

Impact of the history of physics course on university non-STEM students' views on the nature of science

Chunying Zuo,¹ Qinxuan Zhou,² Wei-Zhao Shi^{1,3,*} and Jingying Wang^{4,†}

¹*School of Science, University of Science and Technology Liaoning, Anshan, Liaoning 114051, China*

²*Graduate School of Education, Harvard University, Cambridge, Massachusetts 02138, USA*

³*Graduate School of Education, Peking University, Haidian, Beijing 100871, China*

⁴*Faculty of Education, Beijing Normal University, Haidian, Beijing 100875, China*



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Empirical research on whether offering history of science electives at the university level enhances students' understanding of the nature of science (NOS) remains scarce. This study aims to investigate the impact of enrolling in a history of science course on undergraduates' understanding of the nature of science. In this study, the history of physics elective employed three distinct instructional methods: conventional lecture-based teaching, lecture-based teaching combined with explicit instruction and individual reflection, and lecture-based teaching combined with explicit instruction and group reflection. Teaching effectiveness was assessed by administering the SUSSE questionnaire to 160 participants before and after the course, supplemented by cognitive network analysis of students' reflective reports on the nature of science within the authentic context of the COVID-19 pandemic. A randomly selected control group of non-STEM majors who did not enroll in the course was included for comparison. Results demonstrated that all three instructional models significantly improved students' NOS conceptions across multiple dimensions, with the explicit instruction and group reflection approach showing optimal comprehensive effectiveness. However, none of the instructional models produced a statistically significant improvement in students' understanding of the scientific laws and theories dimension.

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I. INTRODUCTION

The criteria for scientific literacy that citizens should possess have expanded over the past century. Initially, it referred to citizens' understanding of core scientific concepts and basic models (content knowledge) as well as research methods (procedural knowledge). Now, it has developed to include an understanding of the nature of science (NOS) (epistemological knowledge). However, epistemological knowledge of science is still rarely addressed [1]. When dealing with social scientific issues like the COVID-19 pandemic, one's view of the nature of science influences their perception and response. A naive view of the nature of science is considered a reason why individuals cannot decipher useful information from the news and believe in conspiracy theories [2]. This phenomenon is unsurprising, as one's interpretation of empirical data and trust in scientific processes are deeply

influenced by their NOS views [3]. Besides the global pandemic that has swept through our lives, social scientific events emerge endlessly. How can the public make correct decisions in such scientific events? To analyze these events, people need to understand some basic scientific knowledge to evaluate simple scientific evidence. However, in many cases, having scientific knowledge alone is not enough [4]. The public should understand how scientists work to judge the reliability of scientific claims in personal and public decision-making [5,6]. This becomes increasingly important in the post-truth era, where more information is available, but its sources are becoming more complex and difficult to understand.

A. College students' views on the nature of science

Students' understanding of the nature of science directly affected their response to scientific events they experienced [7]. Empirical studies revealed that most students (from elementary to university level) hold naive views on the nature of science. Science was often portrayed as a static collection of facts rather than a dynamic process of knowledge construction [8]. Students always perceived science as formulas and concepts in textbooks, and distinguishing between scientific laws, theories, hypotheses, facts, and

*Contact author: vcshih@aliyun.com

†Contact author: wangjingying8018@126.com

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evidence was a challenging task for them [9]. Sadly, students did not want science classes to involve discussions that allowed them room for interpretation; instead, they found security in believing that science was a set of facts [10]. In the pretertiary education stage, influenced by exam-oriented education, current standardized tests focused only on scientific concepts (content knowledge) or methods themselves (procedural knowledge) rather than epistemological knowledge and did not measure students' understanding of the nature of science [11]. Although students had undergone extensive problem-solving training, they still did not have a grasp of science in their minds and lacked a deep understanding of its nature.

Over the past few decades, assessing and attempting to enhance K-12 students' understanding of the NOS has been a focal point of science education research. However, attention to college students' views on the NOS is a relatively new area of study. Abd-El-Khalick conducted an investigation on 153 undergraduate and graduate students at a Western State University in the United States. The study showed that most participants, whether they were science or nonscience majors, held naive or inaccurate ideas about NOS [12]. Ibrahim *et al.* surveyed 179 first-year physics majors at a South African university regarding their understanding of the nature of science, and the results indicated that more than half of the university students lacked a deep understanding [13]. Koksall and Cakiroglu conducted a case study on the views of four graduate students majoring in biology education in Turkey using the VNOS-C open-ended questionnaire. The results also revealed that students had insufficient understanding of the tentative nature of scientific knowledge, its objectivity, sociocultural embeddedness, the hierarchical relationship between hypotheses, theories, and laws, as well as the creativity and imagination in science [14]. Thao-Do and Yuenyong used a self-made questionnaire to survey students at Can Tho University, a local university in Vietnam, and similarly found that students' understanding of the nature of science was not mature [15]. Shi and Wang conducted a study using the views of nature of science (VNOS) questionnaire to investigate the NOS understanding among mathematics and physics majors at a Chinese university. Their findings revealed that students from both majors exhibited underdeveloped NOS comprehension [16]. In a more recent study, Algarni and Alahmad surveyed 501 female chemistry majors from eight universities in Saudi Arabia and found that these female university students had an immature understanding of multiple dimensions, including the differences between theories and laws, as well as the subjectivity of scientific research and the influence of social and cultural factors on science [17]. In light of the above findings, the goal of helping college students develop informed views on NOS has become an important theme.

B. Using history of science to teach about NOS in college

The idea of using the history of science to teach the nature of science can be traced back to the mid-20th century. To help non-STEM majors understand science, James Bryant Conant, a former president of Harvard University, specifically designed case courses in the history of science as part of the general education curriculum. Conant's target audience was clear: those who would pursue careers outside of science and technology. This approach aimed to help them connect the development of natural sciences with progress in other areas of human activity. In Conant's view, achieving this goal required an understanding of the methods of scientific experimentation and the recognition that scientific research is an organized social activity. Its purpose is to dispel the ignorance of laypeople regarding what science can or cannot accomplish [18].

A substantial body of research has demonstrated that teaching the history of science to students enhances their understanding of the nature of science. Jones was the first to conduct a course experiment at a university [19]. In this teaching experiment, the instructor not only covered traditional physics concepts, principles, and methods but also facilitated discussions on the historical development, philosophy of science, and the interplay between science and society. The results showed that the experimental course proved more effective than the traditional course in enhancing students' understanding of the nature of science. Eshach *et al.* developed a 36-h course called "Nobel Prizes and the Nature of Science" at Taiwan Normal University, with 10 undergraduate physics majors participating [20]. It was worth noting that the researchers did not merely present the historical stories of Nobel laureates to students; instead, they asked students to find the historical stories of Nobel laureates themselves and discuss what aspects of the nature of science they embodied. The study found that after the course, students showed significant improvements in their understanding of various aspects of the nature of science. More recent research conducted by Nyarko and Rudge reported that the participants in the study were 37 students from a community college in the Midwestern United States who enrolled in a one-semester course on physical geology [21]. The course incorporated the history of plate tectonics and employed an explicit reflective teaching method. The results indicated that there was a significant improvement in students' views on the nature of science after the teaching intervention.

However, some research indicated that the teaching of the history of science was not significantly effective. Abd-El-Khalick and Lederman conducted a study exploring the impact of history of science courses on college students' understanding of concepts related to the nature of science [22]. The study used a sample of 181 majors specializing in biological sciences or physics and employed a pretest

and post-test design to assess the effectiveness of the instructional intervention. The results showed that there was no significant change after the course, indicating a weak effect of the instructional intervention. This finding suggested that the pure historical case teaching method has limitations in enhancing students' understanding of science. Dass conducted a study at a university in the Midwestern United States to investigate the impact of a history of science course on students' understanding of the nature of the scientific enterprise (NOSE) [23]. The course was primarily composed of 52 undergraduate and graduate students majoring in biology. The views on science-technology-society instrument was used as both a pretest and a post-test. In concurrence with those reported by Abdel-Khalick and Lederman, the research also indicated that there was little improvement in students' overall understanding of NOSE.

Integrating scientific content with the history of science requires too much classroom time and can distract from the concepts that need to be taught. Given the pressure on teachers to cover scientific content and the limited time available, incorporating the history of science into teaching seemed impractical [21]. To effectively teach scientific knowledge, science teachers would inevitably adopt a selective approach. Although the integration of the history of science into university science courses to enhance students' understanding of the nature of science has been implemented for decades, most of these efforts have primarily focused on science majors and typically incorporated historical content as a supplementary component. These are merely used as a "sugar coating" for scientific knowledge to enhance students' interest in learning rather than to help students better understand the process of scientific development. By tailoring historical materials, only the figures and examples along the main line of scientific development are retained, creating an illusion for students. As a result, a series of fascinating and often mythical anecdotes emerges. This issue resonates with critiques by American science historian Klein, who argued at the symposium on physics history and physics education that physics curricula inevitably subject historical narratives to selection, truncation, and distortion, rendering them "historical in name but ahistorical in substance" [24]. Goldwhite further posited that preserving the integrity of science history requires its exclusive treatment within dedicated disciplinary courses, insulated from the instrumental demands of mainstream science education [25].

C. Research focus

A citizen with higher education in non-STEM fields such as humanities, social sciences, or business and management may eventually need to evaluate the work of scientists and consider how scientific endeavors should be funded. Without research experience, they are often unable to grasp the core issues in discussions about

contemporary scientific developments. This is not due to a lack of scientific knowledge or familiarity with the specialized terminology used by scientists but rather stems from their misunderstanding of what science is, viewing it as a knowledge system without a past and ignoring the process by which scientific knowledge is produced, especially the human factors involved in scientific progress. To understand science, it is essential to acquire foundational scientific knowledge, but memorizing exhaustive factual details about research is unnecessary. If one comprehends the nature of science, such information can be retrieved from books or articles when needed. What truly matters is grasping how scientific inquiry operates as a dynamic, human-driven endeavor shaped by evidence, skepticism, and societal influences.

Currently, the empirical research on the impact of history of science courses on non-STEM students' views on the nature of science is quite scarce. In this study, the elective course on the history of physics adopted three distinct teaching models: lecture-based instruction (without explicit reflection processes), lecture-based instruction combined with explicit and individual reflection, lecture-based instruction combined with explicit and group reflection. The study focused on the following research questions:

RQ1. Can taking history of physics courses enhance non-STEM students' understanding of the nature of science?

RQ2. Which teaching model for history of physics is the most effective?

II. METHODS

This experiment was conducted during the fall semester of 2024 at a Chinese university. The history of physics elective course for non-STEM students was first offered. The course lasts for 8 weeks with one session per week, each lasting 2 h. The instructor for the history of physics elective course came from the department of physics, possessing extensive experience in both physics research and educational studies. The curriculum primarily covered: the modern physics revolution, including Galileo's new physics and the era initiated by Newton; the evolution of electromagnetism from Faraday to Maxwell; atomic structure models and quantum theory, as well as the ether hypothesis leading to relativity theory.

A. Participants

The participants in this experiment were 120 non-STEM students who enrolled in the elective course on the history of physics. Here, non-STEM students were those who came from humanities and social sciences majors. Among them, there were 82 females and 38 males. Additionally, 40 non-STEM students who did not enroll in the history of physics course were randomly selected as the control group. Among them, there were 28 females and 12 males.

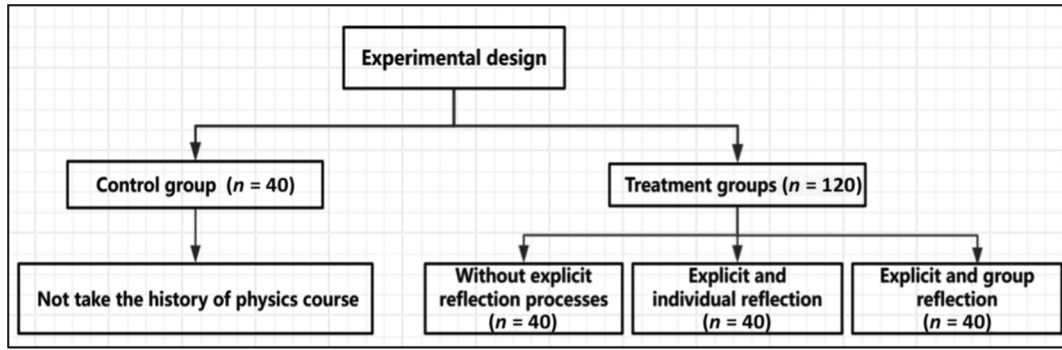


FIG. 1. Teaching design for the history of physics elective course.

B. Teaching interventions

A total of 120 non-STEM students enrolled in the history of physics course were randomly assigned to three classes with 40 students in each, implementing three distinct instructional approaches. Class 1 served as the regular history of physics teaching group, where only historical knowledge was delivered. Since no session for reflecting on the nature of science, there was some extra time compared to the other two classes. To ensure that the students in the three classes spend a similar amount of time in class, a knowledge test was distributed for an open-book examination to review and consolidate what they had learned after the regular lecture for Class 1. Class 2 combined historical physics knowledge teaching with explicit instruction and individual reflection. Namely, in addition to historical knowledge delivery, the instructor also posed explicit questions related to the nature of science, prompting students to reflect individually, produce written reports, and finally submit to the instructor. Class 3 integrated historical physics knowledge teaching with explicit instruction and group reflection. The instructor randomly selected four students to form a group. Beyond historical knowledge instruction, the instructor raised explicit NOS questions for students to collaboratively discuss in small groups. Through group discussions, individuals compared and reconciled their perspectives with others' viewpoints and revised their initial proposals during collaborative dialogues. This iterative process culminated in consensus-building through effective communication, resulting in the submission of a consolidated group report. Additionally, 40 students were randomly selected from non-STEM majors who did not enroll in the history of physics course as a control group. Figure 1 illustrates the design of the teaching for non-STEM majors in the history of physics elective course.

C. Instrument

The students' understanding of science and scientific inquiry (SUSSI) questionnaire was administered to assess participants' views on the nature of science before and after the intervention. The SUSSI questionnaire evaluated

six aspects of the nature of science: observation and inference, the tentative nature of scientific theories, scientific laws and theories, the influence of society and culture on science, creativity and imagination in scientific investigation, and methods of scientific inquiry. The questionnaire was administered to college students in three culturally diverse countries (the United States, Turkey, and China) to analyze the differences among the three countries. The reliability and validity of the questionnaire performed well [26]. The SUSSI scale consisted of 24 Likert-type items and 6 open-ended questions, with each Likert item offering five response options: "Strongly Disagree, Disagree, Uncertain, Agree, Strongly Agree," scored on a five-point scale.

As educators, when imparting the nature of science to learners, the goal was not merely to enable students to memorize a series of definitions [27,28]. Instead, students should be provided with opportunities to apply, analyze, and evaluate their understanding of the nature of science. Wong and Hodson stated that the aim of learning the nature of science is to enable students to evaluate scientific issues and understand contemporary scientific phenomena [29]. So, it is crucial to assess students' ability to identify and explain the nature of science in real-life situations. After completing the SUSSI Likert scale and open-ended questions, students were provided with a summary of scientific reports related to COVID-19. They were tasked with drafting a report to conduct an in-depth analysis of the nature of science revealed in COVID-19-related reports. During the process, students were allowed to search for more detailed related reports on the Internet, but it was emphasized that they must complete the task independently.

D. Data collection and analysis

Two rounds of data collection were conducted using the SUSSI questionnaire before and after the teaching intervention. Both questionnaire administrations were completed under teacher supervision. During later experimental stages, students were further tasked with analyzing the COVID-19 socioscientific event by writing reports identifying NOS characteristics reflected in related

scientific reports. Students were explicitly informed that their responses would not affect their final grades for the course, ensuring the authenticity and validity of their answers.

1. Quantitative analysis

Descriptive and inferential statistical analyses (such as ANOVA, paired sample t tests, etc.) were conducted on the scores of the SUSSI questionnaire for students who took the history of physics course with three different teaching modes before and after the educational intervention, as well as for a control group of students who did not take the course.

2. Qualitative analysis

Students may choose the same statement on a Likert scale for completely different reasons, and these complex details are difficult to capture in quantitative Likert-scale analysis. Therefore, a qualitative analysis method was also employed as a supplement. Six open-ended questions from the SUSSI questionnaire were used, allowing students to elaborate on their views on the nature of science by citing history of physics course examples. Students' open-ended responses were scored using the SUSSI criteria and coded as: unclassifiable, naive, transitional, or informed.

3. Epistemic network analysis

Epistemic network analysis (ENA) can help researchers address the following questions: How do different student

groups with varying learning styles approach the same task related to the nature of science? What core ideas dominate their perspectives? Do distinct groups exhibit different conceptual linkages? After the history of physics elective course, a summary of COVID-19-related scientific reports was compiled and distributed to each student. Students wrote about their understanding of the nature of science as reflected in the scientific reports.

In this study, the students' statements were qualitatively analyzed and coded, and then an online epistemic network analysis tool was used to quantitatively analyze the co-occurrence frequency of ideas and convert them into a two-dimensional visual map to represent the differences in cognitive network structures among different student groups. The graph includes nodes and connecting lines. Nodes represent the most expressed view categories among group members, and the network connecting lines represent the connections between these views. The thickness of the line indicates whether there is a relatively frequent connection between two categories, that is, the frequency of their co-occurrence. The online epistemic network tool [48] was developed by Professor Shaffer based on the idea that the connection structure between cognitive elements is more important than isolated elements [30]. If multiple dimensions of the nature of science can be presented simultaneously in a student's report, then these dimensions may be interrelated, and a network connection can be established. If only one category is found in the report statement, no connection can be created.

The report statements written by students were classified into six dimensions: observation and inference,

TABLE I. Coding example for student's report statements.

Student	Statements	OI	T	STL	SCE	CI	SM
No. 2–19	There are multiple scientific inquiry methods. When searching for intermediate hosts of viruses, some researchers employed codon bias analysis, while others utilized deep learning algorithms.	0	0	0	0	0	1
No. 2–19	Scientists' inferences are influenced by their own knowledge and experience. As snakes are commonly found in Wuhan's markets, some scientists initially considered them as potential intermediate hosts for. However, other scientists deemed this unlikely, arguing that both bats and humans are mammals, while snakes are reptiles. If the virus were to find an intermediate host between bats and humans, a more logical choice would be another mammal, rather than a reptile.	1	0	0	0	0	0
No. 2–19	The cultural traditions of China and the West differ significantly. In formulating treatment plans for patients, China adopts an integrated approach combining traditional Chinese medicine (TCM) and Western medicine. TCM therapies are profoundly influenced by the Chinese natural philosophy of yin-yang dialectics (unity of opposites).	0	0	0	1	0	0
No. 2–19	The emergence of new evidence can lead to changes in scientific theories. During the initial phase of the pandemic, scientists had not yet identified clear evidence of human-to-human transmission of the COVID-19 virus, but later publicly confirmed its capability for such transmission.	0	1	0	0	0	0
No. 2–19	Science is innovative. Traditional data collection relies on virological clinical data collected from hundreds of medical institutions nationwide, suffer from slow acquisition speeds. To enable real-time pandemic surveillance, scientists innovatively turned to indirectly gather data such as over-the-counter medication sales data.	0	0	0	0	1	0

changes in scientific theories, scientific laws and theories, social and cultural influences on science, imagination and innovation, and scientific inquiry methods. The coding procedures are as follows: first, two researchers discussed the coding criteria and conducted a small-scale pilot coding. Cohen's Kappa coefficient was 0.80 for the pilot coding. To enhance coding consistency, they communicated and negotiated once again to resolve disagreements before completing the remaining coding task. As shown in Table I, the coding followed these rules: no. 2–19 presented the coding of no. 19 student from Class 2; the six columns on the right represented the six dimensions of nature of science: the letter “OI” represented the dimension of observation and inference, “T” for the dimension of tentativeness, “STL” for the dimension of scientific theories and laws, “SCE” for the dimension of social and cultural embeddedness, “CI” for the dimension of creativity and imagination, and “SM” for the dimension of scientific methods. Coding standards: If a statement reflected the corresponding dimension of the nature of science, it will be marked 1 in the column corresponding to that dimension; if not, it will be marked 0. For example, no. 19 student from Class 2 wrote in the report: “There are multiple scientific inquiry methods. When searching for intermediate hosts of viruses, some researchers employed codon bias analysis, while others utilized deep learning algorithms.” This statement indicated that the student recognized that scientific methods are diverse, so it is marked as 1 under the letter “SM” representing the dimension of scientific methods. Table I presents the coding examples for all statements in the report of no. 19 student from Class 2.

III. RESULTS

A. Quantitative analysis of the SUSSI questionnaire

Before the teaching intervention, statistical analysis was conducted on the total scores and the scores of six dimensions. The p values of the Levene's test for homogeneity of variance were all greater than 0.05. Therefore, the hypothesis of homogeneity of variance was accepted. The p values of the one-way ANOVA for each dimension and the total score all showed greater than 0.05. The results indicated that before the teaching intervention, there were no significant differences either in the total scores or in the average scores of the six dimensions between the three classes and the control group.

After the teaching intervention, the SUSSI questionnaire was used again to assess the views on the nature of science among students in three classes and the control group.

Paired-sample t tests were conducted on the scores before and after the teaching intervention. From Table II, it can be observed that the post-test scores of students in all three classes are higher than the pretest scores in the total score and six dimensions. However, according to the

paired sample t test, in Class 1, where students received regular history of physics instruction, there was a significant improvement only in three specific dimensions: theory change, imagination and innovation, and inquiry methods. However, the improvements in the dimensions of observation and inference, laws and theories, and society and culture were not statistically significant. The average post-test scores of Class 2 students in the total score and all six dimensions of their understanding of the nature of science were higher than their average pretest scores. According to the paired sample t test, except for the dimension of laws and theories, where the p value was greater than 0.05, the p values for the other five dimensions and the total score were all less than 0.05. This indicates that the teaching method combining explicit instruction with individual reflection did not significantly improve students' epistemological level regarding scientific laws and theories, but it did significantly enhance their epistemological levels in the five dimensions of observation and inference, theoretical change, society and culture, imagination and innovation, and inquiry methods. Similar to Class 2, the paired sample t test showed that explicit instruction with group reflection adopted by Class 3 significantly improved students' epistemological levels in the five dimensions: observation and inference, theoretical change, society and culture, imagination and innovation, and inquiry methods. However, no significant enhancement was observed in their understanding of the “laws and theories” dimension (p value > 0.05). Paired samples t test for four groups were shown in Table II.

ANOVA and LSD *post hoc* test were also conducted on the scores in six dimensions. The results are shown in Table III; c represents the control group that did not take the history of physics course, 1 represents Class 1 with regular history of physics knowledge teaching, 2 represents Class 2 with explicit teaching and individual reflection, and 3 represents Class 3 with explicit teaching and group reflection. Table III showed that the Sig values of the Levene's test for homogeneity of variances were all greater than 0.05, so the hypothesis of homogeneity of variances was accepted. Except for the scientific laws and theories dimension, the p values of the F test for the total score and other dimensions were all less than 0.05.

There were significant intergroup differences in both the dimension of observations and inferences ($F = 11.5$, $p = 0.0016$) and the dimension of social and cultural embeddedness ($F = 20.7$, $p < 0.001$). The LSD *post hoc* test results consistently showed the characteristic of $c \approx 1 < 2 < 3$, demonstrating that there were clear gradient differences in the teaching effectiveness across these two dimensions. Extremely significant intergroup differences were observed in both the dimension of tentativeness ($F = 83.5$, $p < 0.001$) and the dimension of scientific methods ($F = 50.3$, $p < 0.001$), with the LSD *post hoc* test results showing $c < 1 \approx 2 \approx 3$ for both

TABLE II. Paired samples t test for four groups.

	Group	Pretest (SD)	Post-test (SD)	t	p
Observations and inferences	Class 1	13.1 (2.1)	13.3 (2.0)	1.5	0.15
	Class 2	13.0 (2.3)	14.5 (1.7)	5.8	< 0.001
	Class 3	13.5 (2.2)	15.3 (1.6)	6.6	< 0.001
	Control	13.3 (2.0)	13.3 (2.0)	1.4	0.16
Tentativeness	Class 1	13.5 (1.8)	16.9 (1.1)	17.3	< 0.001
	Class 2	13.3 (1.7)	16.9 (1.1)	14.0	< 0.001
	Class 3	13.5 (2.0)	17.3 (1.1)	12.1	< 0.001
	Control	13.4 (1.7)	13.4 (1.7)	1.0	0.32
Scientific theories and laws	Class 1	10.1 (1.8)	10.3 (1.5)	1.1	0.26
	Class 2	10.2 (1.6)	10.3 (1.5)	0.27	0.79
	Class 3	10.1 (1.8)	10.3 (1.6)	1.4	0.18
	Control	10.1 (1.6)	10.3 (1.5)	0.47	0.64
Social and cultural embeddedness	Class 1	11.4 (2.1)	11.6 (1.9)	0.74	0.46
	Class 2	11.5 (2.1)	13.0 (1.7)	7.2	< 0.001
	Class 3	11.4 (2.1)	14.2 (1.6)	9.8	< 0.001
	Control	11.5 (2.0)	11.5 (2.0)	0.10	0.92
Creativity and imagination	Class 1	12.1 (1.8)	13.7 (1.3)	6.7	< 0.001
	Class 2	12.1 (1.5)	14.6 (1.3)	9.8	< 0.001
	Class 3	12.1 (1.6)	15.0 (1.2)	12.8	< 0.001
	Control	12.1 (1.6)	12.1 (1.6)	0.57	0.57
Scientific methods	Class 1	13.2 (2.0)	16.0 (1.1)	13.0	< 0.001
	Class 2	13.1 (1.7)	16.0 (1.0)	9.0	< 0.001
	Class 3	13.1 (2.0)	16.1 (1.1)	12.2	< 0.001
	Control	13.1 (2.0)	13.2 (1.8)	0.81	0.42
Total	Class 1	73.3 (7.5)	81.6 (5.7)	12.6	< 0.001
	Class 2	73.2 (6.8)	85.2 (4.7)	11.6	< 0.001
	Class 3	73.6 (7.3)	88.2 (4.1)	16.1	< 0.001
	Control	73.5 (7.1)	73.9 (7.3)	0.02	0.98

TABLE III. ANOVA and *post hoc* tests of the four groups in the post-test.

	Levene statistic	Sig	F	p	LSD <i>post hoc</i>
Observations and inferences	0.46	0.45	11.5	0.002	$c \approx 1 < 2 < 3$
Tentativeness	2.26	2.25	83.5	< 0.001	$c < 1 \approx 2 \approx 3$
Scientific theories and laws	0.29	0.28	0.02	0.89	$c \approx 1 \approx 2 \approx 3$
Social and cultural embeddedness	0.28	0.27	20.7	< 0.001	$c \approx 1 < 2 < 3$
Creativity and imagination	1.76	1.75	35.6	< 0.001	$c < 1 < 2 \approx 3$
Scientific methods	2.24	2.23	50.3	< 0.001	$c < 1 \approx 2 \approx 3$
Total	2.18	2.18	52.2	< 0.001	$c < 1 < 2 < 3$

dimensions. This indicated that the control group was significantly inferior to classes 1, 2, and 3, while no statistically significant differences were found among classes 1, 2, and 3. And there was also an extremely significant intergroup difference in the dimension of creativity and imagination ($F = 35.6$, $p < 0.001$). The LSD *post hoc* test revealed $c < 1 < 2 \approx 3$, meaning that

the teaching effectiveness showed successive significant differences in this dimension, with no significant difference between Class 2 and Class 3. The ANOVA results for the dimension of scientific theories and laws showed no significant intergroup difference ($F = 0.02$, $p = 0.89$), which was further verified by the LSD *post hoc* test with the result of $c \approx 1 \approx 2 \approx 3$, suggesting that there were no

statistical differences in the effectiveness of various teaching models in this dimension. In terms of the total score, the research exhibited extremely significant inter-group differences under different teaching models ($F = 52.2$, $p < 0.001$). The LSD *post hoc* test result was $c < 1 < 2 < 3$, reflecting that the overall teaching effectiveness of each class presented continuous and obvious gradient significant differences.

B. Qualitative analysis of the SUSSI questionnaire

Qualitative research required students to accurately articulate their own views on the nature of science. However, collecting such data before teaching interventions was particularly challenging, as students often have a limited understanding of the nature of science prior to the intervention. Students were instructed to elaborate in detail on their viewpoints for each dimension of the SUSSI instrument after completing its Likert-scale quantitative section. Students' open-ended responses were scored using the SUSSI criteria and coded as: unclassifiable, naïve, transitional, or informed. Unclassifiable responses referred to the following three scenarios: no response provided, respondent stated they did not know the answer, and irrelevant response that did not address the question. In this study, student performances categorized as unclassifiable primarily involved no response provided.

Overall, the dimensions that scored higher on the Likert-scale items also showed higher proportions of transitional and mature responses in the open-ended questions. In contrast, the dimension with the lowest score on the Likert-scale items, such as the theory and laws dimension, had the highest proportions of naïve and unclassifiable responses in the open-ended questions. Before the teaching intervention, both the response rate and the quality of students' answers to the open-ended questions were poor, with many students choosing not to respond. It is common for students to refrain from answering when they are unfamiliar with the content of the questions or do not know how to respond, especially for students in the lower-achieving group. For example, Liu and Lederman conducted a survey using the VNOS open-ended questionnaire as a tool; they also found that respondents with naïve views of the nature of science exhibited insufficient enthusiasm in answering the open-ended questions, and the phenomenon of not responding was severe [31]. After the teaching intervention, the rate of unanswered questions decreased in all three classes, particularly in Class 2 (explicit with individual reflection) and Class 3 (explicit with group reflection). Except for the dimension of scientific theories and laws, the proportion of informed performance increased across other dimensions in all three classes. Students in the control group who did not take the course exhibited similar responses to the open-ended questions as their performance on the Likert-scale section. In both the pretest and post-test phases, the response rate

and quality of the students' answers to the open-ended questions were poor, showing insufficient enthusiasm, and the phenomenon of not responding was severe. The distribution of responses to open-ended questions in the three classes and the control group before and after the intervention is detailed in Figs. 2–5.

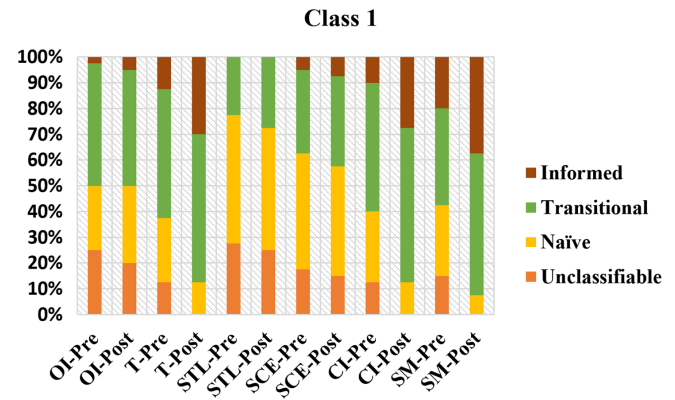


FIG. 2. Preperformance and postperformance of Class 1 on open-ended questions.

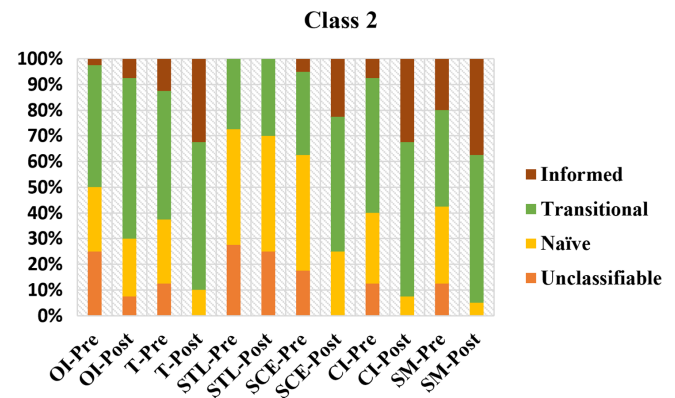


FIG. 3. Preperformance and postperformance of Class 2 on open-ended questions.

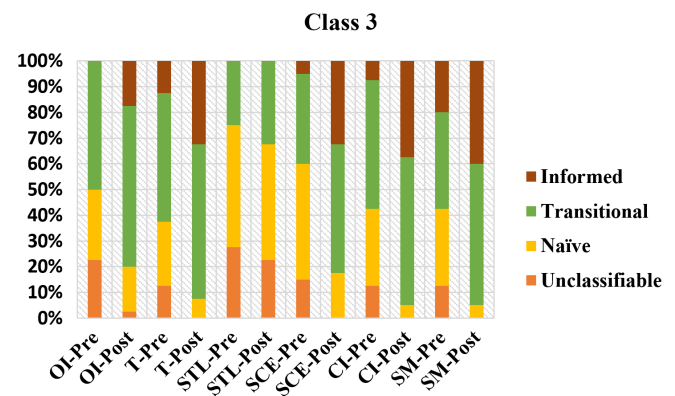


FIG. 4. Preperformance and postperformance of Class 3 on open-ended questions.

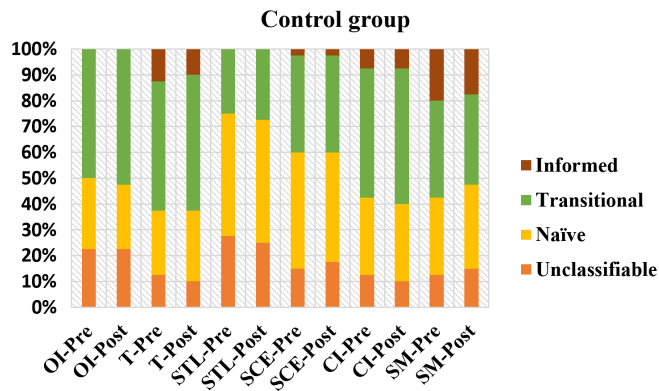


FIG. 5. Preperformance and postperformance of the control group on open-ended questions.

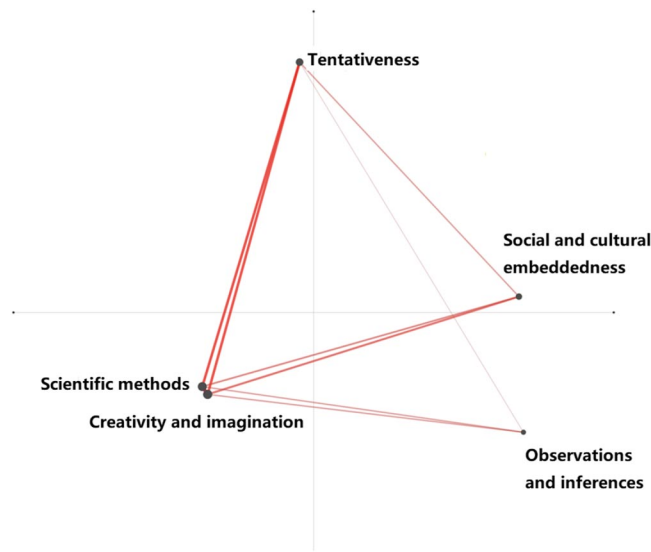


FIG. 6. Epistemic network structure of Class 1.

C. Epistemic network analysis on students' statements on COVID-19 scientific reports

Researchers on the nature of science increasingly recognized the importance of considering cross-conceptual connections beyond merely declarative knowledge. The multiple dimensions of the nature of science were often regarded as interconnected [32]. By using the interrelationships among these dimensions as an observational lens, a more nuanced examination of the epistemic structures and levels within student populations could be conducted [33,34]. Epistemic network analysis, which visualized data by modeling the connection structures among various elements, served as an analytical tool for examining similarities and differences among different groups. The nodes on the graph represented the most frequently expressed viewpoint categories among members of a group, while the network connections represented the links between these viewpoints. The thickness of the lines

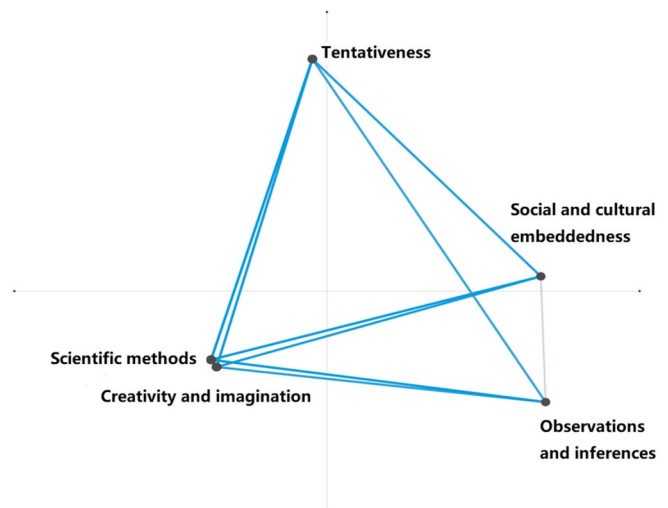


FIG. 7. Epistemic network structure of Class 2.

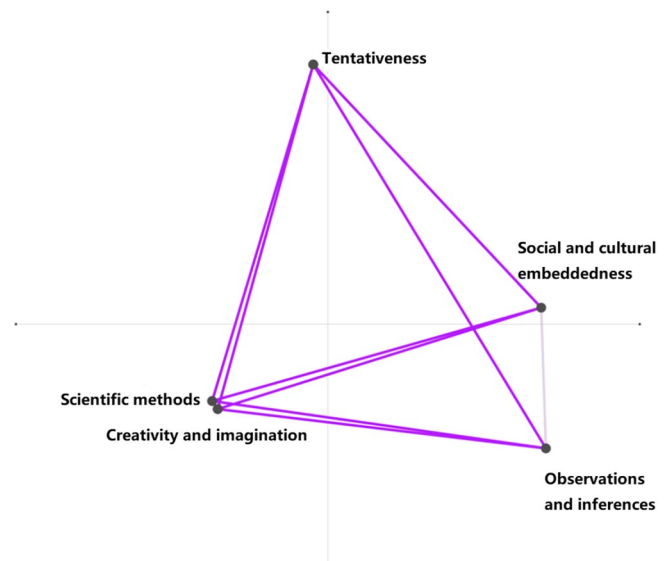


FIG. 8. Epistemic network structure of Class 3.

indicated whether there were relatively frequent connections between the two categories.

To analyze the specific characteristics of epistemic structures among different student groups under various teaching modes, the ENA online tool was used to generate respective epistemic network structure diagrams [30].

Figure 6 presents the epistemic network structure of students from Class 1, who received regular instruction on the history of physics. Figure 7 shows the epistemic network structure of students from Class 2, who participated in explicit instruction combined with individual reflection. Figure 8 depicts the epistemic network structure of Class 3, who engaged in explicit instruction combined with group reflection. Figure 9 illustrates the epistemic network structure of control group students who did not

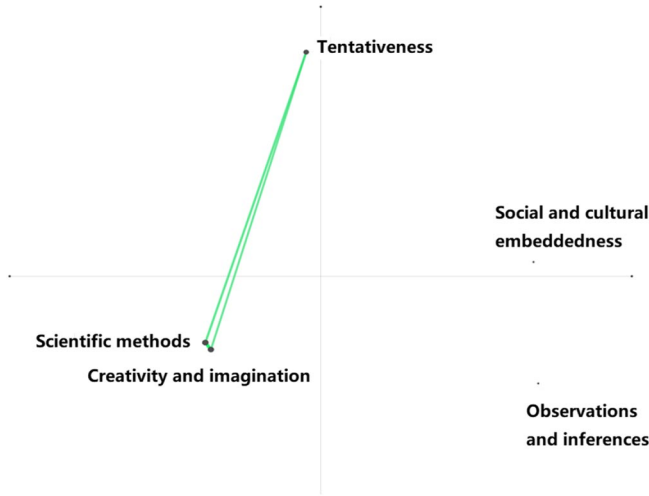


FIG. 9. Epistemic network structure of the control group.

enroll in the history of physics course. In these figures, the nodes represented the various encoded dimensions, with their size related to the frequency of occurrence of each dimension. The thickness of the lines connecting the nodes correlated with the frequency of co-occurrence between the corresponding dimensions.

It could be seen that the epistemic network structures of Class 2 (individual reflection) and Class 3 (group reflection) were more balanced. Students in both classes were capable of integrating multiple NOS dimensions and interpreting the nature of science reflected in COVID-19-related scientific reports from multifaceted perspectives. By contrast, Class 1, which received regular instruction, exhibited a pronounced structural imbalance in its epistemic network, characterized by weak associations between the dimension of observation and inference and the social and cultural dimension. The control group, which received no history of science instruction, showed an even more severe imbalance. Significant co-occurrences were limited

TABLE IV. Comparisons of network centroids across classes on the x - and y -axes.

Comparison	Axis	Group	M	SD	t	p
Class 1 vs Class 2	X	Class 1	-0.16	0.27	10.84	< 0.001
		Class 2	0.34	0.11		
	Y	Class 1	0.01	0.34	-0.49	0.62
		Class 2	-0.02	0.05		
Class 2 vs Class 3	X	Class 2	0.34	0.11	2.99	< 0.001
		Class 3	0.40	0.03		
	Y	Class 2	-0.02	0.05	-1.60	0.12
		Class 3	-0.03	0.02		
Control vs Class 1	X	Control	-0.58	0.41	5.56	< 0.001
		Class 1	-0.16	0.27		
	Y	Control	0.04	0.54	-0.25	0.80
		Class 1	0.01	0.34		

to pairs among the dimension of theoretical change, the dimension of inquiry methods, and the dimension of imagination and innovation. Notably, no student responses referred to the dimension of observation and inference or the social and cultural dimension.

To quantitatively examine the differences in students' cognitive network structures, an independent samples t test was conducted on the network centroids across the ENA space [30]. The results are shown in Table IV. M indicates the average spatial location of the network centroids for each group along each axis, reflecting the central tendency of the group's cognitive network structure. SD measures the dispersion or variability of individual centroids around the group mean, representing the degree of cognitive consistency or homogeneity within each class. All pairwise comparisons showed significant differences only on the x axis; all y axis p values were greater than 0.05, indicating no statistical significance.

A difference map between two groups can be generated by subtracting overlapping connections at identical positions, thereby assigning the final connections to the group with higher co-occurrence frequency. The epistemic network subtraction between Class 2 (explicit with individual reflection) and Class 3 (explicit with group reflection) was shown in Fig. 10. As can be seen, the connections between the dimension of observation and inference and the dimension of social and cultural appeared in purple, indicating that the co-occurrence of these dimensions among Class 3 students was better than that of Class 2. There were no remaining connections after the subtraction between other dimensions, suggesting that the differences in co-occurrence among other dimensions were not statistically significant.

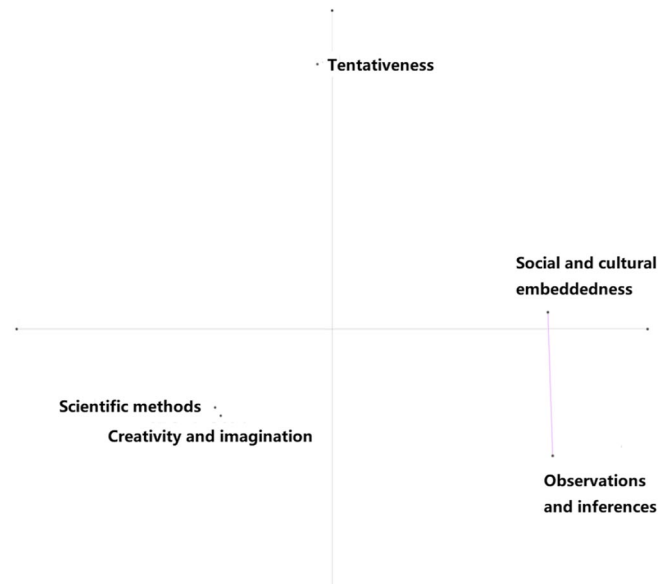


FIG. 10. Epistemic network subtraction between Class 2 and Class 3.

IV. DISCUSSION

Previous studies had shown that the teaching method of integrating the history of science with the scientific knowledge was not significantly effective in enhancing students' understanding of the nature of science. The main reason was that it was difficult to incorporate the real history of science into science knowledge teaching. To keep the history of science complete, it should be taught only in special courses. These courses should be separate from the instrumental demands of regular science education [25]. A combination of a complete history of science, explicit instruction, and reflection on the nature of science was necessary to help students construct their own understanding of the nature of science [35,36]. Universities can present a relatively complete history of science to students through elective courses, especially for non-STEM majors who have fewer opportunities to engage with science courses. This study explored whether elective courses on the history of physics for non-STEM majors can effectively enhance their understanding of the nature of science and which teaching mode is more effective. The research findings were as follows:

The elective course on the history of science taught in the conventional teaching mode can effectively improve students' views on the nature of science, but it was not effective in all dimensions. Students still performed poorly in the dimensions of observation and inference, as well as society and culture. A possible reason was that students were accustomed to exam-oriented education, where the focus of learning was memorizing some scientific historical facts, such as who created these theories in what period and what methods were used to obtain new evidence. Obviously, historical events had become a kind of knowledge that students memorized by rote. To address this, teachers need to provide controversial, explicit questions in class to prompt students to reflect on the complexity behind scientific events, rather than simply memorizing some historical events and ignoring the influence of human subjectivity and social culture in the process of scientific inquiry [37].

Based on the evaluation results before and after the teaching interventions, both in the Likert-scale section and the open-ended question section, Class 3, which adopted the teaching model of explicit instruction with group reflection, performed the best. Next was Class 2, which used the teaching model of explicit instruction plus individual reflection. Finally, there was Class 1, which simply imparted the knowledge of the history of physics. A possible explanation was that group reflection, as a socially constructivist learning approach, was more effective in enhancing understanding of the nature of science than individual reflection, where learners construct knowledge on their own. Social constructivism emphasized the role of society and language communication in knowledge construction [38], which was like the relationship between

a standalone computer and the Internet. Dialogue with others played a very important role in knowledge construction. When we heard others' ideas, we evaluated them rather than simply absorbing them in a predetermined form. Essentially, traditional science history classrooms merely provided students with an objectified form of scientific capital, presented through blackboard text and video images. Only through group discussions, collective reflection, and experiencing the clash and exchange of ideas could students develop embodied scientific capital [39].

In the assessment of the NOS as reflected in scientific reports about the socioscientific issue of COVID-19, the class employing explicit instruction with group reflection again demonstrated the best performance. The cognitive structure of students in Class 3 was the most complex and rich, followed by Class 2, who engaged in individual reflection. The cognitive network structure of Class 1, who were only taught scientific history knowledge, was imbalanced, showing weak connections between the social and cultural dimension, the observation and inference dimension, and other dimensions. Applying the family resemblance approach, Erduran and Dagher categorized the nature of science into two domains: the cognitive system and the social institutional system [40]. This study found that there was a weak correlation between the social and cultural dimension of the nature of science and other dimensions that can be attributed to the cognitive system category. The result was similar to the findings of previous studies, indicating that students' understanding of the dimension that science was influenced by society and culture is difficult to change [41–43]. If the sociocultural context of science were ignored, students would not be able to understand the real work of scientists [29]. Overall, there was a strong similarity between students' understanding of the nature of science in the real scenario of the socioscientific event COVID-19 and the results of the SUSSI questionnaire survey.

The three teaching modes were not effective in improving students' understanding of the dimension of scientific laws and theories. Even students who had undergone explicit and reflective science history courses still lacked a sufficient understanding of the distinction between scientific laws and theories. This was similar to the findings of Parker *et al.* at a private university in the United States [44] and Petersen *et al.* at a technical university in Germany [45]. Possible explanations were as follows: first, students' naive preconceptions typically formed the cognitive basis for their misinterpretations of scientific epistemology. Students often hold the entrenched preconception that scientific laws exist inherently in nature, awaiting discovery by scientists rather than being human constructs. They typically perceived scientific laws as hierarchically superior to scientific theories, believing that theories become laws once substantiated by sufficient

evidence. This highlighted how NOS instruction fundamentally involved conceptual change, a process of modifying such preconceptions that typically originate in elementary education and become increasingly resistant to modification over time [46]. The second challenge lay in the terminological complexity of NOS concepts. Students' difficulties in distinguishing between scientific theories and laws may stem from the inherent complexity of these terms. As Lederman *et al.* demonstrated, given the overlapping conventional meanings of scientific theory and scientific law in everyday usage, it was unsurprising that students develop such persistent misconceptions about their fundamental differences in scientific practice [47].

DATA AVAILABILITY

The data that support the findings of this article are not publicly available because they contain sensitive personal information. The data are available from the authors upon reasonable request.

APPENDIX: TEACHING CASE ON THE EVOLUTION OF ATOMIC STRUCTURE MODELS

1. Teaching objectives

To master the six most important models in the evolution of atomic models, understand the advantages and disadvantages of each model, as well as the social and cultural background of model establishment. To recognize the nature of science contained in this case. The specific nature of science reflected in this teaching case includes: science is influenced by political and cultural factors (ancient Greek democratic system), the constructiveness of science (models are not real descriptions of nature), the empiricism of science (scientific experimental evidence), the tentativeness, cumulateness and creativity of science (establishment of new models and improvement of old ones), the limitations of science (models have limited scopes of application and degrees of accuracy), the subjectivity of science (scientists' knowledge background and expectations affect the design of experiments and analysis of observational results), and the sociality of science (science requires recognition from the scientific community).

2. Teaching content

The Lecturer presented a brief history of the development of atomic models in the form of pictures and texts. Figure 11 presented an example of a slide with the history of atomic models.

The following text outlines six key milestones spanning from the philosophical speculation of ancient Greece to Schrödinger's electron cloud model.

a. The conceptual origin of atoms

City-states in ancient Greece established a democratic system that encouraged people to conduct rational explanations through free debates. The main feature of this early form of science was the abstractness of debate. A natural philosopher's theory was supported not by experimental data or their practical skills but by the logic and rationality on which it was based, which won public acclaim at that time. The philosopher Democritus proposed that the origin of all things was atoms and the void. Atoms were indivisible material particles, and the void was the place where atoms moved.

b. Dalton's model

The advent of the Chemical Revolution demonstrated the importance of experimental evidence. While conducting meteorological surveys, Dalton attempted to solve the problem of why gases in the atmosphere mixed so thoroughly despite their different specific gravities. Based on conclusions drawn from his own experimental results, the size of individual particles of one pure gas must differ from those of another gas. It was the work that led Dalton to conceive concepts such as chemical atoms and atomic weights, arguing that atoms are indivisible, rigid, solid spheres. However, many of his contemporaries doubted the validity of Dalton's basic assumptions about atoms; although they acknowledged the instrumental value of atoms, they remained skeptical of their real existence.

c. Thomson's model

In 1897, Thomson's cathode emission experiment with vacuum tubes proved the existence of electrons and measured the charge-to-mass ratio of electrons, causing a sensation throughout the physics community. The discovery of electrons challenged Dalton's solid sphere atomic theory. Thomson proposed that atoms are uniformly positively charged spheres. Tiny negatively charged electrons were thought to be embedded in these positively charged clouds like seeds in a watermelon or plums in a pudding; hence, it was named the Plum Pudding Model.

d. Rutherford's model

In 1909, Geiger and Marsden conducted the alpha particle scattering experiment under the supervision of Rutherford. In this experiment, alpha rays emitted from the radioactive element polonium were used to bombard a gold foil approximately 0.00004 cm thick. Observations revealed that: the vast majority of alpha particles passed directly through the gold foil, a small number underwent large deflections, and very few were reflected back with a deflection of nearly 180°. Thomson's model could not account for this phenomenon, and the subsequent multiple-scattering theory was only able to explain this anomaly

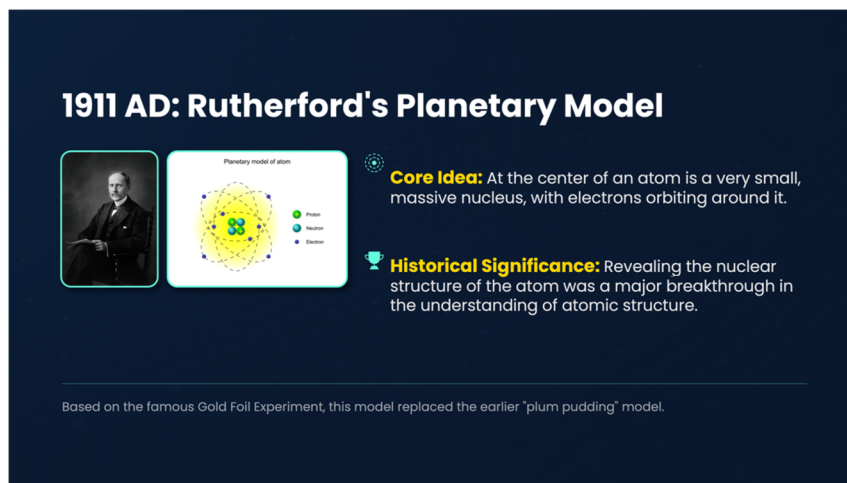


FIG. 11. Example of a slide with the history of atomic models.

qualitatively. At the end of 1910, Rutherford proved through calculations that large-angle scattering of alpha particles passing through a single atom could only be possible if positive charges were assumed to be concentrated at the center of the atom, with electrons revolving around the nucleus in circular paths.

This model contradicted that of his teacher Thomson and was met with a cold reception due to its stability problem. It aroused almost no response at the International Physics Conference in 1911. Numerous improvements were later made to the alpha scattering experiment, and comprehensive experimental data further validated Rutherford's theory.

e. Bohr's model

Rutherford's model of electrons orbiting the nucleus was unstable, as it would lead to energy loss of electrons and eventual collision with the nucleus. Bohr did not abandon this theory despite the difficulties of Rutherford's model; after all, it was strongly supported by the alpha particle scattering experiment. He therefore attempted to incorporate the concept of quantization into Rutherford's model. He learned the theory of radiation generated by valence electron transitions from Stark's works and Sommerfeld's quantum theory, inherited the work of his predecessors, and established the stationary state transition atomic model basically applicable to atomic phenomena in 1913. Electrons could only revolve in certain allowed orbits called shells or energy levels, each associated with a specific amount of energy. These orbits are known as stationary states or energy levels. Nevertheless, Bohr's modified version of Rutherford's model still failed to explain complex spectral phenomena of atoms other than hydrogen.

f. Schrödinger's model

In 1926, the Austrian physicist Schrödinger advanced Bohr's atomic model. Schrödinger used mathematical

equations to describe the probability of finding an electron at a certain position. This model can be described as a nucleus surrounded by an electron cloud. The electron cloud is an informal term in physics used to describe the position of electrons around the nucleus. The densest regions in the cloud are where electrons are most likely to exist, with the highest probability appearing on Bohr's orbits.

3. Explicit questions on the nature of science

1. Why did scientific thought originate in ancient Greece? How did the democratic system and social culture foster attempts to explain nature through logic?
2. Dalton's model was proposed based on experimental evidence, yet many of his contemporaries doubted the real existence of atoms. Why is experimental evidence sometimes insufficient to convince everyone?
3. Is a model a true description of nature, or is it a tool constructed for the convenience of explaining phenomena?
4. The discovery of electrons overturned Dalton's solid sphere theory. Does this mean Dalton's earlier model was wrong? How should we view the succession of scientific theories?
5. How does a scientist's background knowledge influence their observations?
6. Why was Rutherford's new model initially opposed by his teacher Thomson and met with a cold reception from the scientific community?
7. Bohr did not abandon Rutherford's model; instead, he creatively introduced Planck's concept of quantization. Does the emergence of a new theory represent a complete overthrow of the old theory, or rather a revision and refinement of it?

8. From Dalton's solid sphere to Schrödinger's probability cloud, atomic models have become increasingly abstract. Can we say that the electron cloud represents the true nature of the atom?
9. Do you think new atomic models will emerge in the future? Why or why not?

4. Student reflection

After completing the study of the history of atomic model development, in response to the explicit questions on the nature of science provided by the Lecturer, students

in Class 2 (explicit with individual reflection) independently constructed new understandings of the nature of science through individual reflection based on course content and relevant historical details online, and finally submitted individual reports. Students in Class 3 (explicit with group reflection) expressed their own views through group discussions, continuously compared and coordinated their personal ideas with those of others, revised their own propositions in dialogue, and reconstructed their personal views. Finally, a consensus was reached through communication, and group reports were submitted.

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