses as interconnected physical processes, mathematics provides us with the possibility to explore their internal connections. This might just be the blessing brought by the combination of mathematics and physics.

4. Evaluation

In the past six years teaching process (2018-2023), we purposefully designed some questions that can evaluate students' mastery of six skills (Table 1) in in-class tests, experiments, reports, midterm and final exams. By analyzing students' scores on corresponding questions, we can evaluate their achievement in a specific skill. Fig. 4 shows the average achievement (blue) of Chimie Pékin students over 6 years. For comparison, the performance of the control group is shown in orange. The control group consists of students from other colleges/departments at BUCT who have not implemented this teaching paradigm innovation. Since other colleges/departments do not specifically design test questions for the six skills in their teaching activities, we choose the questions as close as possible to the topics for evaluation. This statistical result fully demonstrates that the proposed teaching paradigm innovation can significantly enhance students' six skills, particularly in areas of Investigation and Communication.

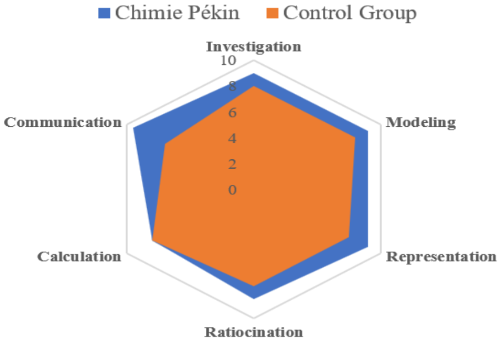

Figure 4. Evaluation and Comparison

5. Conclusions

In the practice of *Geometrical Optics* teaching in Chimie Pékin, by comparing the teaching content and structure of existing textbooks related to *Geometrical Optics* to analyze their strengths and weaknesses in training students to achieve six skills, which are the core skills required for outstanding engineers, we revolutionized the teaching paradigm from two aspects: (1) a Sign Rules based on Cartesian Coordinate, and (2) a Unified Object-Image Relation Model. Comparative evaluations show that these innovations improve the achievement of outstanding engineers' training goals. Our reform not only strengthens the mathematical and physical foundations, paving the way for students to continue their future study of *Physics*, but also help the students unleash their creativity and imagination by instilling this way of thinking, which is highly beneficial for the cultivation of outstanding engineers [7]. In the future work, we will continue to fine-tune the paradigm to further enhance its practicality. On the other hand, we plan to generalize this strategy to other optical and physical courses, comprehensively consolidating the scientific foundation of students in the preparatory cycle.

Acknowledgements

This work was supported by “Talent Cultivation Team of Physical Experiments Teaching”.

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