





## Enhancing high school students' critical thinking through the historical models of gene function

 Linh, Do Thuy<sup>1</sup>  
Hung, Mai Van<sup>2</sup>  
Trung, Dinh Le<sup>3</sup>  
 Phuong, Le Thi<sup>++</sup>

<sup>1,2,3</sup> VNU University of Education, Hanoi, Vietnam.

<sup>1</sup> Email: [dothuylinh@vnu.edu.vn](mailto:dothuylinh@vnu.edu.vn)

<sup>2</sup> Email: [hungmv@vnu.edu.vn](mailto:hungmv@vnu.edu.vn)

<sup>3</sup> Email: [lethiphuong@vnu.edu.vn](mailto:lethiphuong@vnu.edu.vn)

<sup>3</sup> Hanoi National University of Education, Hanoi, Vietnam.

<sup>3</sup> Email: [ledinhtrungnue@gmail.com](mailto:ledinhtrungnue@gmail.com)



(+ Corresponding author)

### ABSTRACT

#### Article History

Received: 11 April 2025

Revised: 19 January 2026

Accepted: 31 March 2026

Published: 20 April 2026

#### Keywords

Critical thinking

Genetics

Historical approach

Historical models.

Developing students' critical thinking skills is one of the most significant challenges in contemporary education, particularly within K-12 settings. Numerous strategies have been proposed to foster the development of critical thinking among students. This study advocates for a historical approach that utilizes various models of gene function—namely Mendelian, Classical, Biochemical-Classical, Neoclassical, and Modern models—which were previously proposed in earlier research. The aim is to assist students in acquiring new knowledge in a comprehensive, logical, and systematic manner. By examining the problem of genes from the beginning of their developmental trajectory, students gain insights into the evolution of gene functions from multiple perspectives. This approach helps them understand the conflicts that arise during research processes related to gene functions, evaluate the advances and limitations of discoveries in this field, and thereby enhance their critical thinking skills. The study assessed students' critical thinking based on five key elements: (1) a comprehensive and objective examination of scientific knowledge; (2) analysis of conflicts within or between scientific paradigms; (3) justification of proposed resolutions and predictions of future trends; (4) unbiased evaluation of conflict resolution strategies, including their strengths and weaknesses; and (5) identification and correction of errors in the resolution process. The findings indicated that these five elements of critical thinking are strongly interconnected and are essential components of critical thinking. Additionally, experiencing historical models of gene function has a positive impact on students' critical thinking.

**Contribution/Originality:** This study is one of the few investigations that have examined the impact of teaching historical models of gene function on students' critical thinking skills. By adopting a historical approach to genetics instruction, the research provides new insights into how critical thinking can be developed through educational practices.

## 1. INTRODUCTION

Critical thinking is one of the core 21<sup>st</sup>-century competencies. It is a vital topic in modern education. Critical thinking is frequently considered an internal cognitive process (Garrison, 1992). There are numerous strategies for developing critical thinking skills in students, all of which prioritize the requirement for students to analyze, synthesize, and evaluate information to solve problems and draw conclusions rather than merely repeating knowledge (Snyder & Snyder, 2008).

Several articles published about gene models, gene concepts, and their implications for genetics teaching have argued that a significant challenge in enhancing students' understanding of genetics arises from the inconsistent and predominantly non-historical approach used to present models of genes and their roles within biological systems. These models are often depicted as if they represent a linear and cohesive progression, rather than a collection of diverse models, each employed within specific contextual frameworks (Dos Santos, Joaquim, & El-Hani, 2012; Flodin, 2009; Gericke & Hagberg, 2007; Smith & Adkison, 2010). Nevertheless, there are two facets of science when it comes to understanding it: knowledge within science and knowledge about the nature of science. Knowledge within science refers to the content, such as laws, models, theories, concepts, and ideas, as well as the methods used by scientists, including experimental techniques and procedures. Knowledge about the nature of science, on the other hand, pertains to how scientists develop and utilize scientific knowledge. This includes addressing research questions, collecting and analyzing scientific data, and deciding whether to accept or reject findings published in research journals (Ryder, Leach, & Driver, 1999). There is a growing expectation that students will graduate from school with not only knowledge in science but also with an understanding of scientific principles and methods (Bevilacqua, Giannetto, & Matthews, 2001; McComas, Clough, & Almazroa, 1998).

In the Vietnam context, on December 26<sup>th</sup>, 2018, the Vietnamese Ministry of Education and Training unveiled the new General Education Curriculum. The general education program aims to comprehensively develop students' competencies and values, encompassing three primary competencies (autonomy and self-study, communication and collaboration, problem-solving and creativity) and five core values (patriotism, compassion, diligence, honesty, and responsibility) (Vietnamese Ministry of Education and Training, 2018b). Critical thinking is essential for achieving the objectives of the comprehensive development of competencies and values outlined by the General Education Curriculum. The requirements for students to assess, evaluate, support, criticize, and argue relevant problems are fundamental characteristics of critical thinking. In accordance with the objectives of the General Education Curriculum for the high school level, it is crucial to promote critical thinking alongside primary competencies and core values in students. With the launch of the new General Education Curriculum, the revised Biology curriculum has also been introduced. The Biology subject is responsible for fostering biological competence in students as an aspect of natural science competence developed during secondary education. Biological competence encompasses several elements: biological awareness, understanding the living world, and applying acquired skills and knowledge. To achieve the goal of fostering biological competence, students are expected to discuss and evaluate the impact of various problems. Teachers may employ exercises that involve critical and creative thinking, such as open-ended questions, integrated with feedback throughout the learning process. In other words, students are expected to develop more advanced critical thinking skills when learning biology (Vietnamese Ministry of Education and Training, 2018a).

In this study, we proposed employing historical models specifically, models of gene function to teach genetics to high school students. This approach aims not only to help students perceive knowledge of genetics systematically and comprehensively but also to foster their understanding of the nature of science, which is closely linked to critical thinking (González-Howard & McNeill, 2020; Noroozi, 2018; Tolvanen, Jansson, Vesterinen, & Aksela, 2014; Weinstock, 2006). This study aims to examine whether the historical approach of employing models of gene function can enhance students' critical thinking skills. It seeks to address the research question: How effective is teaching historical models of gene function in improving students' critical thinking abilities?

## **2. THEORETICAL FRAMEWORK AND BACKGROUND**

### *2.1. Intention to Foster Critical Thinking through Teaching Historical Approach*

#### *2.1.1. Overall About Critical Thinking*

Critical thinking is not a new concept. It has long been advocated within the scientific community to define what constitutes critical thinking. Much of the educational literature considers critical thinking a meta-cognitive thinking

skill, described as "reasonable reflective thinking focused on deciding what to believe or do" (Ennis, 1989). This concept can also be adapted to another perspective: "the propensity and skill to engage in an activity with reflective skepticism" (McPeck, 2016). A person with critical thinking skills can ask relevant questions, gather important information, and analyze that information effectively and creatively. They are capable of reasoning logically based on the data they have collected and can arrive at reliable and trustworthy conclusions about the world, which enables them to navigate and succeed in life (Schafersman, 1991). Moore (2013) identified seven definitional aspects of critical thinking, derived from various disciplinary backgrounds: (i) as judgment; (ii) as skepticism; (iii) as simple originality; (iv) as sensitive readings; (v) as rationality; (vi) as activist engagement with knowledge; and (vii) as self-reflexivity (Moore, 2013). Generally, students who can think critically can develop skepticism with such given information and then objectively perceive problems from various aspects, even contradictory aspects. From there, students can analyze, synthesize, evaluate information, and give reasonable opinions and arguments to prove personal views. Critical thinking requires students to use new information or adapt existing knowledge to find rational solutions to new situations (Lewis & Smith, 1993; Perkins & Murphy, 2006).

### *2.1.2. Developing Critical Thinking Through Teaching Science Education By Historical Approach*

It is a commonly accepted belief that one of the main objectives of science education is to foster the development of critical thinking skills (Bailin, 2002). However, traditional teaching methods, such as content-based instruction, have largely disregarded critical thinking and instead rely on students' memorization for learning (Firdaus, Kailani, Bakar, & Bakry, 2015; Santos, 2017). Science is often presented as dogma a collection of unequivocal, indisputable, and unexamined facts, similar to how individuals are indoctrinated into a belief system rather than being integrated into a critical, inquisitive community (Derry, 1999). Research indicates that many students graduate from school science with the belief that the primary goal of science is the establishment of a valid fact (Driver, Leach, Millar, & Scott, 1996). Critical thinking is essential to scientific practice; without debate and evaluation, establishing reliable knowledge would be unfeasible (Osborne, 2014). Educators can employ various instructional methods to enhance students' critical thinking abilities through effective questioning (Mills, 1998; Osborne, 2014; Pedrosa-De-Jesus, Moreira, Lopes, & Watts, 2014; Yusuf & Adeoye, 2012), such as project-based learning (Firdaus et al., 2015), inquiry-based learning (Duran & Dökme, 2016), or a historical approach (Burian, 2013; Stinner, McMillan, Metz, Jilek, & Klassen, 2003; Tolvanen et al., 2014).

The historical approach is used in science education to enhance students' critical thinking by providing opportunities to analyze and evaluate scientific information within a broader context. Stinner et al. (2003) examined the historical development of scientific ideas and the social and cultural factors that influenced them. By understanding these influences, students can develop a more nuanced comprehension of scientific concepts and their applications. This approach helps students critically assess the limitations and potential biases of scientific research, as well as consider the ethical implications of scientific discoveries. Additionally, case studies enable students to apply their knowledge and skills to real-world problems, further enhancing their critical thinking abilities. He and his group also proposed twenty groups of case studies, including Mendel's experiments in plant hybridization (Stinner et al., 2003). Furthermore, Tolvanen et al. (2014) implemented a historical approach by analyzing lesson plans that incorporated historical experiments and narratives to teach the nature of science in chemistry education. These narratives should prompt students to explicitly discuss noticeable conflicts or controversies that arise within a particular narrative. Engaging with such narratives encourages students to think critically about the scientific process and the role of creativity in science (Tolvanen et al., 2014).

### *2.1.3. Developing Critical Thinking Through Teaching Genetics By Historical Approach*

The Swedish national biology curriculum for upper secondary school emphasizes the importance of developing students' ability to use biological theories and models, as well as understanding their validity and limitations (The

Swedish National Agency for Education, 2011). It is essential for students to balance respecting the depth of scientific knowledge with maintaining a healthy skepticism towards exaggerated claims about what science can achieve. The field of genetics has been continuously evolving due to the development of new experimental tools. These innovations have helped to clarify previously unresolved research questions and have led to revised understandings of the structure, location, and function of genes. Consequently, these insights have prompted further revisions and a search for more accurate experimental answers to discrepancies among different scientific perspectives (Burian, 2013; Lin, Cheng, & Chang, 2010). Burian (2013) utilized illustrative episodes from the history of genetics to teach the process of scientific discovery, how hypotheses are made, verified, and corrected. This approach helps students understand that science is open-ended, incomplete, and constantly developing. Such background knowledge is valuable when students face real-life questions that require them to rely on or critically evaluate scientific claims related to genetics and allied sciences. This method promotes scientific literacy by fostering skepticism and critical thinking while still appreciating the progress made in the field (Burian, 2013).

Lin et al. (2010) designed a historical episodes map with four storylines: the genetics, reproductive, cytology, and technology lines, along with more than 20 related historical events to demonstrate the long and complex development of classical genetics (Lin et al., 2010). Typically, students mainly focus on two gene models: the Neoclassical and Mendelian models (Agorram et al., 2010), with particular emphasis on Mendel and his work when teaching classical genetics. The historical episodes map depicts science as a non-linear process, highlighting the dialectic between theory and observation. Teaching this map alongside associated discussions promotes students' understanding of the nature of science and their attitudes toward it, helping them realize that the development of the extensive framework of classical genetics is a long and continuous process involving contributions from many scientists. As students' epistemic development progresses, their skills in critique and argumentation also develop proportionally (González-Howard & McNeill, 2020; Noroozi, 2018; Weinstock, 2006).

Critical thinking occurs in response to specific tasks, questions, problems, or challenges. This includes activities such as solving problems, evaluating theories, conducting inquiries, interpreting works, and engaging in creative tasks (Bailin, 1990). These challenges always exist within particular contexts. Developing critical thinking in science education involves focusing on the tasks, problems, and issues in the science curriculum that require or prompt critical thinking (Bailin, 1990). It is also believed that it is not enough for an individual to lack a basic commitment to rational inquiry, which enables them to use the resources and attitudes associated with critical thinking. These attitudes or habits of mind include respect for reason, an inquiring attitude, open-mindedness, and fair-mindedness (Bailin, Case, Coombs, & Daniels, 1999). There are two different approaches to cultivating thinking skills. Some researchers claim that thinking skills must be taught separately (Lipman, 2014), whereas others assert that these skills can be integrated into school subjects (Butera et al., 2014; Rajendran, 2008; Swartz & Parks, 1994). This research aims to cultivate critical thinking among students within the context of biology, as integrating thinking skills into instruction is a fundamental approach for teachers in teaching students how to think (Butera et al., 2014).

## 2.2. Historical Models of Gene Function

“Model” is a highly polysemous term extensively used in science. Scientists are continually constructing and refining models of the world as part of their research (Gieryn, 2010). Models consist of interconnected concepts that relate to a system or process. Concepts are fundamental components of a model, serving as the foundation for theoretical statements. Their significance becomes evident when integrated into a model, contributing to its overall structure (Halloun, 2007). Scientific models are conceptual constructs created by the scientific community to represent relevant aspects of experience, articulated in the form of natural systems and processes (Dos Santos et al., 2012). Alternatively, models can be viewed as representations of specific features of a phenomenon, an intellectually intriguing means of isolating a segment of the experiential world created to facilitate the development of explanations or predictions (Gericke, Hagberg, & Jorde, 2013). Models support the visualization of phenomena, thereby aiding

investigations (Gilbert & Osborne, 1980). They occupy a position between observed reality and scientific theory. (Stinner et al., 2003). A single phenomenon can be described by different scientific models, known as historical models. (Gericke et al., 2013). This paper uses the term "historical models" to refer to various scientific models describing the same phenomenon, such as gene function.

Gericke and Hagberg (2007) have defined five different historical models of gene function, including the Mendelian model, the Classical model, the Biochemical-Classical model, the Neoclassical model, and the Modern model (Gericke & Hagberg, 2007). Since the Mendelian paradigm, advancements in genetics over the past decade have revealed significant abnormalities in the nature of genes, resulting in a deeply critical reconsideration of the concept of the gene itself and demanding a paradigm shift (Portin, 2015). Thus, Smith and Adkison (2010) proposed an extended Modern model that serves as an instructional model considered more appropriate for introductory college and perhaps advanced high school biology instruction (Smith & Adkison, 2010). This model includes the work of the Human Genome Project and the ENCODE Project. Although the ENCODE definition of the gene has just been proposed and has not yet been recognized as the consensus paradigm, teachers need to understand that the complex and ever-evolving research surrounding genetic structure and function demands a shift in our understanding of genes from solely ontological entities to epistemological entities (Rheinberger & Müller-Wille, 2004). In our current research, we will incorporate the work of both articles to introduce students to five historical models of gene function, illustrating the evolution of our understanding from Mendel's foundational work to a contemporary perspective (see Figure 1). These models are the Mendelian, Classical, Biochemical-Classical, Neoclassical, and Modern models of gene function. The Modern model integrates updated information from the Human Genome Project and the ENCODE Project, according to Smith and Adkison (2010).

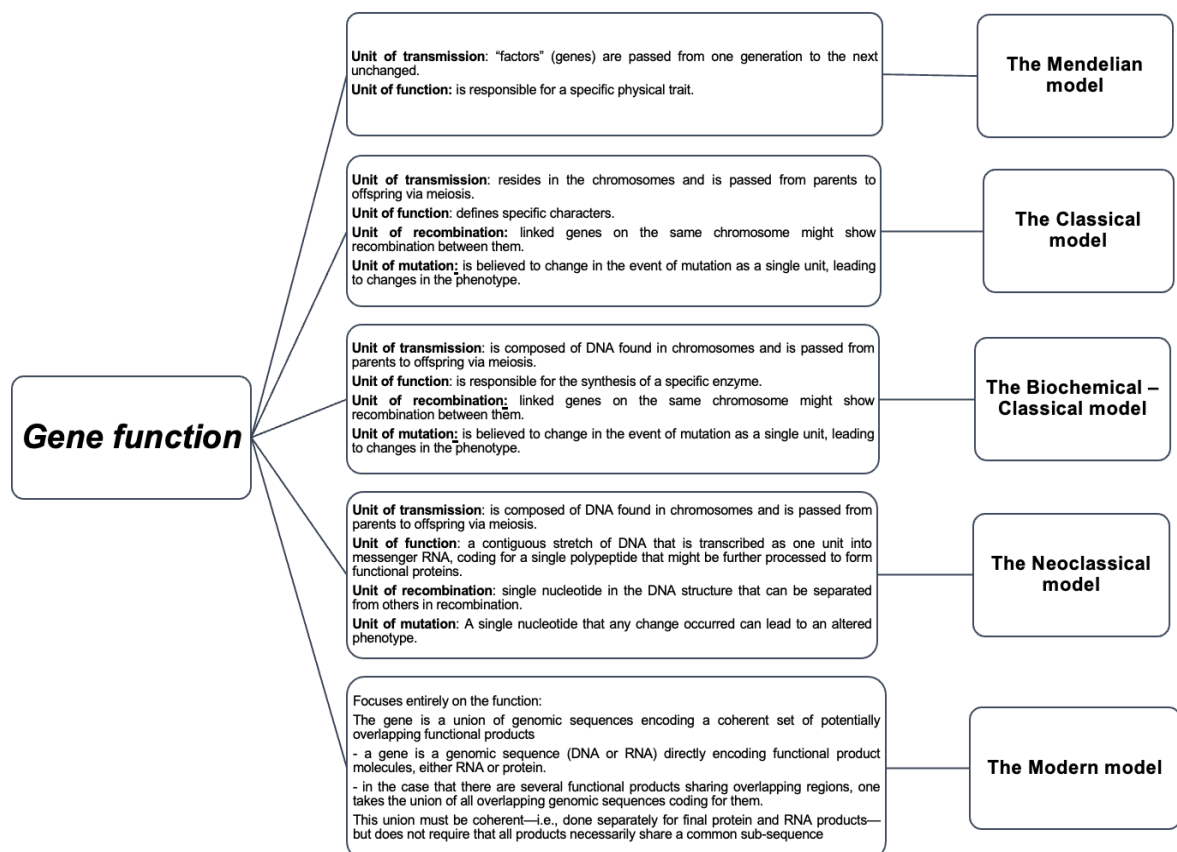


Figure 1. Five historical models of gene function

**Note:** These five historical models were developed by Gericke and Hagberg (2007) and revised by Gericke and Hagberg (2007) and Smith and Adkison (2010).

Based on the previous literature, we are convinced that teaching historical models of gene function to foster critical thinking among students, especially high school students, should adhere to at least two essential criteria. Firstly, it should effectively illustrate the intricate evolution of genetics to produce a more comprehensive understanding. Secondly, it must be closely aligned with the current curriculum framework to ensure its acceptability and utilization by biology teachers. In this study, five gene models were used to teach the evolution of genetics, including both progress and setbacks. Associated questions appended to each model were also provided to encourage in-depth discussions regarding how the new gene concept was modified or, in some cases, contradicted the existing one (Gericke & Hagberg, 2007; Smith & Adkison, 2010).

### 3. METHODOLOGY

#### 3.1. Lesson Plan Design

We categorized genetic knowledge that appeared in the Vietnamese Biology curriculum into five historical models of gene function, as proposed by Gericke and Hagberg (2007) and Smith and Adkison (2010). To ensure that students understand the historical context, specifically when, where, and how the models were created, we incorporated historical information that elucidates how the models were later found to be limited in other contexts (Tolvanen et al., 2014). Historical information was conveyed through conflicts or controversies between rival theories, scientists, or other parties to stimulate students' arguments and consequently enhance their critical thinking. A historical model of gene function could be taught in a series of lessons. However, each lesson, which typically encompasses an entire unit of knowledge, would usually start with a conflict that encourages students to pose questions and engage in discussion, thereby stimulating their curiosity and interest to explore knowledge. For example, when teaching the Mendelian model, the reason why the results of his early research were neglected until 1900 was introduced to the students; even late in his career, Mendel stated: "My scientific work brought me such satisfaction, and I am convinced the entire world will recognize the results of these studies" (Dunn, 2003). This introduction may trigger students' skepticism regarding how scientific theories are examined to arrive at conclusions that are most widely accepted by the scientific community.

When designing lessons to develop critical thinking skills in students by teaching gene concepts through a historical approach, attention should be paid to these key principles:

*i) Ensure to emphasize the inherited characteristics of genetics:* Biological information, particularly in the field of genetics, has inherited characteristics. Prior innovations serve as the foundation for newly discovered knowledge, yet this knowledge is refined through investigation and the resolution of constraints and inaccuracies. The understanding of genetics has advanced alongside societal progress, often even preceding practical applications. Consequently, employing gene models should facilitate the integration of various models, enabling students to understand the reasoning behind the operation of natural laws and thereby develop logical thinking skills in science.

*ii) Demonstrate the logic of developing genetics knowledge:* Every hypothesis undergoes a process of emergence and evolution. The development process is intricate and tortuous, sometimes advancing, sometimes regressing, and sometimes even reaching a deadlock. Regardless of how these hypotheses developed historically, their growth can be interpreted through logical reasoning.

The fundamental essence of genetics revolves around the acquisition of research about genes. Extensive research has been conducted by scientists on the subject of genes, with geneticists progressively elucidating the intricacies of gene structure and function. Understanding of gene function varies at each developmental stage. In this research, each historical model of gene function serves as a representation of gene function throughout significant changes, so the system of gene models must effectively depict the logical process for discovering genetic knowledge, particularly the discovery of genes.

*iii) Each gene model should include at least one conflict or controversy* because "science should be portrayed as a human and social endeavor; the portrayal must include perspectives on motivations of scientists, on conflicts, controversies, and blind alleys"

(Höttecke, Henke, & Riess, 2012). Including conflicts would help present the tentative, social, and epistemological nature of science and, subsequently, develop students' critical thinking skills. These conflicts or controversies could arise between rival theories, scientists, or other parties (Tolvanen et al., 2014).

Bernstein (1995) developed a negotiation model in which students are confronted with credible yet antagonistic arguments. Students are challenged to manage the tension between opposing viewpoints. This tension serves as a component that can stimulate critical thinking. Controversial issues can be presented and discussed in the classroom; students can be asked to argue for or against a particular topic. Debate can be used as a tool to promote critical thinking among students. After debating, students are expected to see improvements in their ability to search for literature and make evidence-based decisions. Regardless of the teaching methods employed, students should be exposed to analyzing the benefits, problems, and solutions related to various issues to prepare them for real-life decision-making (Bernstein, 1995). Encouraging students' critical thinking skills and stimulating all cognitive activities can be achieved if the lesson begins with a conflict, such as a disagreement between scientists' opinions, scientific failures, or the limitations of scientific theories.

3.2. Context of the Study – The Teaching Approach Using Historical Models of Gene Function

Genes are the central focus in genetics, serving as the "red thread" that runs throughout the field. When employing a historical approach to teaching gene models, conflicts often serve as foundational material. Research findings frequently lead to the development of new theories that build upon previous achievements while addressing limitations to resolve unresolved problems. By utilizing historical models of gene function, this study aims to shed light on the understanding of genes across different stages of development.

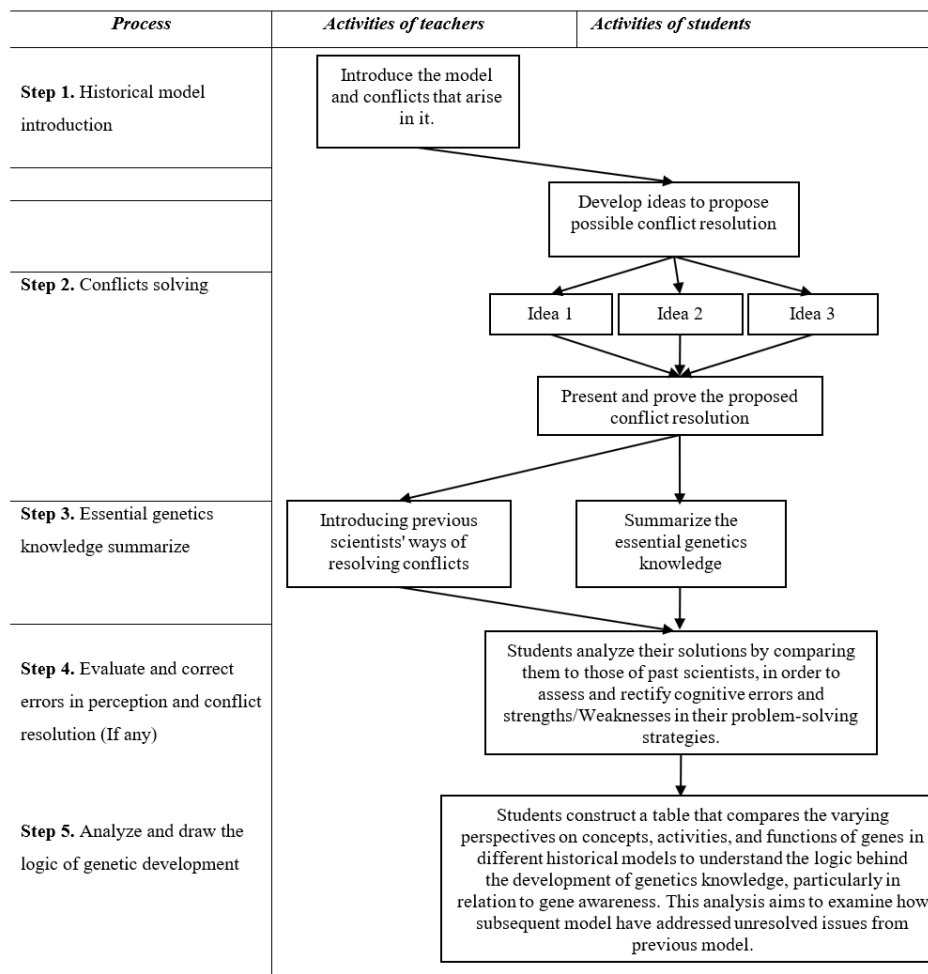


Figure 2. Diagram illustrating the process of teaching historical models of gene function to develop critical thinking.

It will also highlight any limitations in current understanding, technologies, and techniques used to support these models. Students need to understand potential conflicts that can arise within and between different gene models. Consequently, students will recognize that our current knowledge of genetics is limited and incomplete. The field of genetics has experienced rapid growth and development due to advances in science and technology. As research progresses, concepts and proposed models are subject to ongoing modifications, updates, additions, and even contradictions to existing theories.

In our study, we adapted the gene concepts put forth by Gericke and Hagberg (2007) incorporating several vital updates made by Smith and Adkison (2010) for the current Biology curriculum in Vietnam (see Figure 1). Students are encouraged to discuss the conflicts that have emerged within the models and the conflicts between the two subsequent models.

The instructional approach encompasses activities for both teachers and students at each step, as illustrated in the subsequent diagram (see Figure 2). An example of teaching process design for “The Neoclassical model” is presented in the Appendix.

### 3.3. Assessing Critical Thinking of the Students

Based on the literature research on critical thinking and the characteristics of teaching the history of gene functions, we proposed a critical thinking framework consisting of five components: (1) Examine scientific theories comprehensively and objectively; (2) Analyze conflicts arising within or between scientific theories; (3) Suggest and justify solutions to conflicts and understand the rationale behind the development of scientific theories; (4) Evaluate solutions to conflicts objectively, identifying the advantages and disadvantages of each; (5) Identify errors in conflict resolution and implement corrective actions. To assess the students' critical thinking, rubrics were designed following fourteen rubric design elements by Dawson (2017) (see Appendix). Each critical thinking component was presented at three levels in ascending order to help students self-assess their achievement. Students were expected to achieve level 3, instead of levels 1 and 2.

In each lesson, the teacher provided a series of questions to help students critically examine the logical development of gene functions, enabling them to understand both the correctness and limitations of each gene function model. At the end of each model, the teacher would explain the rubric and the meaning of each critical thinking component, and students would use their performance during the learning process to self-assess their critical thinking (Table 1 provides examples demonstrating how teachers can explain critical thinking components to facilitate students' self-assessment). It is important to note that the results of students' self-assessment of critical thinking serve only as a reference for teachers to improve their instruction and will not affect the final score of the subject.

**Table 1.** An example of how teachers explain the rubric to students to help them self-assess their critical thinking skills, applied to the Mendelian model.

Critical thinking component	Example of how teachers would explain to the students
Examine scientific theories comprehensively and objectively	Students can understand that genetics research is a process. What Mendel discovered about gene function is not always correct in every case. Students are expected to develop skepticism towards scientific statements.
Analyze conflicts arising within or between scientific theories	Students are able to raise questions about the conflicts that appeared in Mendel's work on inheritance, such as: - Is there any conflict in perspective on the unit of inheritance in genetic theories before Mendel (focused on the Blending theory of inheritance) and Mendel's laws of inheritance? - There were many researchers in the field of genetics who used the crossbreeding method before Mendel. Why was only Mendel called "the father of genetics"?

Critical thinking component	Example of how teachers would explain to the students
	<ul style="list-style-type: none"> <li>- What factors contributed to the delayed recognition of Mendel's groundbreaking research, published in 1865, until the early 1900s??</li> <li>- Are Mendel's laws of inheritance always right in every case? Think about other cases that might not be covered by Mendel's laws of inheritance (what if the "hereditary factors" do not locate on the chromosome or even inside the cell, or the hereditary factors do not locate on the same chromosome?).</li> <li>- During his cross-breeding experiments with peas, Mendel observed some intriguing phenomena: plants with brown seed coats consistently had purple flowers and black dots in their leaf axils; plants with light-colored seed coats had white flowers and no black dots in their leaf axils. Are these phenomena explained by Mendel's laws of inheritance?</li> </ul>
Suggest and justify solutions to conflicts and ascertain the rationale behind the development of scientific theories	Students should suggest and justify their answers to questions based on their understanding of inheritance. They are encouraged to work in groups and thoroughly discuss conflict resolution. As a result, students are expected to recognize the logical progression of ideas regarding genes and their functions, both before and within the context of the Mendelian model. Through this process, they can understand how the Mendelian model addressed unresolved issues from earlier genetic research.
Evaluate solutions to conflicts objectively, identifying the pros and cons of each	After teachers provide the answers to all questions, students are asked to compare their ideas for solving the questions with those of other students and Mendel's. Students are encouraged to work in groups so they can analyze the strengths and weaknesses of their problem-solving strategies.
Identify errors in conflict resolution and implement corrective actions	Students can identify cognitive errors and issues in problem-solving strategies, take actions to correct them, and improve their understanding of the next historical model.

### 3.4. Data Collecting and Analyzing Methods

The study aims to demonstrate how teaching historical models of gene function influences the development of critical thinking skills among high school students. The pedagogical experiment was conducted at three high schools located in Hanoi and Hoa Binh Province, Vietnam. In each participating school, one experimental class and one control class were selected. A total of 100 students were assigned to the intervention group, while 105 students comprised the control group. All participants were in grade 12, as genetics content is exclusively taught at this educational level. Additionally, students in both groups enrolled in the same academic year, followed the national educational curriculum, and studied Biology courses. To ensure comparability, the experimental and control groups were matched based on academic aptitude, learning motivation, and their average scores in Biology in grade 11, as well as overall academic performance.

The experimental and control classes were taught the genetics part during the pedagogical experiment period. In each school, the control and experimental classes were instructed by the same teacher at the same time for the same duration, using the same resources (textbooks) and evaluation standards. Only the experimental classes were exposed to five historical models related to gene function. The experimental class followed an intervention approach to teaching (see Figure 2), in which genetics knowledge was delivered through five historical models of gene function. Students engaged in thorough discussions of the conflicts within each model as well as conflicts between different models. Meanwhile, the control classes studied genetics according to the biology curriculum provided by the Vietnamese Ministry of Education and Training. The genetic knowledge was delivered sequentially as follows: the Neoclassical model, the Biochemical-classical model, the Mendelian model, the Classical model, and the Modern model. For the control classes, teachers provided regular instruction with little or no discussion on the development process of genetics.

Once each historical model of gene function has been completed, the rubrics were provided and explained to the students directly by teachers. This approach helps prevent students from completing the rubrics carelessly or misunderstanding them. Students would use the rubric to evaluate their own critical thinking, which tends to improve if they achieve level 3 rather than levels 1 or 2. The data was collected and analyzed using SPSS to examine the development of students' critical thinking in the experimental group and compare it to that of the control groups during the intervention involving five historical models of gene function. The qualitative data was obtained through interviews conducted after completing all the lessons and will be used for further analysis of students' ideas.

#### 4. RESULTS

##### 4.1. Evaluate the Development of Students' Critical Thinking Through Experiencing Historical Models of Gene Function

We computed the mean value of all five elements of critical thinking and assessed the percentage of students who achieved level 3 (the highest level) in performing critical thinking through experiencing historical models of gene function in the learning process.

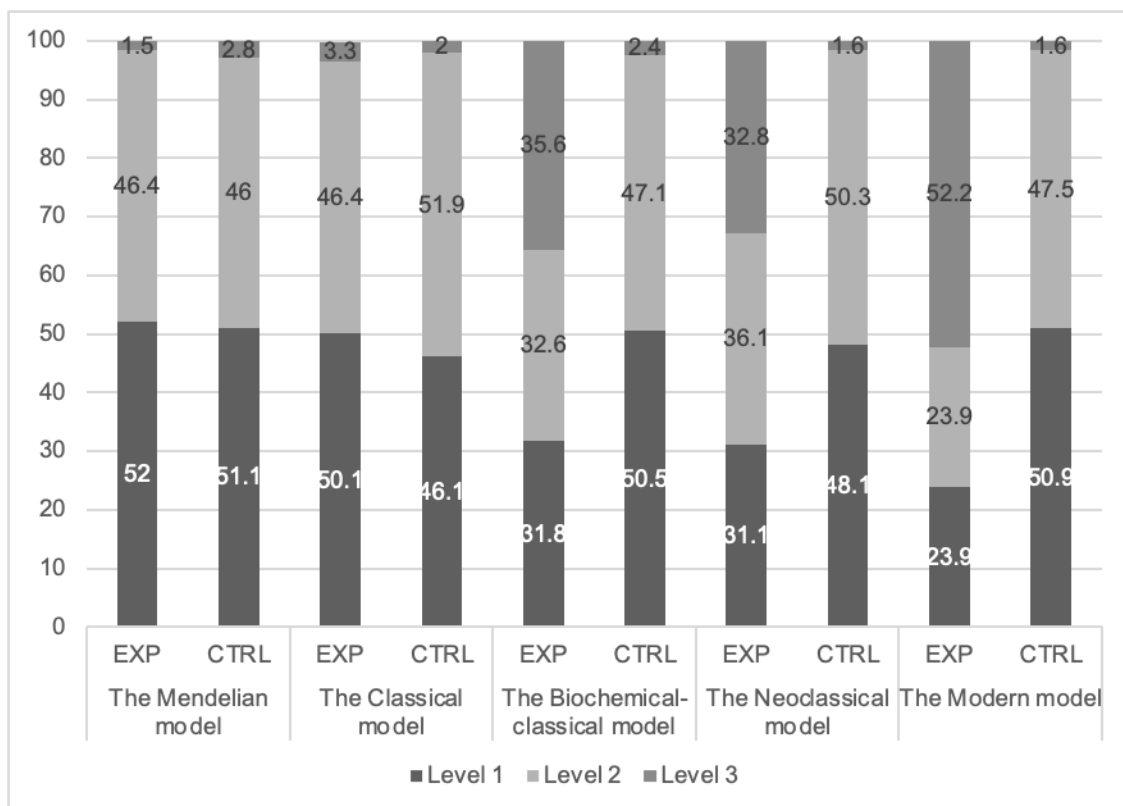


Figure 3. Percentage of students achieving different levels in performing critical thinking in experimental and control groups across five historical models of gene function.

Figure 3 shows the comparative distribution of students' critical thinking levels between the experimental and control groups across five historical models of gene function is analyzed. During the exposure to these five historical gene models, the experimental group showed a progressive increase in the number of students reaching the highest level (level 3), while levels 1 and 2 gradually decreased. In contrast, the control group did not exhibit any noticeable change in the distribution of critical thinking levels.

After studying the Mendelian model, both the experimental and control groups exhibited relatively high and comparable achievement rates at levels 1 and 2. However, the achievement rate at level 3 was low in both groups. Specifically, at level 1, the experimental group accounted for 52.0% of the total, while the control group accounted for 51.1%. At level 2, the experimental group had 46.4%, and the control group had 46%. At level 3, the experimental group had 1.5%, and the control group had 2.8%.

It is unclear how much progress students have made after mastering the Classical model. The experimental group and the control group differed significantly, especially from the Biochemical-Classical model onward. After completing the Biochemical-Classical model, the experimental group had a similar distribution of students across levels 1, 2, and 3 (31.8% at level 1, 32.6% at level 2, and 35.6% at level 3). In contrast, the control group had a lower percentage of students reaching level 3, with 50.5% at level 1, 47.1% at level 2, and only 2.4% at level 3. This disparity persisted until the Neoclassical model, when the experimental group's percentages of students at levels 1, 2, and 3 became comparable (31.1% at level 1, 36% at level 2, and 32.9% at level 3). A large percentage of students attained levels 1 and 2, while only a small percentage reached level 3 in the control group (48.1% at level 1, 50.3% at level 2, and 1.6% at level 3). Following the implementation of the Modern model, a significantly greater proportion of students in the experimental group attained level 3 compared to the control group and previous models. Specifically, in the control group, 50.9% of students reached level 1, 23.9% reached level 2, and 52.2% reached level 3. In the experimental group, 23.9% reached level 1, 23.9% reached level 2, and only 1.6% reached level 3.

To determine the statistical significance of differences in students' achievement levels across various models, we employed the two independent samples t-test for each pair of models within the experimental group. The mean value of critical thinking in the later models consistently exceeds that of the earlier models. Furthermore, as the models progress, the mean values increasingly diverge from the initial model. The average critical thinking scores for the Classical, Biochemical-Classical, Neoclassical, and Modern models, compared to the Mendelian models, differ by -0.028, -0.574, -0.544, and -0.832, respectively. These differences are statistically significant at a significance level (Sig) of less than 0.05 (Fisher, 1970).

4.2. Evaluate The Development of Students' Critical Thinking Component Elements Through Experiencing Historical Models of Gene Function

Overall, across different historical models of gene function, every element of critical thinking has undergone a steady shift. Specifically, levels 1 and 2 have decreased gradually, whereas level 3 has increased gradually. The change was pronounced in the experimental group but was not evident in the control group, as shown in Table 2.

Table 2. Percentage of Achievement of Critical Thinking Elements in the Control Group and Experimental Group

Critical thinking component elements	Level	Mendelian model		Classical model		Biochemical-Classical model		Neoclassical model		Modern model	
		EXP	CTRL	EXP	CTRL	EXP	CTRL	EXP	CTRL	EXP	CTRL
Element 1	Level 1	48.5	49.5	51.5	41.4	26.2	57.6	33	35.4	18.4	50.5
	Level 2	48.5	49.5	46.6	58.6	31.1	41.4	36.9	61.6	27.2	49.5
	Level 3	3	1	1.9	0	42.7	1	30.1	3	54.4	0
Element 2	Level 1	54.4	43.4	47.6	46.5	32	47.5	39.8	53.5	25.2	52.5
	Level 2	43.7	53.5	47.6	52.5	33	48.5	32	46.5	17.5	45.5
	Level 3	1.9	3.1	4.8	1	35	4	28.2	0	57.3	2
Element 3	Level 1	54.4	52.5	58.3	43.4	34	49.5	34	49.5	27.2	50.5
	Level 2	45.6	44.4	40.8	52.5	28.2	48.5	35	46.5	19.4	46.5
	Level 3	0	3.1	0.9	4.1	37.8	2	31	4	53.4	3
Element 4	Level 1	47.6	52.5	47.6	53.5	34	48.5	29.1	51.5	23.3	43.4
	Level 2	51.5	44.4	46.6	44.4	37.9	48.5	37.9	47.5	29.1	55.6
	Level 3	0.9	3.1	5.8	2.1	28.1	3	33	1	47.6	1
Element 5	Level 1	55.3	57.6	45.6	45.5	33	49.5	19.4	50.5	25.2	57.6
	Level 2	42.7	38.4	50.5	51.5	33	48.5	38.8	49.5	26.2	40.4
	Level 3	2	4	3.9	3	34	2	41.8	0	48.6	2

To determine the statistical significance of any differences in the percentage of students' achievement on critical thinking component elements across different models, we employed the two independent samples t-test for pairs of experimental and control groups within each constituent element of each model. The results are shown in Table 3.

**Table 3.** Testing the difference in achievement of critical thinking elements between control and experimental groups through historical models of gene function.

Historical Models of Gene Function	Component elements	Mean (EXP-CTRL)	t-value	Sig(2-tailed)
The Mendelian model	Element 1	0.02020	0.287	0.774
	Element 2	-0.18182	-2.514	0.014
	Element 3	-0.03030	-0.436	0.664
	Element 4	0.03030	0.456	0.650
	Element 5	-0.02020	-0.261	0.794
The Classical model	Element 1	-0.11111	-1.654	0.101
	Element 2	-0.05051	-0.728	0.469
	Element 3	-0.13131	-1.680	0.096
	Element 4	0.02020	0.276	0.783
	Element 5	0.0342	0.284	0.469
The Biochemical-Classical model	Element 1	0.74747	8.001	0.000
	Element 2	0.45455	4.813	0.000
	Element 3	0.47475	5.022	0.000
	Element 4	0.43434	4.453	0.000
	Element 5	0.52525	5.494	0.000
The Neoclassical model	Element 1	0.28283	3.003	0.003
	Element 2	0.45455	4.338	0.000
	Element 3	0.46465	4.608	0.000
	Element 4	0.52525	6.068	0.000
	Element 5	0.70707	7.762	0.000
The Modern model	Element 1	0.82828	8.075	0.000
	Element 2	0.89899	8.642	0.000
	Element 3	0.74747	7.266	0.000
	Element 4	0.68687	7.005	0.000
	Element 5	0.75758	7.311	0.000

When assessing the constituent elements of critical thinking through the two models, the Mendelian model and the Classical model, the control group demonstrated higher values than the experimental group in some elements. For example, in the Mendelian model, the mean values of elements 2, 3, and 5 were all negative, specifically -0.18182, -0.03030, and -0.02020, respectively. In contrast, the Bioclassical model showed that the experimental group consistently had larger values than the control group for all elements, with positive mean values.

In addition, the mean value increased from the Mendelian model to the Modern model. The mean values of the critical thinking elements between the experimental group and the control group varied as follows: from -0.03030 to 0.03030 in the Mendelian model, from -0.13131 to 0.0342 in the Classical model, from 0.43434 to 0.74747 in the Bioclassical model, from 0.28283 to 0.70707 in the Neoclassical model, and from 0.68687 to 0.89899 in the Modern model. However, in the Mendelian and Classical models, the significance (Sig) values were greater than 0.05, indicating that the differences were not statistically significant. Conversely, in the Bioclassical model, the Sig values were below 0.05, suggesting that the differences were statistically significant. This result indicates that teaching historical models of gene function can enhance the development of critical thinking components among students, especially under the influence of experimental factors.

Furthermore, when comparing each individual element of critical thinking across pairs of models, the mean value of each pair increased from the Mendelian model to the other models. For example, considering element 5, the mean values between the Mendelian model and the remaining models were -0.126, -0.544, -0.738, and -0.796, respectively. This result indicates that the later models demonstrate more developed elements of critical thinking compared to the initial model.

When evaluating the mean values between Mendelian and Classical models across all elements, the significance (Sig) values were greater than 0.05, indicating that the differences in achievement for all elements between these two models are not statistically significant. This may be attributed to the limited experimental duration and students' unfamiliarity with the teaching method based on historical models, which likely hindered the development of critical

thinking skills. Table 4 presents the results of testing differences in students' achievement for each critical thinking element when comparing the Mendelian model with the other four models. The Sig values were all below 0.05, indicating that the differences in achievement across all five elements were statistically significant.

**Table 4.** Testing the differences in achievement of critical thinking elements between each pair of historical models of gene function.

Component elements of critical thinking	Pairs of historical models of gene function	Mean value	t-value	Sig(2-tailed)
Element 1	Mendelian model – Classical model	0.029	0.456	0.650
	Mendelian model – Bioclassical model	-0.718	-7.262	0.000
	Mendelian model – Neoclassical model	-0.466	-4.990	0.000
	Mendelian model – Modern model	-0.883	-10.347	0.000
Element 2	Mendelian model – Classical model	-0.058	-0.800	0.425
	Mendelian model – Bioclassical model	-0.553	-6.363	0.000
	Mendelian model – Neoclassical model	-0.447	-4.416	0.000
	Mendelian model – Modern model	-0.922	-10.353	0.000
Element 3	Mendelian model – Classical model	0.010	0.148	0.882
	Mendelian model – Bioclassical model	-0.553	-5.867	0.000
	Mendelian model – Neoclassical model	-0.524	-5.382	0.000
	Mendelian model – Modern model	-0.796	-7.826	0.000
Element 4	Mendelian model – Classical model	0.010	0.148	0.882
	Mendelian model – Bioclassical model	-0.515	-5.764	0.000
	Mendelian model – Neoclassical model	-0.495	-5.481	0.000
	Mendelian model – Modern model	-0.757	-7.577	0.000
Element 5	Mendelian model – Classical model	-0.126	-1.805	0.074
	Mendelian model – Bioclassical model	-0.544	-5.956	0.000
	Mendelian model – Neoclassical model	-0.738	-8.256	0.000
	Mendelian model – Modern model	-0.796	-7.974	0.000

#### 4.3. Qualitative Analysis of Experimental Results Demonstrates the Development of Critical Thinking

In addition to assessing students' development of critical thinking skills through quantitative analysis of their experiences with models of gene function in history, we engaged in direct discussions with teachers and students during the implementation process to gather further feedback. When asked the general question, "How are genes studied?" most students appeared quite confused, despite having studied genetics in ninth grade and throughout middle school. Students were able to articulate that "a gene is a segment of a DNA molecule with a specific genetic function," but when asked, "How is the concept of genes related to Mendel's discoveries?" they remained confused. At the same time, students also found the terms gene-allele, genotype-phenotype, and others perplexing. Many students could explain the content of inheritance laws when prompted, but many still struggled to connect these laws to the cytological foundations of the inheritance process.

Students in the experimental group demonstrated significant engagement and enthusiasm. They showed passion and actively participated in research to resolve conflicts related to historical models while acquiring knowledge about genetics. When studying the Neoclassical model, students particularly displayed a strong interest in understanding the reasoning behind the conclusion that "DNA is the genetic material, not protein." To reach this conclusion, scientists engaged in extensive debates regarding whether DNA or protein constitutes the genetic material. They conducted numerous experiments and tests to validate DNA as the genetic material, including Griffith's experiment, Hershey and Chase's experiment, and Oswald Avery's experiment.

Additionally, after learning about all five historical models of gene function, students in the experimental group can explore the logic of genetic development (in terms of gene activity and function) from the beginning to the present. Some students even asked: "In the future, with the vigorous advancement of science and technology, will the molecular model of genes remain accurate?" Is DNA still the genetic material, or will it be a different material? Students spontaneously perceive genetics as an ongoing research endeavor characterized by acknowledgment and refutation.

## 5. DISCUSSION

Knippels identified five domain-specific challenges from the literature regarding the inadequate understanding of genetics: (1) specific vocabulary and terminology, (2) mathematical content of genetic tasks, (3) cytological processes of cells, which mainly relate to chromosome structure and its processes, (4) the abstract nature resulting from the sequencing of the biology curriculum, and (5) the intricate nature of genetics, which involves concepts and processes from various systematic levels (Knippels, Waarlo, & Boersma, 2001). Genetics education in Vietnam faces several challenges. Studies conducted in Vietnamese indicate that high school students often exhibit reluctance toward studying biology, particularly genetics, because they perceive genetic knowledge as too complex and requiring extensive calculations. The concepts are often disjointed, making it difficult for students to follow and understand the material. Specifically, within the Vietnamese biology curriculum, genetic knowledge is systematically organized into the following models: the Neoclassical model, the Biochemical-classical model, the Mendelian model, the Classical model, and the Modern model. This sequence discourages students from perceiving genetics as an ongoing process where subsequent discoveries address issues unresolved by previous models. Consequently, students find it challenging to understand genetics concepts within the context of scientific development. Additionally, students tend to accept knowledge as unchanging truths. Drawing from the historical models of gene function and the perspective of the nature of science as described by Gericke and Hagberg (2007) an effective teaching approach should help students recognize the explanatory limitations of each gene model and understand how new models have overcome these deficiencies (Gericke & Hagberg, 2007). To do this, students would discuss external consistency problems between different models and internal consistency problems within them. Using historical models of gene function in education allows students to explore knowledge through the logical processes of research and discovery, enhancing knowledge acquisition and fostering critical thinking abilities. The students may view, with skepticism, the evolution of gene definitions and functions as a developmental process that encompasses errors and corrections. All genetic terminology and processes are learned in an exploratory sequence, which can help students connect and understand these terms more easily. The quantitative analysis indicates that the experimental group exhibited greater development in critical thinking than the control group, with a gradual increase observed through the historical models. The qualitative results indicate that students in the experimental group demonstrated a more positive, engaged, and proactive learning attitude.

In their paper, Gericke and Hagberg (2007) propose integrating the nature of science with the history of science in genetics and gene function education, in which the models and their similarities and limitations may be used to enhance students' understanding (Gericke & Hagberg, 2007). This approach aids students in understanding that explanatory models are constructs developed over time for specific purposes, which may be flawed or inadequate in various respects (Kinnear, 1991). A practical approach to this may involve model-revising problem-solving, which occurs when existing models fail to explain data, necessitating adjustments to the entities or processes involved. Gericke and Hagberg (2007) also emphasized the significance of educators in genetics, acknowledging the existence of models and their differences. A key perspective on the nature of science, developed by Lederman and Abd-El-Khalick (1998) connects it to various epistemological issues. These issues encompass the empirical and tentative aspects of science, the role of creativity and subjectivity, the distinction between observation and inference, the impact of social and cultural influences, and the differences between scientific theories and laws (Lederman & Abd-El-Khalick, 1998). Teaching genetics through historical models of gene function can help students understand the nature of science, especially its tentative nature. Scientific knowledge is subject to modification and refinement when new evidence arises, rather than being seen as absolute or perfect (Mueller & Reiners, 2023). The qualitative results showed that students demonstrated an awareness of the dynamic nature of science, particularly in the field of genetics, which is continually evolving and being updated.

Before the experiment involving historical models of gene function, a survey was conducted with high school students and teachers. The results indicated that both groups expressed interest and considered it essential for

students to learn about genetics broadly and genes specifically within their discovery and development context. According to Lin and his colleagues, although science teachers recognize the potential advantages of incorporating the history of science into science education, challenges such as limited teaching time and the inclusion of the history of science in textbooks remain significant obstacles (Lin et al., 2010). These problems are reported by Vietnamese teachers as well. After the implementation, while the benefits of teaching genetics through historical models of gene function in fostering critical thinking among students are evident, teachers noted that this approach demands significant time and effort to learn and master the instruction. Teachers faced challenges in implementing the genetics part, which is already extensive in the Biology curriculum. Due to the limited coverage of the history of science in Vietnamese Biology textbooks, teachers had to allocate more time to restructure the lessons following historical models of gene function. This teaching approach also required significant lesson time, particularly for students to reflect and develop strategies to address conflicts. Teacher feedback is valuable, as we will conduct additional research and make adjustments to improve the teaching of genetics using historical models of gene function and strategies to introduce conflicts while ensuring alignment with Vietnamese educational practices.

## 6. CONCLUSION

The study proposed a framework for critical thinking and assessed its development through experience with historical models of gene function. The findings will enable students and teachers to achieve a deeper understanding of the developmental logic within genetic research, thereby allowing for a restructuring of lessons that not only enhances students' understanding of genetic knowledge but also fosters their critical thinking. This study can serve as a foundation for further research aimed at applying the historical approach to various branches of biology, including ecology and evolution, as well as other fields within the natural sciences such as chemistry and physics. Furthermore, the validity and effectiveness of the critical thinking framework developed in this study can also be evaluated by replicating the process on a larger scale of participants.

**Funding:** This research was supported by the VNU University of Education under the Research (Grant number: QS.22.11).

**Institutional Review Board Statement:** This study was approved by the Institutional Review Board of [Vietnam National University, Vietnam], under protocol number [IRB No. 2505/QD-DHGD], dated December 26, 2022. Informed verbal consent was obtained from all participants, and all data were anonymized to protect participant confidentiality.

**Transparency:** The authors state that the manuscript is honest, truthful, and transparent, that no key aspects of the investigation have been omitted, and that any differences from the study as planned have been clarified. This study followed all writing ethics.

**Competing Interests:** The authors declare that they have no competing interests.

**Authors' Contributions:** All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.

## REFERENCES

- Agorram, B., Clement, P., Selmaoui, S., Khzami, S. E., Chafik, J., & Chiadli, A. (2010). University students' conceptions about the concept of gene: Interest of historical approach. *US-China Education Review*, 7(2), 9-15.
- Bailin, S. (1990). Creativity, discovery, and science education: Kuhn and Feyerabend revisited. *Interchange*, 21(3), 34-44. <https://doi.org/10.1007/BF01809418>
- Bailin, S. (2002). Critical thinking and science education. *Science & Education*, 11(4), 361-375. <https://doi.org/10.1023/A:1016042608621>
- Bailin, S., Case, R., Coombs, J. R., & Daniels, L. B. (1999). Conceptualizing critical thinking. *Journal of Curriculum Studies*, 31(3), 285-302. <https://doi.org/10.1080/002202799183133>
- Bernstein, D. A. (1995). A negotiation model for teaching critical thinking. *Teaching of Psychology*, 22(1), 22-24. [https://doi.org/10.1207/s15328023top2201\\_7](https://doi.org/10.1207/s15328023top2201_7)

- Bevilacqua, F., Giannetto, E., & Matthews, M. R. (2001). *Science education and culture: The contribution of history and philosophy of science*. Dordrecht, Netherlands: Springer Science & Business Media.
- Burian, R. M. (2013). On gene concepts and teaching genetics: Episodes from classical genetics. *Science & Education*, 22(2), 325-344. <https://doi.org/10.1007/s11191-011-9367-y>
- Butera, G., Friesen, A., Palmer, S. B., Lieber, J., Horn, E. M., Hanson, M. J., & Czaja, C. (2014). Integrating mathematics problem solving and critical thinking into the curriculum. *Young Children*, 69(1), 70-77.
- Dawson, P. (2017). Assessment rubrics: Towards clearer and more replicable design, research and practice. *Assessment & Evaluation in Higher Education*, 42(3), 347-360. <https://doi.org/10.1080/02602938.2015.1111294>
- Derry, G. N. (1999). *What science is and how it works*. Princeton, NJ: Princeton University Press.
- Dos Santos, V. C., Joaquim, L. M., & El-Hani, C. N. (2012). Hybrid deterministic views about genes in biology textbooks: A key problem in genetics teaching. *Science & Education*, 21(4), 543-578. <https://doi.org/10.1007/s11191-011-9348-1>
- Driver, R., Leach, J., Millar, R., & Scott, P. (1996). *Young people's images of science* (Vol. 20). Philadelphia, PA: Open University Press.
- Dunn, P. M. (2003). Gregor Mendel, OSA (1822–1884), founder of scientific genetics. *Archives of Disease in Childhood – Fetal and Neonatal Edition*, 88(6), F537–F539. <https://doi.org/10.1136/fn.88.6.F537>
- Duran, M., & Dökme, I. (2016). The effect of the inquiry-based learning approach on student's critical-thinking skills. *Eurasia Journal of Mathematics, Science and Technology Education*, 12(12), 2887–2908. <https://doi.org/10.12973/eurasia.2016.02311a>
- Ennis, R. H. (1989). Critical thinking and subject specificity: Clarification and needed research. *Educational Researcher*, 18(3), 4-10. <https://doi.org/10.3102/0013189X018003004>
- Facione, P. A. (2015). *Critical thinking: What it is and why it counts*. Millbrae, CA: Insight Assessment.
- Firdaus, F., Kailani, I., Bakar, M. N. B., & Bakry, B. (2015). Developing critical thinking skills of students in mathematics learning. *Journal of Education and Learning*, 9(3), 226–236. <https://doi.org/10.11591/edulearn.v9i3.1830>
- Fisher, R. A. (1970). Statistical methods for research workers. In I. Olkin, S. G. Ghurye, W. Hoeffding, W. M. Madow, & H. B. Mann (Eds.), *Breakthroughs in statistics: Methodology and distribution*. In (pp. 66–70). New York: Springer.
- Flodin, V. S. (2009). The necessity of making visible concepts with multiple meanings in science education: The use of the gene concept in a biology textbook. *Science & Education*, 18(1), 73-94. <https://doi.org/10.1007/s11191-007-9127-1>
- Garrison, D. R. (1992). Critical thinking and self-directed learning in adult education: An analysis of responsibility and control issues. *Adult Education Quarterly*, 42(3), 136–148. <https://doi.org/10.1177/074171369204200302>
- Gericke, N., Hagberg, M., & Jorde, D. (2013). Upper secondary students' understanding of the use of multiple models in biology textbooks—The importance of conceptual variation and incommensurability. *Research in Science Education*, 43(2), 755-780. <https://doi.org/10.1007/s11165-012-9288-z>
- Gericke, N. M., & Hagberg, M. (2007). Definition of historical models of gene function and their relation to students' understanding of genetics. *Science & Education*, 16(7), 849-881. <https://doi.org/10.1007/s11191-006-9064-4>
- Giere, R. N. (2010). *Explaining science: A cognitive approach*. Chicago, IL: University of Chicago Press.
- Gilbert, J. K., & Osborne, R. J. (1980). The use of models in science and science teaching. *European Journal of Science Education*, 2(1), 3-13. <https://doi.org/10.1080/0140528800020103>
- González-Howard, M., & McNeill, K. L. (2020). Acting with epistemic agency: Characterizing student critique during argumentation discussions. *Science Education*, 104(6), 953-982. <https://doi.org/10.1002/sce.21592>
- Halloun, I. A. (2007). Mediated modeling in science education. *Science & Education*, 16(7), 653-697. <https://doi.org/10.1007/s11191-006-9004-3>
- Höttecke, D., Henke, A., & Riess, F. (2012). Implementing history and philosophy in science teaching: Strategies, methods, results and experiences from the European HIPST project. *Science & Education*, 21(9), 1233-1261. <https://doi.org/10.1007/s11191-010-9330-3>

- Kinnear, J. F. (1991). Using an historical perspective to enrich the teaching of linkage in genetics. *Science Education*, 75(1), 69-85. <https://doi.org/10.1002/sc.3730750107>
- Knippels, M. C., Waarlo, A. J., & Boersma, K. T. (2001). *Coping with the abstract and complex nature of genetics in upper-secondary biology education: interim report of a developmental research project*. Paper presented at the Proceedings of the III Conference of European Researchers in Didactic of Biology (ERIDOB): September 27th-October 1st 2000, Santiago de Compostela (Spain), Universidade de Santiago de Compostela.
- Lederman, N., & Abd-El-Khalick, F. (1998). Avoiding de-natured science: Activities that promote understandings of the nature of science. In *The nature of science in science education: Rationales and strategies*. In (pp. 83-126). Dordrecht, Netherlands: Springer.
- Lewis, A., & Smith, D. (1993). Defining higher order thinking. *Theory Into Practice*, 32(3), 131-137. <https://doi.org/10.1080/00405849309543588>
- Lin, C.-Y., Cheng, J.-H., & Chang, W.-H. (2010). Making science vivid: Using a historical episodes map. *International Journal of Science Education*, 32(18), 2521-2531. <https://doi.org/10.1080/09500691003746015>
- Lipman, M. (2014). Thinking skills fostered by philosophy for children. In *Thinking and learning skills*. In (pp. 83-108). UK: Routledge.
- McComas, W. F., Clough, M. P., & Almazroa, H. (1998). The role and character of the nature of science in science education, The nature of science in science education: Rationales and strategies. In (pp. 3-39). Dordrecht: Springer.
- McPeck, J. E. (2016). *Critical thinking and education*. UK: Routledge.
- Mills, J. (1998). Better teaching through provocation. *College Teaching*, 46(1), 21-25. <https://doi.org/10.1080/87567559809596228>
- Moore, T. (2013). Critical thinking: Seven definitions in search of a concept. *Studies in Higher Education*, 38(4), 506-522. <https://doi.org/10.1080/03075079.2011.586995>
- Mueller, S., & Reiners, C. S. (2023). Pre-service chemistry teachers' views about the tentative and durable nature of scientific knowledge. *Science & Education*, 32(6), 1813-1845. <https://doi.org/10.1007/s11191-022-00374-8>
- Noroozi, O. (2018). Considering students' epistemic beliefs to facilitate their argumentative discourse and attitudinal change with a digital dialogue game. *Innovations in Education and Teaching International*, 55(3), 357-365. <https://doi.org/10.1080/14703297.2016.1208112>
- Osborne, J. (2014). Teaching critical thinking? New directions in science education. *School Science Review*, 95(352), 53-62.
- Pedrosa-De-Jesus, H., Moreira, A., Lopes, B., & Watts, M. (2014). So much more than just a list: Exploring the nature of critical questioning in undergraduate sciences. *Research in Science & Technological Education*, 32(2), 115-134. <https://doi.org/10.1080/02635143.2014.902811>
- Perkins, C., & Murphy, E. (2006). Identifying and measuring individual engagement in critical thinking in online discussions: An exploratory case study. *Journal of Educational Technology & Society*, 9(1), 298-307.
- Portin, P. (2015). The development of genetics in the light of Thomas Kuhn's theory of scientific revolutions. *Recent Advances in DNA & Gene Sequences (Formerly Recent Patents on DNA & Gene Sequences)*, 9(1), 14-25.
- Rajendran, N. S. (2008). *Teaching & acquiring higher-order thinking skills: Theory & practice*. Malaysia: Publisher: Sultan Idris University of Education.
- Rheinberger, H.-J., & Müller-Wille, S. (2004). *Gene*. In E. N. Zalta (Ed.), *The Stanford Encyclopedia of Philosophy*. Stanford, CA: Metaphysics Research Lab, Stanford University.
- Ryder, J., Leach, J., & Driver, R. (1999). Undergraduate science students' images of science. *Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching*, 36(2), 201-219.
- Santos, L. F. (2017). The role of critical thinking in science education. *Journal of Education and Practice*, 8(20), 159-173.
- Schafersman, S. D. (1991). *An introduction to critical thinking*. Amherst, NY: Prometheus Books.
- Smith, M. U., & Adkison, L. R. (2010). Updating the model definition of the gene in the modern genomic era with implications for instruction. *Science & Education*, 19(1), 1-20. <https://doi.org/10.1007/s11191-008-9161-7>
- Snyder, L. G., & Snyder, M. J. (2008). Teaching critical thinking and problem solving skills. *Delta Pi Epsilon Journal*, 50(2), 90-99.

- Stinner, A., McMillan, B. A., Metz, D., Jilek, J. M., & Klassen, S. (2003). The renewal of case studies in science education. *Science & Education*, 12(7), 617-643. <https://doi.org/10.1023/A:1025648616350>
- Swartz, R. J., & Parks, S. (1994). *Infusing the teaching of critical and creative thinking into content instruction: A lesson design handbook for the elementary grades*. Washington, DC: ERIC.
- The Swedish National Agency for Education. (2011). *Aim of the subject of Biology at upper secondary school in Sweden*. Sweden: The Swedish National Agency for Education.
- Tolvanen, S., Jansson, J., Vesterinen, V.-M., & Aksela, M. (2014). How to use historical approach to teach nature of science in chemistry education? *Science & Education*, 23(8), 1605-1636. <https://doi.org/10.1007/s11191-013-9646-x>
- Vietnamese Ministry of Education and Training. (2018a). *Biology curriculum (released with Circular no. 32/2018/TT-BGDĐT date 26/12/2018)*. Vietnam: Vietnamese Ministry of Education and Training.
- Vietnamese Ministry of Education and Training. (2018b). *General education curriculum (released with Circular no. 32/2018/TT-BGDĐT date 26/12/2018)*. Vietnam: Vietnamese Ministry of Education and Training.
- Weinstock, M. P. (2006). Psychological research and the epistemological approach to argumentation. *Informal Logic*, 26(1), 103-120.
- Yusuf, F. A., & Adeoye, E. A. (2012). Developing critical thinking and communication skills in students: Implications for practice in education. *African Research Review*, 6(1), 311-324. <https://doi.org/10.4314/afrrrev.v6i1.26>

## APPENDIX

The alignment of rubric for assessing critical thinking and fourteen rubric design elements of Dawson (2017).

Rubric design elements	Description	Rubric for assessing critical thinking
<i>Specificity</i>	<i>Task-specific</i> : applies to a specific instance of assessment in a particular course unit. <i>Task-type</i> : could be reused across a range of individual tasks. <i>Department-wide or institution-wide</i> : could be used to assess all work across entire departments.	The rubrics are task-type rubrics, which means they could be used to assess the critical thinking of high school students through a series of lessons about the development of gene function. Each lesson could have a slight revision to the rubrics to better fit its content.
<i>Secrecy</i>	Some rubrics remain secret to students and serve solely as scoring sheets for evaluation, while others are shared as part of the assessment and feedback provision.	The rubrics are shared with students for their self-assessment on critical thinking as well as to serve as a guideline for developing their own critical thinking.
<i>Exemplars</i>	Although not obligatory, many uses of rubrics include exemplars of work that illustrate specific criteria or quality descriptions.	At the end of the gene model, a well-done work was introduced to students with the rubrics (after their self-assessment).
<i>Scoring strategy</i>	Holistic scoring strategy: require the user to considers all criteria and consolidates them into a single overall quality assessment. Analytic scoring strategy: require the user to provide a series of judgements regarding certain criteria, which are often combined formulaically to yield an overall mark.	We used analytic scoring strategy to design the rubrics, which require students to make judgements regarding individual criteria of critical thinking, and they were combined to determine an overall mark.
<i>Evaluative criteria</i>	Evaluative criteria serve for distinguishing acceptable responses from unacceptable ones and are typically positioned in the leftmost column of a rubric.	In the rubrics, the evaluative criteria are five components of critical thinking which are (1) Examine scientific theories comprehensively and objectively; (2) Analyze conflicts arising within or between scientific theories; (3) Suggest and justify solutions to conflicts and ascertain the rationale behind the development of scientific theories; (4) Evaluate solutions to conflicts objectively, identifying the pros and cons of each; (5) Identify errors in conflict resolution and implement corrective actions. These occupy the leftmost column of the rubric.
<i>Quality levels</i>	The words used to identify quality levels may come from learning outcomes taxonomies, and can also be expressed through grade levels, or statements of student proficiency.	The rubrics were shown in forms of tables. Each component of critical thinking was expressed at three different levels, from level 1 to level 3. Each level typically occupied one cell, and described

Rubric design elements	Description	Rubric for assessing critical thinking
<i>Quality definitions</i>	Each quality definition typically represents a particular evaluative criterion at a particular quality level.	with different words from Bloom's taxonomy to identify quality levels. The students use these to understand the characteristics of certain evaluative criterion at a given level and to inform judgements about quality.
<i>Judgement complexity</i>	The rubric requires the user to exercise judgment in identifying the quality definitions presented in a student's work. The judgments are necessarily complex and expert.	The rubrics contained qualitative judgement. All the evaluative criteria were expressed at three levels. Distinguishing between three levels requires making a qualitative judgement.
<i>Users and uses</i>	Rubrics are not only tools to support assessors in making summative judgments but also help provide feedback to teachers while supporting students in self and peer assessment and interrogating the requirements of a task.	The rubrics were tools to support teachers in assessing the critical thinking of the students through their self-assessment. Besides, the rubrics also served to help students to understand what critical thinking is and how to develop their critical thinking through experiencing with historical models of gene function.
<i>Creators</i>	The creation of rubrics is not just the responsibility of the teacher administering the assessment; it also involves textbook publishers, institutions, professional organizations, researchers, and online resources. Rubric experts and students may also participate in the rubric creating process.	We, as researchers specializing in education from recognized teacher training universities, created the rubrics based on literature work on the framework of critical thinking for high school students.
<i>Quality processes</i>	Different approaches might be employed to ensure the validity of the rubrics: performing statistical analyzes, referencing established rubrics, comparing to authentic criteria used for evaluating similar tasks, seeking advice from pedagogical experts, and engaging in iterative development and stakeholder feedback.	The rubrics used in this study were referred to the core critical thinking skills published in Facione's paper (Facione, 2015). They were then thoroughly revised by other pedagogical experts and high school teachers with substantial expertise in teaching advanced Biology.
<i>Accompanying feedback information</i>	Rubrics may serve as a tool to articulate feedback, occasionally replacing in-text commentary or as a supplement.	The rubrics used as formative in-class assessment tools to stimulate students' discussions on the logical development of gene function, moving from the Mendelian model to the Modern model, which is not always straightforward.
<i>Presentation</i>	Rubrics are usually displayed in a form of grid, table or matrix populated by text. However, the information on rubrics also could be presented in other forms such as images, Venn diagram, or sophisticated technology-mediated rubrics.	The rubrics were paper-based table of text.
<i>Explanation</i>	Rubrics are accompanied by varying explanations which could be either simple as being asked to complete the rubric or more detailed.	The rubrics were accompanied by the instructions: "Use the rubric to conduct an honest self-assessment based on your engagement with the lesson. The self-assessment results will not affect the final outcomes but will serve as a reference for me (the teacher) to help improve the learning experience."

An example of a teaching process for the Neoclassical model of gene function to develop critical thinking of high school students

### Step 1. Historical model introduction

During this step, teachers should introduce conflicts between the current model of gene function being studied and the preceding model or conflicts that arise when uncovering the model being studied. Discovering new scientific knowledge relies on assimilating past scientific advancements to address unresolved conflicts left by prior discoveries. Various conflicts could be introduced during the teaching process, which may include:

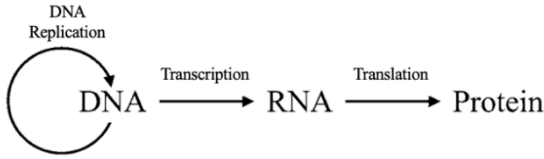
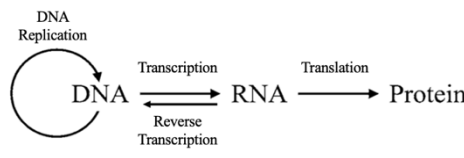
- The need for scientists to discover new knowledge based on existing data;
- Disagreements that emerge during the research process;
- The need to address and overcome limitations in previous studies through subsequent research.

When instructing the Neoclassical model, students will learn basic knowledge of molecular biology, establishing a crucial groundwork for a new era of genetic research conducted at the molecular level. The teaching process is structured into five lessons, with conflicts used as illustrated in the Table 5.

It is important to remember that the teaching process of all models of gene function must adhere to the knowledge distribution set forth by the Vietnamese Ministry of Education and Training.

**Table 5.** Conflicts used in teaching the Neoclassical model.

Main contents	Conflicts used for instruction
<i>Lesson 1. The structure and function of DNA and DNA replication</i>	
<ul style="list-style-type: none"> <li>- The structure and function of DNA;</li> <li>- The structure and function of gene;</li> <li>- DNA replication.</li> </ul>	<ul style="list-style-type: none"> <li>- When Morgan's research group proposed the bead theory that genes are located along chromosomes, two chemical components of chromosomes (DNA and protein) were considered two candidate compounds for role of genetic material. Among them, the evidence in favor of protein seemed to prevail. In particular, some biochemists have classified proteins into the group of macromolecules that have both high functional specificity and diversity - which are properties of genetic material. A significant question has emerged: What is responsible for genetic materials?</li> <li>This view has gradually changed from the results of a number of studies in microorganisms. Inheriting genetic research methods from Mendel and Morgan, one of the most important factors in determining genetic material is choosing the appropriate experimental organism. The role of DNA as genetic material was first discovered in bacteria and viruses: Griffith, Hershey - Chase's experiments to prove that DNA is genetic material and not protein.</li> <li>- When learning about the structure and function of the DNA molecule, there was a competition between several scientists with several different proposed models. Finally, Watson and Crick were winners in this competition with two previously published data by other scientists: (1) Photo 51, taken by Rosalind Franklin, showed that DNA consists of 2 long strands twisted around each other to form a double helix structure, the distance between the two strands is very uniform, about 20 Angstroms; (2) Scientist Chargaff's experiment proves the quantities of A and T are equal, as well as G and C, in which A and G are classified as large bases and C and T are classified as small bases.</li> <li>- After discovering the double helix structure of the DNA molecule, Watson and Crick proposed a model of DNA replication: one strand of the DNA molecule will act as a template to synthesize a complementary strand. However, such a model of DNA replication has yet to be tested. At that time, three models of DNA replication were proposed:             <ul style="list-style-type: none"> <li>+ Conservation model: the two "mother" and "daughter" strands combine after replication.</li> <li>+ Semi-conservative model: the two strands of the "mother" double helix strand are separated, and each strand is used as a template to synthesize a new double strand.</li> <li>+ Dispersion model: Each strand of two "daughter" double-stranded DNA molecules is a mixture of old and newly synthesized segments.</li> </ul> </li> <li>However, later, thanks to the discovery of the DNA polymerase enzyme and the experiments of Meselson and Stahl, the semi-conservative model of DNA replication was proven correct. Meselson and Stahl's experiment is considered a typical example of a very effective and reasonable experimental design to test scientific hypotheses.</li> </ul>
<i>Lesson 2. Transcription and translation</i>	
<ul style="list-style-type: none"> <li>- RNA and transcription;</li> <li>- Reverse transcription;</li> <li>- Genetic code and translation;</li> <li>- DNA – RNA – protein relationship</li> </ul>	<p>In 1970, after discovering the double helix structure of DNA with Watson, Crick proposed a model of the flow of genetic information from DNA to protein, from the nucleus to the cytoplasm, through an intermediate "carrier". This "carrier" will "read" the genetic information stored on DNA and bring the appropriate amino acids, attaching them together to form a polypeptide chain. The significant question has emerged: What material is responsible for the intermediate "carrier"?</p> <p>At that time, RNA was considered a candidate for "carrier material", since RNA was found abundantly in the cytoplasm.</p> <p>Through series of experiments, scientists have found that there are types of RNA with the following characteristics:</p> <ul style="list-style-type: none"> <li>+ some RNAs are very small in size, carrying amino acids at one end, then carry those amino acids to the ribosome for protein synthesis (tRNA);</li> <li>+ some RNAs can be detected in ribosomes, which are large in size (mRNA);</li> <li>+ some RNAs attach to proteins to form ribosomes - where proteins are synthesized (rRNA).</li> </ul> <p>- According to Crick's proposal, the flow of genetic information is generalized in the following diagram and be called "The Central Dogma"</p>

Main contents	Conflicts used for instruction
	<div style="text-align: center;">  </div> <p>Genetic information flows in one direction from DNA to RNA by transcription, but does the Central Dogma remain unchanged over time? However, in 1970, Temin and his colleagues discovered a reverse process: DNA is synthesized from the RNA template (viral genome) through reverse transcriptase. A typical example is the case of the HIV virus. HIV has an RNA genome. When entering the host cell, HIV RNA will be reverse-transcribed into double-stranded DNA and inserted into the host cell's genome. At a certain time and under certain conditions, the viral DNA installed in the host cell's genome is transcribed into RNA and viral proteins, continuing to help the virus destroy the host cell and spread to other cells. Therefore, the Central Dogma should be revised as below (please note that the Central Dogma will undergo continuous revisions; nonetheless, this version was presented to students to align with the Biology curriculum. However, the students were aware of the ongoing updates to the Central Dogma model as technology has advanced rapidly).</p> <div style="text-align: center;">  </div> <p>- Crick, after proposing a path for transmitting genetic information from DNA to protein, realized a problem: In the flow of genetic information from DNA to protein, there must be some material connecting DNA and amino acids, which he called an adaptor molecule. Initially, he thought that proteins comprised about 20 types of amino acids, so there would have to be 20 types of connecting materials. However, using physicochemical methods, scientists have discovered that the structure of this connecting material is a tiny RNA molecule consisting of only about 80 nucleotides with a 3-strand shape like a clover leaf. This molecule carries an anticodon at one end, complementary to the coding triplet (codon) on the mRNA molecule, and an amino acid at the other end.</p>
<i>Lesson 3. Gene expression regulation</i>	
<ul style="list-style-type: none"> <li>- Operon <i>lac</i>;</li> <li>- Significance of gene expression regulation;</li> <li>- Application of gene expression regulation.</li> </ul>	<p>The "one gene - one enzyme" theory proposed by Tatum and Beadle holds true for most bacterial genes. Bacteria can control the production of enzymes that catalyze metabolic reactions in response to changing environmental conditions by regulating the expression of their genes.</p> <p>However, the question that emerged is: Has the "one gene – one enzyme" theory remained unchanged over time? The answer is no. The one-gene-one-enzyme hypothesis is not considered totally accurate today, as advancements in genetic understanding have demonstrated that genes can encode more than just enzymes and can be responsible for multiple proteins through processes such as alternative splicing.</p>
<i>Lesson 4. Gene mutation</i>	
<ul style="list-style-type: none"> <li>- Definition and types of gene mutation;</li> <li>- Causes and mechanisms of occurrence;</li> <li>- Role of gene mutation.</li> </ul>	<ul style="list-style-type: none"> <li>- In the 1900s, the use of X-rays was prevalent in the fields of medicine, pharmacy, and industry. Charles Russell Bearden conducted experiments to prove that when toad eggs are fertilized with X-ray-treated sperm, they will form abnormal embryos that cannot develop into tadpoles. From there, Muller hypothesized that X-rays could cause genetic mutations, thereby changing the phenotype. Through experiments on mutating fruit flies with X-rays and performing crosses, then comparing with control samples not treated with X-rays, Muller confirmed that genes are tangible materials, carrying genetic information, and can be mutated by X-rays.</li> <li>- In the chromosome theory of Boveri and Sutton, genes are conceived as beads on a string, distributed throughout the chromosomes, and mutations can only occur in the spaces between genes. However, Watson and Crick later published the structure of DNA, suggesting that DNA is a continuous chain of nucleotides. Benzer, in 1955, performed experiments to prove that mutations can occur at a single nucleotide within a gene and lead to a change in the nucleotide sequence.</li> </ul>

Main contents	Conflicts used for instruction
	From there, Benzer introduced the theory of genes: genes are structural units (cistrons), recombination units (recon), and mutation units (mutons). In particular, the concept of gene as a structural unit (cistron) is commonly used. Recombination units (recon) and mutation units (muton) are considered single nucleotides.
<i>Lesson 5. The gene – environment – phenotype relationship</i>	
- The interaction of the genotype the environment.	During the era of Mendel, Morgan, and biochemical genetics, little attention or study was given to the environment's influence on gene expression in gene research. Modern genetics has revealed that an interaction of environmental and genetic factors influences the expression of an organism's phenotype. Multiple genes in an organism contribute to various features through diverse interactions, whereas environmental factors influence the extent of phenotypic expression.

### Step 2. Conflicts solving

Teachers use a system of questions and suggestions to encourage students to engage in scientific thinking and logical reasoning to form personal judgments. During the warm-up activity prior to studying the structure and function of DNA, teachers raised a conflict: In the 1900s, the prevailing belief among scientists was that proteins served as genetic material. This belief stemmed from the fact that proteins consisted of 21 different amino acids, whereas DNA molecules were composed of only four types of monomers: A, T, G, and C. The Hershey-Chase experiment refuted this perspective.

Subsequently, teachers ask students to follow the description of the Hershey-Chase experiment and play the role of these scientists to explain that the material carrying genetic information is DNA, not protein. It could be accomplished by addressing these suggested questions:

- This is a study involving the infection of bacterial cells by phage T<sub>2</sub>. Phage T<sub>2</sub> comprises an outer protein shell and a DNA core inside the head. When invading a bacterial cell, phage T<sub>2</sub> will inject a substance into the bacterial cell. What do you think that substance is?
- DNA is rich in phosphorus but lacks sulfur, whereas proteins include sulfur. Do the radioactive isotopes <sup>35</sup>S and <sup>32</sup>P label DNA or protein?
- Why must we shake the bacterial cell vigorously after the phage infects it?
- Based on your initial hypothesis, in the experiment involving labeling protein with the isotope <sup>35</sup>S, which isotope will be present in the bacterial sediment, and which isotope will be present in the solution? Please provide further clarification or details.
- In the experiment involving labeling protein with the isotope <sup>32</sup>P, based on your initial hypothesis, which isotope will be present in the bacterial sediment, and which isotope will be present in the solution? Please provide further clarification.

### Step 3: Essential genetics knowledge summarize

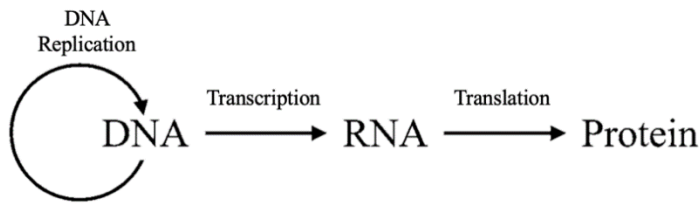
The step of summarizing and extracting the critical knowledge from the lesson is crucial. The fundamental understanding involves understanding and exploring genetics at each stage, matching each specific model of gene function.

### Step 4: Evaluate and correct errors in perception and conflict resolution (if any)

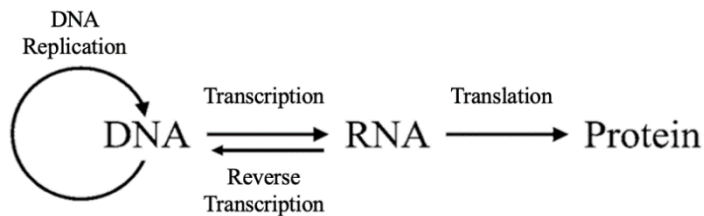
This step is crucial in fostering students' critical thinking skills. Upon completing the session, teachers should organize for students to self-examine and compare their own conflict-resolution strategies with those of other students and earlier scientists. By doing this comparison, students will reinforce their understanding and correct their cognitive misconceptions, identifying the strengths and weaknesses in their conflict resolution strategies. Simultaneously, students will understand and embrace the notion that numerous diverse viewpoints might exist regarding a scientific matter, thereby effectively developing their critical thinking skills.

After completing the second lesson on transcription, translation, and the relationship between DNA - RNA - protein, the teacher organizes for students to evaluate and compare their conflict resolution strategies with those of other

students, as well as with Crick's proposed diagram illustrating the molecular-level mechanism of heredity. According to Crick's proposal in 1956, the flow of genetic information is generalized in the diagram as follows:



Students being asked about their agreement with this diagram. If not, what is their proposed modification for this diagram? Students will formulate their own hypotheses. After acquiring knowledge of the reverse transcription process, students have the opportunity to improve the diagram illustrating the transmission of genetic information. They can compare their own predictions with the study findings of prior scientists. Subsequently, students assimilate current knowledge and anticipate the possibility of further modifications to the diagram illustrating the transmission of genetic information due to advancements in contemporary science and technology.



**Step 5:** Analyze and draw the logic of genetic development

Considering genes as the “red thread” in genetic research, students are instructed to analyze the differences in perspectives on gene function at different milestone discovery stages. The activity aims to help students understand the logical progression of genetic knowledge development and to develop their critical thinking skills by examining how later models have addressed the unresolved issues of previous models.

After acquiring knowledge of the Neoclassical model, students will construct a comparative table that illustrates the stage of awareness of gene function across models to discern the logical progression of genetic knowledge (as shown in Figure 1).

*Views and opinions expressed in this article are the views and opinions of the author(s), International Journal of Education and Practice shall not be responsible or answerable for any loss, damage or liability etc. caused in relation to/arising out of the use of the content.*