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RESEARCH ARTICLE

A didactic framework to develop complex thinking and to deconstruct and reconstruct knowledge in genetics

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ABSTRACT
In the face of growing complexity, developing the skills to navigate our daily lives has become a major challenge. In French-speaking Belgium, although the decree of the Education Code emphasises the need to prepare students to become responsible citizens, current teaching practices tend to oversimplify complex phenomena, particularly in genetics. To introduce learners to the complexity of genetics, a didactic framework was developed. This framework integrates reflective, systemic, emergentist, and socio-constructivist approaches, whose impact on students' thinking and knowledge was analysed. The results show significant progress, both in students' modes of thinking – marked by critical and nuanced reflection – and in their understanding of key genetic concepts. Among the framework's components, expert interventions and peer discussions proved effective in deconstructing misconceptions, deepening the understanding of complex genetic interactions, and assimilating new concepts. It would be beneficial to integrate these approaches throughout the school curriculum and across disciplines to help students develop thinking that can grasp complexity.

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Complexity; unpredictability; uncertainty; genetics; epigenetics; secondary education

Introduction

In a world increasingly shaped by scientific and technological advances, developing scientific literacy is essential for acting responsibly. This need is particularly emphasised in secondary education, where students must acquire the skills required to navigate a complex environment characterised by uncertainties.

In French-speaking Belgium, the decree of the Code of Fundamental and Secondary Education (Fédération Wallonie-Bruxelles 2019) highlights the importance of preparing all students to become responsible citizens.

However, as Morin (2005) points out, current knowledge education tends to simplify the complexity of the world, which can lead to misconceptions and a partial understanding of societal issues. A striking example of this simplification is found in the field of genetics.

Traditionally, genetics education has emphasised genetic determinism, where genetics is seen as the inheritance of traits conditioned by genes. More recently, epigenetics

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appears to demonstrate that our lifestyle can influence our genetic inheritance (de La Roche Saint-André 2022). This apparent duality between genetics and epigenetics illustrates the complexity of the discipline and the need for an approach that reflects this complexity.

A previous study (Focant, Rezsöhazy, and De Kesel 2025) highlighted the limitations of genetics education in secondary schools in French-speaking Belgium. The results revealed that curricula and textbooks poorly reflect the complexity of genetics and reinforce misconceptions. Beyond this empirical observation, the literature also points to challenges in teaching (epi)genetics.

The literature highlights the specific difficulties associated with teaching (epi)genetics, showing that the phenomena involved rely on networks of interactions, evolving dynamics, and uncertainties that are rarely addressed in classroom practices. When presented in linear or stabilised ways, these contents may lead students to construct misconceptions (N. Gericke and McEwen 2023).

These findings support the need to develop complex thinking, described in the literature as an intellectual posture that acknowledges interactions, uncertainty, and the emergence of new properties (Connac 2018; Morin 2005), while fostering an approach to science education grounded in reflection, dialogue, and the co-construction of knowledge. These theoretical elements led us to identify four complementary approaches – systemic, emergentist, reflective, and socio-constructivist – which we mobilise in this study to support the development of complex thinking among students.

To respond to these challenges, we propose a didactic framework based on a model for thinking about knowledge objects as well as a visual tool to guide its construction. Both elements derive from the theoretical framework used in this study and articulate the four approaches identified as essential for supporting the development of complex thinking. They are presented at the beginning of the Method section.

Theoretical framework

Genetics education is based on constantly evolving knowledge. While classical approaches have long favoured a linear and deterministic view of biological mechanisms, recent scientific advances – particularly in epigenetics – invite us to recognise and integrate their complexity. Yet, this complexity remains largely absent from school curricula.

Addressing this gap requires fostering complex thinking, understood as the ability to approach biological phenomena through interactions, uncertainty, and non-linear dynamics.

In this context, it becomes essential to rethink didactic frameworks by mobilising complementary approaches. Reflective and socio-constructivist approaches primarily allow for the questioning of learning processes, while systemic and emergentist approaches offer tools to conceptualise knowledge objects in all their complexity, and are often discussed together in biology education literature (Assaraf and Orion 2005, 2010a).

Before proposing a new didactic perspective, it is essential to consider previous intervention studies in genetics education. Reviewing these empirical works helps situate our study within ongoing efforts to introduce contemporary genetics – such as epigenetics – into classrooms, to identify the main outcomes and difficulties encountered, and to clarify how our approach builds on and extends this existing research.

Genetics education and its evolution

Genetics education has historically relied on a deterministic view, based on Mendel's laws and the linear transmission of hereditary traits. This approach, focused exclusively on the role of genes, has long dominated curricula and textbooks, contributing to a simplified representation of living systems.

As early as the 1940s, Waddington (2012) introduced the concept of epigenetics to link developmental processes (epigenesis) with genetic mechanisms. Today, epigenetics refers to all modifications in gene expression that do not alter the DNA sequence but can be induced by stimuli from the organism or its environment (Bjornsson et al. 2008; Klosin and Lehner 2016; Rakyan and Beck 2006; Talens et al. 2012).

This evolution in biological knowledge calls for a transformation in the content taught. Clément and Forissier (2000) emphasise the need to move beyond the 'all-genetic' paradigm to include epigenetic mechanisms. Atlan (1999) contrasts classical paradigms with those of emergence and complexity, while Gayon (2016) sees epigenetics as a paradigmatic extension of genetics. Loison (2024), for his part, traces the historical genesis and epistemological tensions of epigenetics, highlighting the conceptual resistance that hinders its integration into education.

As Nicoglou and Merlin (2017) point out, epigenetics challenges gene-centrism by introducing non-coding regulatory mechanisms – sometimes heritable – that complicate the relationship between genotype and phenotype. They show that epigenetics serves as a bridge between various fields of biology, describing it as a 'boundary concept' (Star and Griesemer 1989), meaning a flexible concept that circulates across disciplines such as molecular biology, developmental biology, and ecology.

However, this epistemological shift is still struggling to be reflected in school curricula. The delay in didactic transposition (Colomb 1986) slows the updating of programmes, maintaining simplified and sometimes outdated representations. de La Roche Saint-André (2022) notes that the tension between genetics and epigenetics is often presented as a dichotomy, whereas it should be understood as a dynamic interplay. Kampourakis (2023) calls for a curriculum overhaul to teach genetics through the lens of developmental complexity and gene – environment interactions. Together with Reiss (Kampourakis and Reiss 2018), he stresses the need for biology education to incorporate advances in epigenetics, neurobiology, and developmental biology in order to move beyond traditional paradigms and better prepare students for contemporary challenges.

Several studies highlight the importance of clearly introducing epigenetic concepts into current curricula to improve understanding of the relationships between the genome, the environment, and the traits that emerge, using concrete examples (Clément and Forissier 2000; N. Gericke and McEwen 2023; Stern and Kampourakis 2017).

Genetics is a complex discipline, difficult to teach and to learn (Chastenay et al. 2021; Lewis and Wood-Robinson 2000; Lewis, Leach, and Wood-Robinson 2000; Williams, Montgomery, and Manokore 2012). Castéra and Clément (2014) observed that teachers' level of training influences their conceptions: the higher the level, the less prevalent is innatism – the belief that traits are exclusively determined by genes.

Common misconceptions in genetics

Misconceptions in genetics are well documented and often take the form of reductionism, determinism, and sometimes genetic essentialism – views that suggest genes fully explain phenotypes, solely determine traits, and define an individual's identity (Donovan et al. 2021; Moore, Kampourakis, and Gericke 2025). Genetic essentialism is mentioned here as a conceptual distinction, but the remainder of this study will focus on genetic determinism and reductionism, as they relate to the construction of the didactic framework.

These misconceptions are reinforced by several factors: media and popular culture (Ley, Jankowski, and Brewer 2012; Muela and Abril 2014), curricula and textbooks (Castéra, Bruguière, and Clément 2008; Forissier and Clément 2003; N. M. Gericke et al. 2014; Wahlberg and Gericke 2018). They are found among students, teachers, and pre-service teachers (Casanoves de la Hoz et al. 2022; Del Re 2024), and are influenced by social, educational, and cultural factors (N. Gericke 2021). Kampourakis (2023) and Johnston (2023) criticise the simplistic models derived from Mendelian genetics, which can lead to deterministic conceptions – such as the idea that there is 'a gene for' every trait – thus neglecting the complex interactions between genes and the environment.

These misconceptions should not be dismissed but rather used as levers to identify epistemological obstacles. Taking them into account allows educators to design didactic sequences aimed at overcoming these obstacles (Clément 2014).

This reflection also draws on the findings of the research mentioned in the introduction (Focant, Rezsöhazy, and De Kesel 2025), which highlighted the difficulties encountered by students and teachers when dealing with complex genetic concepts such as penetrance, expressivity, phenotypic variability, and epigenetic mechanisms. These notions – often misunderstood or absent from curricula – provide relevant entry points for exploring the multifactorial nature of genotype – phenotype relationships and for challenging the deterministic and reductionist conceptions still widely present in genetics education.

Previous intervention studies in genetics education

Several studies have explored how to integrate contemporary genetics into classroom practice. In a large secondary school intervention, Zudaire and Napal Fraile (2021) showed that introducing epigenetics through a short sequence helped students recognise the influence of environmental factors on gene expression, while also revealing persistent conceptual barriers such as lack of prior knowledge and enduring deterministic views. Interventions explicitly designed to develop genomics literacy have also shown promise. Donovan et al. (2021) designed a curriculum focused on human genetic variation, multifactorial models and population thinking, demonstrating significant reductions in students' essentialist beliefs.

In the specific domain of epigenetics, N. Gericke and McEwen (2023) developed an expert-informed framework outlining the conceptual and sociocultural themes necessary for ‘epigenetic literacy’. This framework informed the educational design study conducted by Thörne, Gericke, and McEwen (2025), who implemented and refined classroom activities across eleven secondary classrooms. Their study showed that a set of ‘Big Ideas’ grounded in dialogic teaching enables students to move away from deterministic explanations and helps teachers address conceptually challenging content.

Importantly, teachers’ perspectives on integrating epigenetics have also been studied. McEwen, Gericke, and Thörne (2025) showed that, despite professional development efforts, many teachers continue to rely on a selective teaching tradition centred on Mendelian genetics and the so-called ‘central dogma’ of molecular biology, understood as the unidirectional flow of genetic information from DNA to RNA to proteins, with the assertion that this information cannot move in the reverse direction. This tradition tends to reinforce deterministic reasoning and makes it difficult to incorporate epigenetics into everyday classroom practice. Their findings highlight both the structural resistance to curricular change and the need for interventions that support teachers in navigating conceptual and pedagogical transitions towards contemporary genetics education.

Jamieson and Radick (2017) provide experimental evidence that the traditional Mendelian-first approach itself can reinforce deterministic reasoning. Their study demonstrated that university students taught an alternative ‘Weldonian’ curriculum, emphasising developmental context and phenotypic variability, became less determinist than those taught a standard Mendelian introduction. This suggests that the structure and starting point of instruction have substantial conceptual consequences for learners.

These studies show that integrating contemporary genetics and epigenetics into instruction requires explicit attention to gene – environment interaction, dialogic work that supports conceptual restructuring, and professional development that helps teachers move beyond entrenched Mendelian traditions. This approach also helps students engage with key aspects of the nature of science, such as complexity, uncertainty and multi-level interactions.

Complexity, complex thinking, and complex knowledge: didactic implications

Complexity, from the Latin *complexus* (‘that which is woven together’), refers to a fabric of heterogeneous elements linked by interactions, feedback loops, randomness, and uncertainty (Morin 2005). Morin (2005) emphasises that the way knowledge is currently taught fails to grasp complexity. He calls for the development of methods capable of thinking through mutual relationships and reciprocal influences between parts and wholes.

This requirement is part of what he calls complex thinking, conceived as a mode of thinking or intellectual posture (Connac 2018), which allows for a dialogue with reality by taking into account its richness, contradictions, and unpredictability – thus producing complex knowledge, that is, knowledge that connects, contextualises and accepts uncertainty as a component of understanding. It also entails reflexivity regarding the limits, biases, and conditions of validity of knowledge, which Morin refers to as the ‘knowledge of knowledge’ (Berger et al. 2020), a dimension that directly aligns with a reflective approach.

Complex thinking does not reject simplification but situates it within its limits, promoting meta-perspectives, vigilance towards determinisms, and attention to non-linear dynamics such as emergence. Recent studies highlight the tension between linear and complex explanations: Ehras and Dittmer (2026) show that students and teachers tend to value short, linear explanations, even for multicausal or uncertain phenomena, while didactics researchers emphasise the need to integrate not-knowing and multiple causation. Clarifying the status of uncertainty, Blauza, Kremer, and Heuckmann (2025) show that it can stem from the state of knowledge, the nature of the phenomena, or the evolving character of scientific knowledge.

Research also suggests that complex thinking can develop when learners are immersed in dynamic, authentic situations: Lena et al. (2022) document the emergence of multicausal reasoning and linguistic markers of uncertainty in such contexts, echoing a socio-constructivist approach that emphasises authentic situations, cooperation and the co-construction of knowledge.

In socio-scientific debates, students mobilise aspects of complex thinking, yet Bächtold et al. (2023) observe that uncertainty remains rarely considered. Teachers also report insecurity when dealing with content that departs from stabilised factual traditions and involves sociocultural dimensions (Leden, Hansson, and Redfors 2017), which resonates with the challenges of integrating systemic and emergentist approaches, that require working with interactions, non-linear dynamics, variability and phenomena that are difficult to anticipate.

These findings are consistent with Morin (2006), who argues that education to uncertainty is fundamental. In this view, uncertainty becomes a cognitive resource stimulating vigilance, curiosity, and creativity (Pena-Vega 2014). Sormany (1996) similarly advocates a 'sharing of ignorance', understood as making visible uncertainties, limits, and unresolved questions. Nedelec (2018) interprets this principle as potentially forming the backbone of science education, inviting us to conceive of it as a collective and reflective exploration rather than a transmission of certainties.

Taken together, these elements highlight the need to articulate a reflective, socio-constructivist, systemic, and emergentist approach in order to support the development of complex thinking.

Towards a complex thinking in genetics: articulating four approaches

Teaching genetics confronts students with complex phenomena. To design a didactic framework suited to this complexity, we propose articulating four approaches: reflective, socio-constructivist, systemic and emergentist. Together, these approaches are mobilised to support the development of complex thinking in students.

The first two approaches, reflective and socio-constructivist, are generally associated with learning processes: they aim to foster students' awareness of their misconceptions, to help them deconstruct these ideas, and to guide them towards more complex thinking and understanding.

The next two approaches, systemic and emergentist, focus more on the objects of knowledge and the ways of conceptualising them, integrating interactions, non-linear dynamics, variability and emergent phenomena characteristic of complex systems.

This distinction is adopted here to highlight their complementarity within the framework. Together, they offer varied and interconnectable angles to grasp the complexity of living systems.

Each of these four approaches will first be presented individually. Afterwards, the two approaches centred on the objects of knowledge, the systemic and the emergentist, will be examined together, as they are commonly treated alongside one another in the biology education literature.

Reflective approach: thinking about one's thinking

The reflective approach emphasises recognising and questioning learners' preconceptions. It encourages individuals to resist certainties and adopt a critical attitude towards their own beliefs, understood as the ability to evaluate the validity and coherence of one's ideas before making a judgement (Dewey 1933). This approach aligns with Morin's (2005) call to develop a kind of thinking capable of integrating change and the unexpected, in a continuous dialogue with discovery.

This process is essential for fostering deep and nuanced understanding of studied topics. By integrating the reflective approach into all learning processes, learners become critical thinkers of their own practices, capable of navigating complex and ever-evolving environments (Gaussel 2021). According to Solveig Fernagu-Oudet (Zay 2000), reflective analysis allows learners to 'walk while watching themselves walk', illustrating the ability to detach from immediate action to analyse it objectively. This approach transforms learning into an introspective and adaptive experience, better aligned with contemporary educational challenges (Miron and Presseau 2001).

In a discipline like genetics, where spontaneous representations are often deterministic or innatist, the reflective approach helps students become aware of their preconceptions, question them, and build a more nuanced understanding of the diversity of biological mechanisms.

Socio-constructivist approach: learning through dialogue

The socio-constructivist approach values social interaction and collaboration in learning processes. It encourages active listening, open-mindedness, and cooperation to build knowledge. This approach is based on two main dimensions: the constructivist and the social.

The constructivist dimension focuses on building new knowledge from prior knowledge or experiences. These new understandings are considered provisional, as their viability can be questioned and reassessed in light of new information and contexts (Kerzil 2009).

The social dimension highlights the importance of social interactions among individuals involved in constructing new knowledge. According to Vygotsky, learning is a social process where learners build their own understanding through interactions with peers and their environment (Jonnaert and Vander Borght 2008).

In genetics education, this approach allows students to confront ideas, debate issues related to the discipline and collectively construct knowledge open to a plurality of viewpoints. This openness to diverse perspectives and co-construction of knowledge aligns with a way of thinking that recognises the complexity of reality (Morin 2005).

Systemic Approach[1]: thinking about interactions

The systemic approach is based on the fundamental idea that every phenomenon should be understood as a system – a complex set of interactions. In contrast to reductionism, which isolates and fragments elements in order to examine them separately, systems thinking requires an understanding of relationships and overall structure. This approach is essential for analysing and managing organisations, societies, and social or technological systems, where multiple interactions are omnipresent (von Bertalanffy 2012).

Morin (2005) defines complexity as a web of interactions, feedback loops, and randomness, and emphasises the importance of meta-perspectives to grasp the system as a whole. From this perspective, Hamant (2023) notes that performance-driven logic often leads to reducing complexity in order to make it more manageable, at the risk of impoverishing interactions, whereas systems thinking relies precisely on their abundance. In the same vein, Yatchinovsky (2020) shows that the systemic approach helps move beyond a fragmented view of reality by adopting an observational stance capable of connecting elements, recognising their interdependencies, and accepting the uncertainty inherent in open systems.

Emergentist Approach[1]: embracing the unpredictable

The emergentist approach allows us to think about complex phenomena that cannot be reduced to the sum of their parts. It describes emergence as the appearance of new properties resulting from interactions among elements of a system, which cannot be attributed to any one element individually nor predicted by simply adding them together (Sterling et al. 2005). These emergent properties arise from a non-linear dynamic, where the whole exceeds the isolated characteristics of its components.

Morin (2005) emphasises that complexity involves a tension between order and disorder, and that innovation often arises from this encounter. He calls for strategies capable of adapting to the unexpected and relativises determinism, which assumes that outcomes can be predicted from initial conditions. Complex thinking does not reject determinism but integrates it into a more nuanced vision, open to uncertainty and the emergence of novelty.

Systemic and emergentist approaches in biology

Research in science education shows that the systemic and emergentist perspectives are intrinsically linked when analysing and teaching biological complexity. Studies on the development of systems thinking in biology emphasise that learners must work with interactions, feedback loops, organisational levels and dynamic processes to make sense of living systems (Assaraf and Orion 2005, 2010a). These abilities develop progressively, from identifying components and processes to recognising patterns, hidden mechanisms and temporal dynamics, forming the basis of the Systems Thinking Hierarchy (STH) model.

At the same time, research on teachers' pedagogical reasoning shows that biological explanations necessarily involve degrees of uncertainty and partial mechanisms, which must be intentionally managed in class. Teachers frequently rely on 'black-box explication': they explicitly acknowledge where mechanisms remain simplified or incomplete, and justify why these boxes are temporarily kept closed (Livni Alcasid and Haskel-Ittah 2025). This approach does not contradict systems thinking; rather, it complements it by making the limits of explanation visible and by teaching students to work with emergent phenomena whose properties cannot be fully predicted from isolated components. In this sense, Clément (2009) stresses the importance of teaching the interplay between chance and constraints in biological processes, using the concept of emergence to explain how complex behaviours can arise from simple processes combined randomly and selectively. Furthermore, research on the macro-micro problem in biology shows that coherent understanding requires explicit movement across levels of biological organisation, a core feature of the yo-yo strategy described by Knippels and Waarlo (2018).

This interdependence between systemic and emergentist approaches appears clearly in empirical studies on students' reasoning with multiple visual representations in epigenetics. Students engage in a progression from examining isolated visual elements, to comparing representations at the same organisational level, to linking levels vertically, and finally to a fluid 'yo-yo reasoning' across molecular, cellular and organismal scales (Thyberg, Schönborn, and Gericke 2024, 2025). At the highest phase, students not only describe interactions (systemic) but also explain how new properties emerge from them, illustrating the impossibility of dissociating systemic and emergentist thinking in biological phenomena.

Assessment findings reinforce this complementarity. Concept maps successfully capture how students organise system components, relations and dynamics, but they reveal very little spontaneous expression of emergent patterns, homoeostasis, hidden mechanisms, or temporal reasoning, unless such aspects are explicitly scaffolded (Tripto, Assaraf, and Amit 2013). This demonstrates that emergence does not automatically arise from systemic reasoning: it must be intentionally taught within systemic modelling.

Long-term studies further show that students who develop stable systemic competencies, particularly dynamic and cyclic reasoning, are more likely to maintain these capacities over time, whereas fragmented reasoning profiles persistently limit both dimensions (Assaraf and Orion 2010b).

The research demonstrates that systemic thinking provides the structural framework (components, interactions, levels, feedbacks), while emergentist thinking provides the epistemic stance needed to understand novelty, uncertainty and partially known mechanisms. In biology, the two perspectives are therefore inseparable: understanding living systems requires simultaneously modelling how interactions are organised and how new properties arise from them.

Research question

Our research aims to study the impact of a didactic framework, based on reflective, socio-constructivist, systemic, and emergentist approaches, on the ability of students in the final year of secondary school in Belgium (6th year, around 18 years old) to develop complex thinking and to deconstruct their misconceptions in order to reconstruct complex knowledge.

To this end, we ask the following questions:

- How does the didactic framework influence the development of complex thinking and complex knowledge among students, as measured by pre-test and post-test?

- What learning processes emerge in students as they progress towards complex thinking and knowledge, and how do the four didactic approaches contribute to these processes?

We hypothesise that the integration of the reflective, socio-constructivist, systemic, and emergentist approaches within the didactic framework is essential for enabling students to develop complex thinking and to evolve their misconceptions towards complex knowledge.

Methodology

Design and presentation of the didactic framework

A model for thinking about knowledge objects

The first step in our approach was to design a model for thinking about knowledge objects (Figure 1), in response to the requirement formulated by Morin (2005): to develop methods capable of grasping the complexity of reality, taking into account interactions, feedback loops, and unpredictability. This model is rooted in an intellectual posture inspired by complex thinking, which invites us to go beyond simplifications without rejecting them, and to embrace uncertainty as a source of novelty.

The model articulates different ways of thinking about knowledge objects:

The arrows pointing towards the centre of the model represent the dynamics of simplifying thinking:

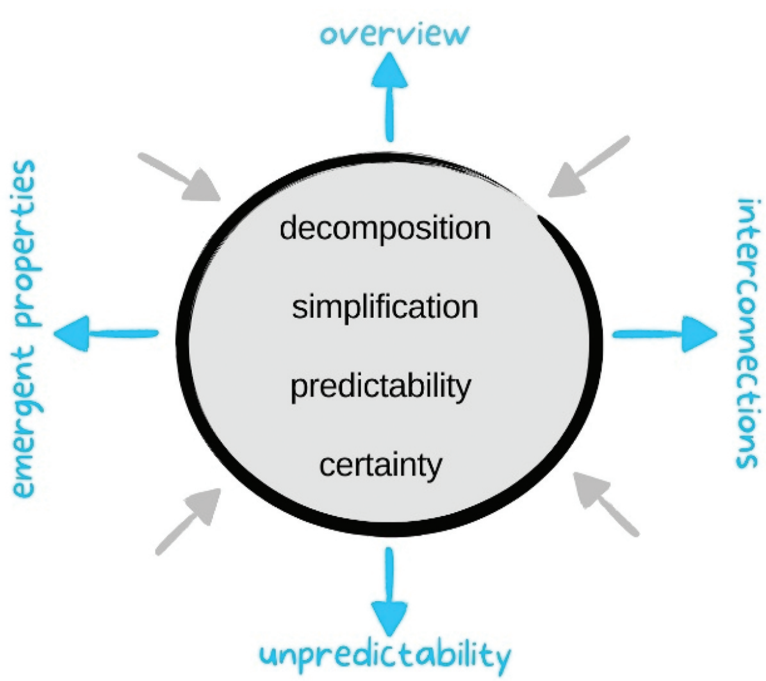

Figure 1. Model for thinking about knowledge objects.

- Decomposition and simplification (reductionist approach)
- Predictability and certainty (deterministic approach)

When faced with a complex phenomenon, we tend to *decompose* and *simplify* it to make it easier to understand and to allow for *predictability*, even though any *certainty* is always relative and subject to a margin of error.

These dynamics reflect a reductionist and deterministic approach, which aims to isolate parts in order to better understand the whole, and to seek simple laws and certainties. Morin (2005) does not reject this kind of thinking, but he highlights its limitations: simplification is necessary, but it must remain aware of its reductive nature.

The addition of arrows pointing outward expresses the dynamics of complex thinking:

- Overview and interconnections (systemic approach)
- Unpredictability and emergent properties (emergentist approach)

When faced with a complex phenomenon, it is essential to maintain an *overview* by examining the *interconnections* between the various factors involved. From these multiple interconnections, *emergent properties* may arise, requiring constant consideration of *unpredictability*.

These dynamics express a systemic and emergentist approach, capable of grasping complexity, thinking in terms of interactions, feedback loops, and emergent phenomena.

Complex thinking integrates these approaches without opposing them. It acknowledges the necessity of simplification while calling for its transcendence in order to better grasp the richness and dynamics of reality. However, the literature presented in the theoretical framework shows that approaches associated with complex thinking – particularly the systemic and emergentist ones – are less spontaneous and require explicit guidance. This is why the proposed model emphasises the outward-oriented dynamics, to support the development of a way of thinking capable of engaging with the complexity of living systems.

In genetics, these two approaches help move beyond a linear view of life. The systemic approach helps students understand biological interaction networks, while the emergentist approach opens up to unpredictability and the emergence of new properties, especially in epigenetic mechanisms.

This model serves as a reference for teachers in designing the framework, and as a reflective tool for students. It is used as a didactic tool throughout the learning process. The keywords displayed on the model serve as anchors to structure discussions, guide analyses, and contribute to the development of a way of thinking capable of engaging with reality and constructing complex knowledge.

A visual tool for designing the didactic framework

In a second phase, it seemed important to integrate two additional approaches into the construction of the framework: the reflective approach and the socio-constructivist approach, which we consider to be part of the learning processes. The reflective approach was integrated from the very beginning of the framework, notably through the collection of students' preconceptions (in the form of a pre-test in our study). It is then addressed throughout the framework to support the evolution of students' representations.

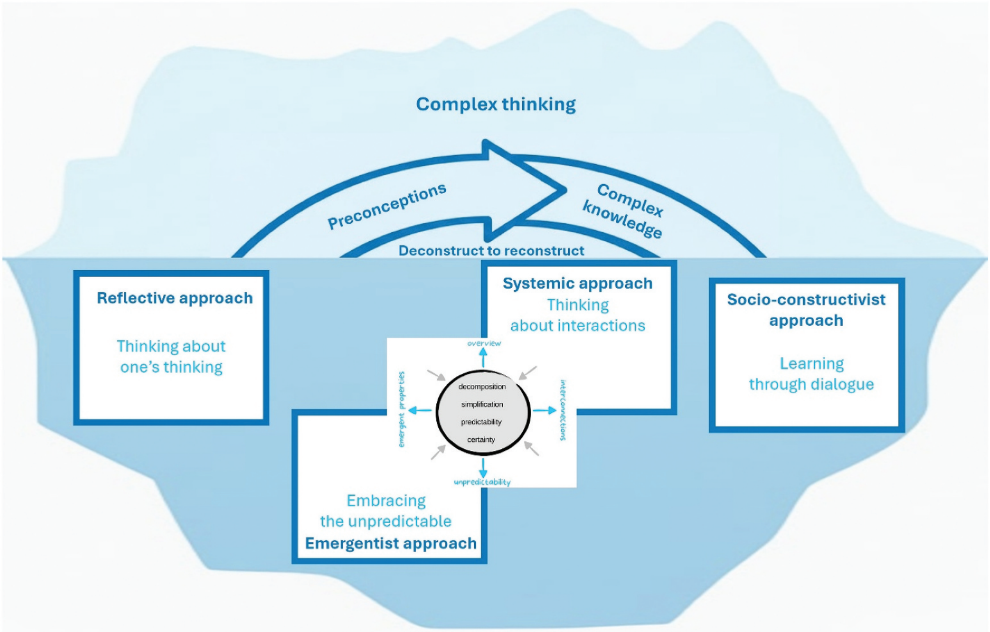

Figure 2. The iceberg – a tool for designing a didactic framework.

The socio-constructivist approach, on the other hand, was mainly implemented at the end of the framework, to allow students to consolidate their learning through dialogue, confrontation of viewpoints, and co-construction of knowledge – and to exercise their complex thinking in a new context.

This reflection led us to create a visual tool, based on the iceberg metaphor (Figure 2), to support the design of the didactic framework by enabling an articulated integration of the four approaches mobilised in this research.

The submerged part of the iceberg brings together the four approaches:

- Reflective and socio-constructivist, which relate to learning processes. They help students become aware of their preconceptions, question them, and reconstruct them through dialogue;
- Systemic and emergentist, which provide a framework for thinking about knowledge objects in their complexity. The model depicted in Figure 1 is placed between these two approaches, highlighting their central role in the development of complex thinking.

The emerged part represents complex thinking as the goal of learning processes – a way of thinking capable of deconstructing misconceptions and reconstructing complex knowledge.

Implementation, activities, and resources

The framework consists of seven activities spread over approximately eight 50-minute sessions. These are presented in Table 1, each linked to one or more of the didactic

Table 1. Implementation and activities of the framework designed to develop complex thinking.

Reflective Approach	Emergentist Approach	Systemic Approach	Socio-constructivist Approach
1. Pre-test (Appendix 1a) 40 minutes			
			2. Discussion Game *Science teacher* 25 minutes
		3. Scenario-based activity and Analysis of Complex Situations (1) (Appendices 2 & 3) *Science teacher* 50 minutes	
	4. Analysis of Complex Situations (2) (Appendix 4) *Science teacher* 25 minutes		
	5. Expert Intervention (Appendix 5) *Molecular biology expert* 100 minutes		
			6. Expert Intervention (Appendix 6) *Philosophy expert* 100 minutes
7. Post-test (Appendix 1a) 40 minutes			

approaches used. The table also indicates, for each activity, the person responsible – either the science teacher, who is also the researcher in this study, or an invited expert – as well as the planned timing.

For each activity, specific resources were developed and/or used to support the development of complex thinking, by articulating the four didactic approaches mobilised in this research.

Pre- and post-test

Activities 1 and 7 consist of a pre-test and a post-test (Appendix 1a), designed to identify, through the pre-test, students' modes of thinking and preconceptions in genetics, and then to analyse, through the post-test, the evolution of these thinking patterns and their knowledge following the implementation of the framework.

The test was validated in two steps: first, it was submitted to two students outside the project, to check its clarity, and then reviewed by researchers specialising in the relevant fields.

It includes four questions, each based on an authentic and varied situation: an article excerpt on hereditary transmission, an interview on psycho-genealogy, popular slogans from the internet or book titles, and an excerpt from Opinion No. 124 of the French National Consultative Ethics Committee (2016) on the challenges of genome sequencing in disease prediction. These situations were selected for their potential to stimulate critical and nuanced thinking, involving concepts such as epigenetic modifications, hereditary transmission, penetrance, and expressivity.

The pre-test also helped confirm certain preconceptions identified in the literature (see theoretical framework) and in a previous study conducted with students at the end of their secondary education (Focant, Rezsöhazy, and De Kesel 2025). These preconceptions served as a basis for designing the framework. While this collection could take other forms outside a research context, it was structured as a pre-test here to align with the protocol that includes a post-test.

The reflective approach is mobilised in both activities, as well as throughout the framework, to help students identify their preconceptions, deconstruct them, and adopt a critical stance towards their own representations.

Discussion game

As a complement to Activity 1, Activity 2 allows students to express their preconceptions and confront them with those of their peers. It consists of a discussion game on genome sequencing. The game used in this framework was downloaded from the PlayDecide website (https://playdecide.eu/), developed as part of a European project aimed at promoting the creation and sharing of discussion games that foster the exchange of opinions on controversial topics. Using cards containing life stories, factual information, or debate topics, students are encouraged to question reductionist and deterministic approaches related to genetic testing, identify and deconstruct misconceptions, and co-construct knowledge – particularly around ethical issues and the uncertainties associated with these tests.

Scenario-based activity + analysis of complex situations (1)

Activity 3 (Appendix 2), designed within a systemic approach, begins with a critical analysis of eight press articles discussing changes observed in astronaut Scott Kelly's DNA after his extended stay in space, compared to his twin brother who remained on Earth. Students identify discrepancies in media narratives: some articles mention genetic mutations, others refer to changes in gene expression, while some report no DNA changes at all. This activity aims to develop students' critical thinking in the face of contradictory sources and allows the teacher to introduce the distinction between genetic changes (alteration of the nucleotide sequence) and epigenetic changes (regulation without sequence modification).

Several didactic tools, developed as part of this research, are used to deepen understanding of epigenetic mechanisms:

- A mind map to be constructed, helping students characterise the two types of modifications.
- A four-level model, used to represent interactions between environmental factors, levels of biological organisation, and molecular actors. This model is applied to two situations (the coat colour of Siamese cats and the differentiated development of bee larvae). It helps students adopt a systemic approach and determine whether the observed phenotypic changes are due to epigenetic mechanisms.
- A document titled 'Some Figures' (Appendix 3), usable independently of the framework, informing students about the proportion of DNA that does not code for polypeptides and its functions – thereby broadening their understanding of the complexity of the human genome.

This activity as a whole supports the systemic approach, helping students become aware of the interconnections between biological actors and develop an overview of the mechanisms linking environment, molecular activity, gene expression, and phenotype.

Analysis of complex situations (2)

Activity 4 (Appendix 4) involves analysing a situation that illustrates phenotypic plasticity in worker bees. Based on a document describing the possible transformation of foragers into nurse bees, students discover that this change is associated with a modification in DNA methylation in the brain, affecting genes related to behaviour.

This situation shows that the phenotype can evolve over time in response to environmental factors, without any modification of the genome. Students are led to recognise that analysing the genome alone is not sufficient to understand phenotypic evolution, and to identify epigenetic mechanisms as factors of reversibility and unpredictability.

The activity supports an emergentist approach, encouraging students to think about the non-linear dynamics of living systems, where emergent properties can arise from interactions between various factors.

Expert intervention in molecular biology

In Activity 5, a researcher specialised in molecular biology was invited to present the scientific foundations of genetics in all their complexity. He clarified key genetic concepts considered essential for teaching, using terms defined in the glossary developed for this research (Appendix 5). This glossary includes concepts such as *phenotypic plasticity, pleiotropy, polygenic traits, penetrance and expressivity of a phenotype, gene expression modifications of genetic and epigenetic origin*, and *epigenesis*. These concepts form a core body of knowledge necessary to understand genetics in its complexity.

Based on research conducted in his laboratory and elsewhere, the expert illustrated several characteristic dimensions of living systems:

- Interconnections:
- Feedback mechanisms: A protein produced from a gene can act back on the DNA (directly or indirectly) to modulate the expression of that gene or other genes (for example: developmental genes — *Hox* genes produce regulators that activate or inhibit other *Hox* genes or their target genes in different embryonic territories, which also involves changes in chromatin status).

Key concept: epigenesis

- Multicausality:
- One cause can have multiple effects: A mutation can lead to various effects in different tissues, organs, or biological functions because the gene is involved in several pathways or processes (for example: the *Hoxa1* gene regulates the expression of different genes in a variety of distinct embryonic processes, like brain patterning, heart development, skull formation . . .).

Key concept: pleiotropy

- One effect can result from the interaction of multiple causes: Most phenotypic traits result from the combination of alleles of several genes that contribute together to the phenotype (for example: the Hoxa1 gene is one among many others acting in a network controlling heart development; mutation in any of these genes can lead to a similar cardiac defect; Lescroart and Zaffran 2018).

Key concept: phenotypic polygenism

- Unpredictability:
- In most situations, an individual carrying a mutation may or may not express the associated phenotype (for example: 13 of 20 *Hoxa1* hexapeptide mutants show an abnormally shaped basioccipital bone; Remacle et al. 2004).

Key concept: phenotypic penetrance

- Malformations of varying severity may be observed in association with a mutation (for example: the same *Hoxa1* mutation can lead to an ear malformation of variable severity; Remacle et al. 2004).

Key concept: phenotypic expressivity

- Emergent properties: The phenotype results from the interaction between the environment and the genotype (for example: daphnias can develop defensive structures, such as helmets or spines, in the presence of predators; Nagano et al. 2023).

Key concept: phenotypic plasticity
In all these phenomena, interactions between genes or epigenetic modifications have been shown or inferred to be at work.

The intervention concluded with a Q&A session, fostering the appropriation of the concepts discussed.

Thanks to his up-to-date knowledge of advances in genetics, the expert provided students with access to knowledge directly drawn from contemporary research. His intervention played a key role in reducing the didactic transposition gap, ensuring a close alignment between the content taught and the most recent scientific discoveries. It also reinforced the legitimacy of the framework by grounding the didactic approaches in a rigorous and dynamic scientific reality.

Indeed, based on laboratory work, the expert illustrated the relevance of the four approaches mobilised in the framework:

- Systemic and emergentist approaches, for thinking about knowledge objects in their complexity;
- Reflective and socio-constructivist approaches, for describing the dynamics of scientific work.

Beyond its value for students, this intervention also provided valuable reference points for teachers, who are often confronted with a complex discipline that is difficult to convey in all its depth.

Expert intervention in philosophy

In Activity 6, a philosophy expert was invited to guide students in transferring the approaches to another complex situation: climate change. Drawing on her expertise in epistemology and critical thinking, she helped students put the previously explored approaches into perspective.

Her intervention stimulated the development of complex thinking, particularly through peer dialogue and the questioning of certainties.

The activity supports a reflective and socio-constructivist approach, encouraging the collective construction of knowledge. It also implicitly mobilises the systemic and emergentist approaches, as students are invited to pay attention to multiple interactions, unpredictable dynamics, and the uncertainty inherent in complex systems.

The structure of this activity is presented in a publication by the expert (Schlögel 2025), a summary of which is included in Appendix 6.

Study participants

The didactic framework was first validated by researchers involved in the project, then tested in an exploratory study conducted from November 2022 to June 2023 with a class of 23 students in the final year of general secondary education (basic science track, with three 50-minute science periods per week), in a school within the Fédération Wallonie-Bruxelles (subsidised private education).

The following year, after adjustments to the framework, a new experiment was conducted from November 2023 to June 2024 with 37 students (Group A) from two schools within the Fédération Wallonie-Bruxelles (subsidised private education). This group included:

- 19 students in the final year of general secondary education (basic science track), who had not chosen the science option;
- 18 students in a 7th-year special science programme. These students chose to extend their schooling to strengthen their scientific skills, feeling they lacked the necessary background to pursue higher education in this field.

The control group (Group B) consisted of 34 students in the final year of general secondary education (general science track), who had chosen the science option and had received more advanced science instruction over four years (five 50-minute science periods per week in 3rd and 4th year, then six periods in 5th and 6th year), except for a few who changed options during their schooling.

In total, 71 students participated in the study: 37 (Group A) experienced the framework, while 34 (Group B) formed the control group.

All students in Groups A and B were informed about the project and agreed to participate, with the approval of school administrations. Participation was voluntary, and anonymity and confidentiality were ensured throughout.

This study fell under the category of regular educational practice according to our university's ethics regulations; therefore, formal ethics committee approval was not required.

The pre-test was administered to both groups at the beginning of the school year, before any implementation of the framework, and the post-test after the experimental period (Group A) or following 'traditional' instruction (Group B).

The 'traditional' teaching received by the students in Group B corresponded to instruction without socio-constructivist activities and without the Expert Intervention activity. The notions addressed in both groups were generally similar; however, in Group B, certain concepts (such as expressivity or phenotypic plasticity) were not explicitly named, and epigenetic mechanisms were not presented as a structuring element linking the phenomena studied.

The socio-constructivist activities carried out in Group A explicitly aimed to encourage students to question and move beyond their preconceptions and, throughout the intervention, to reconstruct knowledge that takes into account the complexity of genetics.

The choice of participants adds particular value to the study: the group that experienced the framework (Group A) did not represent the most scientifically advanced academic profile. As will be shown in the results section, this is reflected in the pre-test scores, where the average for Group B (science option) was slightly higher than that of Group A.

The impact of the didactic framework is all the more significant given that it was experienced by students who were initially less advanced in science, which strengthens the didactic relevance of the results obtained.

Tools and methods for quantitative analysis based on the pre/post-test

To assess the influence of the didactic framework on the evolution of students' thinking patterns – in line with the requirements of complex thinking – and on their appropriation of complex knowledge in genetics, an analysis was conducted based on their responses to the pre/post-test.

The responses were analysed using an evaluation grid (Appendix 1b), constructed based on two axes:

- Mode of thinking, evaluated through three criteria:

The student provides coherent and valid justifications.
The student demonstrates critical thinking (i.e. the ability to question simplistic or deterministic statements and not accept them passively).
The student qualifies their statements by considering interconnections, uncertainties, and unpredictability.

- Knowledge, evaluated through the appropriation of key concepts in genetics.

The link between epigenetic modifications and phenotype – distinction from hereditary transmission.
Distinction between epigenetic modifications and mutations.

Expressivity and penetrance.

For each question, evaluation modalities were defined:

- Question 1 mobilises critical thinking in response to simplifying messages; it examines the understanding of epigenetic mechanisms, their impact on the phenotype, and the issue of hereditary transmission. It allows verification of the appropriation of the concepts: epigenetic modifications, phenotype, hereditary transmission.
- Question 2 explores the use of epigenetics as a tool to legitimise psycho-genealogy practices, by soliciting critical thinking regarding this association. It allows verification of the appropriation of the concepts: epigenetic modifications and mutations.
- Question 3 invites reflection on the scope and validity of simplifying media messages. It allows verification of the appropriation of the concepts: epigenetic modifications and mutations.
- Question 4 questions the limits of genomic sequencing in disease prediction. It allows verification of the appropriation of the concepts: penetrance and expressivity.

The distribution of points per criterion is detailed in the appendix (Appendix 1b).

The mode of thinking is assessed out of a total of 7 points, while knowledge is assessed out of 6 points.

To allow direct comparison between the two axes (mode of thinking and knowledge), each score was rescaled to a 1-point scale. The overall score (mode of thinking + knowledge) was also expressed on a 1-point scale by averaging the two rescaled axes.

The evaluation grid was developed by two designers. It is based on the key concepts that students were expected to acquire, as well as on the competencies they are expected to mobilise when engaging in complex thinking, such as providing coherent and valid justifications, demonstrating critical thinking, and qualifying their statements by taking into account interconnections, uncertainties, and unpredictability.

The four questions of the pre/post-test combined multiple-choice items with open-ended tasks, presented within a limited response space (a few lines maximum), such as: ‘Briefly justify your choice’, ‘Group together the messages that share common features and justify your classification’, or ‘Propose a message intended for a reader and justify your formulation’. For each question, precise and quantified scoring indicators were defined (for example: correct option = 0.5 point; mention of the notions of expressivity or penetrance = 0.5–1 point; consideration of interconnections in the justification: +0.5), as presented in the appendix (Appendix 1b). The indicators were designed in direct alignment with the knowledge criteria and the intended modes of thinking targeted by each question.

The grid underwent several rounds of refinement between the two designers. Analysis of the first student responses revealed situations requiring clarification or adjustment of certain indicators to avoid ambiguity. Following these revisions, the copies were reread and corrected several times to ensure that all criteria were consistently applied and that scoring remained coherent across responses.

Although the test comprises only four items, these correspond to complex and contextualised tasks requiring approximately 40 minutes of work. It is therefore not a standardised instrument based on numerous short items, but an assessment designed to fit within a real teaching context. This characteristic is acknowledged as a limitation inherent to the nature of the tasks proposed.

To evaluate the impact of the framework on student outcomes, a repeated measures ANOVA was conducted. This analysis crossed two factors:

- Within-subject factor: time of evaluation (pre-test vs post-test);
- Between-subject factor: type of instruction received (didactic framework vs 'traditional' instruction).

This statistical analysis allows for the examination of score evolution based on the type of instruction, while accounting for intra-individual variations between the pre-test and post-test.

The interpretation of effect strength is based on the Eta-squared (η^2) value, following Cohen's guidelines (1988).

The pre/post-test was administered to both groups under equivalent conditions:

- Group A ($N = 37$), who experienced the framework;
- Group B ($N = 34$), who received 'traditional' instruction.

The comparison of results between the two groups allows for the measurement of students' progression towards complex thinking and complex knowledge.

Tools and methods for the qualitative analysis of post-framework interviews

In addition to the quantitative analysis, a qualitative analysis was conducted to explore the learning processes mobilised by students in their progression towards complex thinking and complex knowledge. This analysis is based on semi-structured interviews conducted with 12 students from Group A after the implementation of the framework.

Students were selected on a voluntary basis, according to their appreciation of the interventions by the two experts (molecular biology and philosophy), allowing for a diverse sample:

- 5 students who appreciated the entire framework (A1, A2, A8, A9, and A10);
- 3 students who preferred the intervention by the molecular biology expert (A3, A4, and A11);
- 3 students who preferred the intervention by the philosophy expert (A5, A6, and A12);
- 1 student who expressed less appreciation for both interventions (A7).

The interviews, lasting between 30 minutes and 1 hour, were conducted by the authors of the study using a pre-established interview guide (Appendix 7), structured around the following themes:

- The model for thinking about knowledge objects, integrating systemic and emergentist approaches;
- The approach to complexity in genetics and in other disciplines or situations;

- Key concepts in genetics;
- Climate change issues and the critique of opinions on these issues.

All interviews were audio-recorded and conducted in French. For the purposes of the manuscript, the interview excerpts cited in the results were translated into English using Microsoft Co-pilot's translation functionality. The research team then manually reviewed and refined these translations to ensure their accuracy and fidelity to the participants' original meaning.

The interviews were analysed using NVivo 14 software, following a thematic approach.

In a first stage, we identified verbatim excerpts in which students referred either to complex situations, or to the approaches they mobilised to address them, or to their perceptions of the various activities carried out during the framework.

The analysis was conducted within an abductive framework, involving constant movement between the empirical material and the theoretical elements of the study. An initial coding of verbatim excerpts considered relevant for understanding the learning processes at play was carried out. These codes were then progressively organised into broader categories (e.g. complex situations, preconceptions, key concepts, use of the model, activities of the framework, attitudes towards complexity), structured through an evolving conceptual mind map.

In a second stage, these categories were grouped and interpreted to construct more general themes related to students' learning processes. This interpretative step aimed to:

- identify obstacles and facilitators in approaching complexity;
- assess how the proposed model served as a learning support;
- verify students' understanding and appropriation of key genetic concepts.

The entire coding process and the organisation of categories were discussed with a second researcher, which helped refine the analysis and ensure its coherence.

The points of view of the teacher and the two experts were also collected to cross-reference student perceptions with those of the facilitators and to shed light on the effects of the framework from the designers' point of view.

The teacher's point of view was collected through a semi-structured interview at the end of the intervention. The molecular biology expert was interviewed in the same way, while the point of view of the philosophy expert was drawn from a written reflection she produced regarding Activity 6 (Schlögel 2025).

Results

Influence of the didactic framework on pre/post-test score evolution

The statistical analysis of responses to the pre/post-test highlights a significant impact of the framework on students' development, both in terms of their modes of thinking and their appropriation of complex knowledge in genetics. A repeated measures ANOVA with $\alpha = 0.05$ was performed to analyse the evolution of scores between groups.

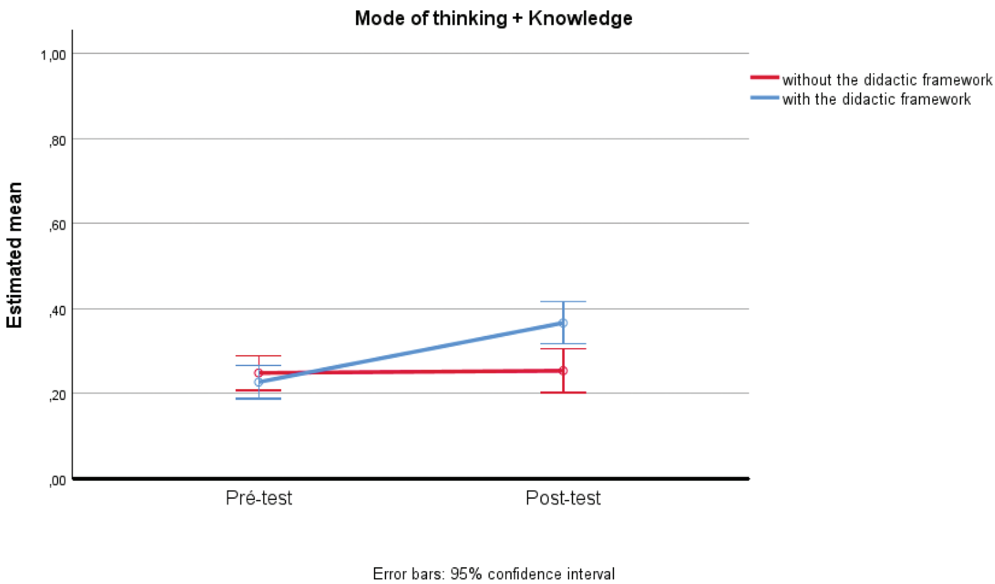

Figure 3. Evolution of estimated marginal means of scores expressed on a 0–1 scale from pre- to post-test for mode of thinking and knowledge, with confidence intervals, for students who did or did not experience the didactic framework ($\eta^2 = 0.173$, $p < 0.001$).

The results show a significant large effect (around 0.14 – according to Cohen's criteria[2]) on the overall evolution of scores ($\eta^2 = 0.173$, $p < 0.001$) (Figure 3).

When analysing the two axes separately, we observe that the teaching intervention had a significant and large effect (around 0.14) on both the mode of thinking ($\eta^2 = 0.115$, $p = 0.004$) (Figure 4) and knowledge ($\eta^2 = 0.120$, $p = 0.003$) (Figure 5).

The statistical analysis of the results obtained for each part of the question associated with an evaluation criterion is detailed in Appendix 1c.

The mean scores calculated for each criterion show a positive progression in Group A, with post-test results consistently higher than pre-test results. In contrast, Group B shows little variation in mean scores, and in some cases, a decrease.

The repeated measures ANOVA (with $\alpha = 0.05$), conducted by evaluation criterion and question component, reveals several statistically significant results, each associated with a medium effect size (around 0.06 – according to Cohen's criteria[2]). These results are highlighted in green in Appendix 1c. They concern the appropriation of concepts such as penetrance and expressivity, the links between epigenetic modifications and phenotype, and hereditary transmission.

In addition, the criterion related to complex thinking, which evaluates students' ability to nuance their responses by considering interconnections, uncertainty, and unpredictability, also shows significant results. Furthermore, the two other criteria within this same axis - one assessing the ability to formulate coherent and valid justifications, and the other evaluating critical thinking - also reach significance, but only for one of the two question parts associated with each. These findings reflect an evolution in the mobilisation of the complex mode of thinking.

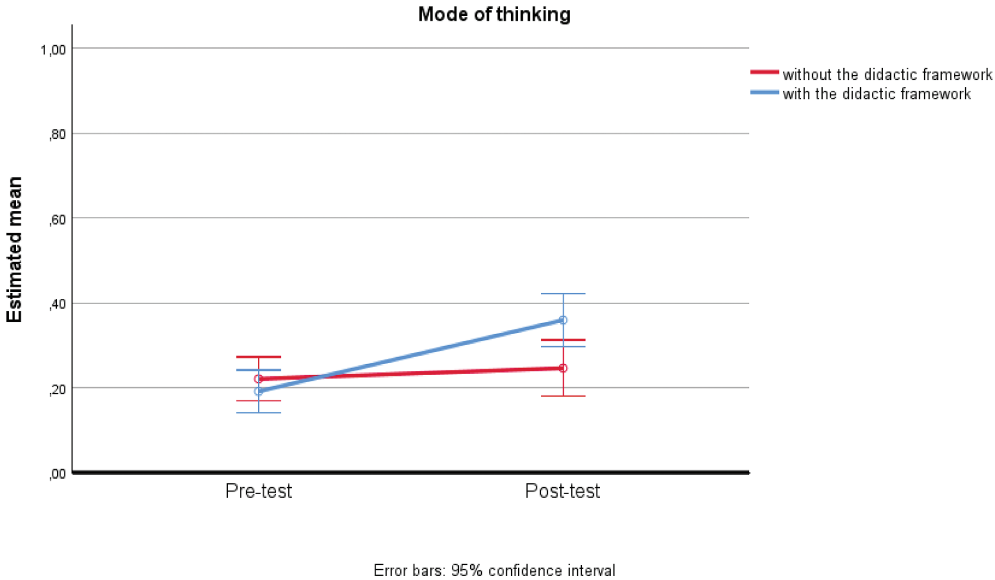

Figure 4. Evolution of estimated marginal means of scores expressed on a 0–1 scale for the mode of thinking between pre- and post-test, with confidence intervals, for the experimental and control groups ($\eta^2 = 0.115$, $p = 0.004$).

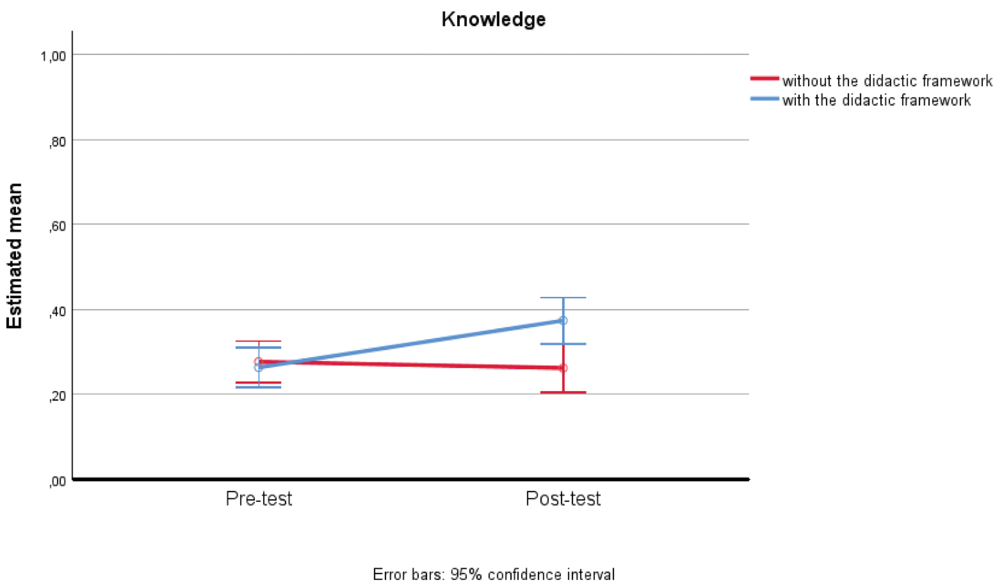

Figure 5. Evolution of estimated marginal means of scores expressed on a 0–1 scale for knowledge between pre- and post-test, with confidence intervals, for the experimental and control groups ($\eta^2 = 0.120$, $p = 0.003$).

Influence of the framework on students' mode of thinking and knowledge

The analysis of the interviews highlights the impact of the framework on how students approach complexity and appropriate key concepts in genetics. The selected verbatim excerpts illustrate transformations in their modes of thinking, linked to the learning situations they experienced.

Difficulties in facing complexity

The interviewed students expressed difficulties in grasping complexity, which is often absent from their school experience. They became aware of a tendency towards simplification (reductionist and deterministic approaches), present in biology as well as in other disciplines:

> In physics, they tell us that friction forces are negligible, everything is negligible . . . and we think that's how it is in real life. (A8)

Engagement in a reflective approach

Some verbatim excerpts show that students engaged in a reflective process, questioning their initial representations and accepting uncertainty. This reflective approach appeared regardless of their appreciation of the experts' interventions.

> Understanding that it's much more complex than it seems is a beautiful approach. (A8)

> It makes me want to know more . . . while realizing that I'll never understand everything. (A10)

One student acknowledged the effect of the activities on her ability to take a step back:

> When I said it (a comment about climate change during Activity 6), I think I hadn't really thought it through. The exercise helped me take a step back. (A6)

Regarding Activities 1 and 7 (pre- and post-test), a student expressed the value of evolving in her choices:

> I thought it was great to have the test twice, so at the beginning you can say what you think and then, once you've understood the material, you can see if you've learned other things that might influence your choice. (A2)

Engagement in a socio-constructivist approach

Peer interactions, especially during Activities 2 and 6, were perceived as powerful learning levers.

The exchanges and information received through the discussion game cards (Activity 2) enabled more critical thinking about genetic testing, as reflected in all interviews:

> Before, I would have said 'Oh cool!' . . . I knew about genetic tests . . . they're super popular on social media . . . now, I think they're useless since they can't really know anything, they won't know everything just from my genome. (A12)

This evolution in students' representations was also noted by the teacher, who observed that the activity sparked surprise, questioning, and a rethinking of preconceived ideas.

Activity 6 elicited mixed reactions.

Several students appreciated the diversity of viewpoints and the richness of the discussions, emphasising the value of debate in better grasping the complexity of the topic:

> It's great to hear how people think . . . you realize how truly complex the topic is. (A9)

> I really liked that there was this philosophical aspect and that we were given this 'tool' that can help us in other areas. (A12)

Other students expressed reservations, mainly related to a lack of preparation and time:

> I think it's too complicated to ask people to take a stance on such a topic. Climate change, I think it's too complex to be left to 18-year-old students who don't really know the subject. (A11)

These critiques highlight the importance of clear framing and sufficient time to allow for genuine appropriation of the issues addressed. This observation aligns with the perspective of the philosophy expert, who described the activity as promising but necessarily limited by the short format. Nevertheless, she noted the richness of the students' questions, which demonstrated their ability to approach climate change in all its complexity, integrating scientific, personal, collective, and political dimensions. The activity thus opened a space for discussion where each student could reflect on their worldview and responsibilities.

Engagement in systemic and emergentist approaches

Activities 3, 4, and 5 were designed to help students work with systemic and emergentist approaches, gradually integrating the model to think about knowledge objects.

In their reflections, students referred to the varied situations from Activities 3 and 4 (genetic testing, astronaut twins, Siamese cat, bees), Activity 5 (laboratory research), as well as the didactic tools, especially the four-level model. The collected verbatim excerpts show the impact of these activities and tools on their understanding of the complex issues related to genetics:

> The first activity with the reading texts, I found it interesting, and even the topic of DNA tests, it's something that's really popular on social media, so it's interesting to see the issues. Personally, I liked how it was approached, that we had to work in groups and all that. (A12)

> There can also be an impact on gene expression from food in bees. We used the model with the levels. This model helps us get an overview . . . to see all the interconnections. (A7)

> I didn't know that people work for decades on a single gene and all its mutations. (A11)

The teacher noted that students were surprised by the contradictions in the news articles about the astronaut twins, which stimulated their critical thinking. She also observed their astonishment at epigenetic mechanisms, particularly their reversibility and complexity. She found that the four-level model, designed for this purpose, proved accessible and effective: it facilitated the understanding of epigenetic mechanisms and helped students determine whether a situation involved them.

Regarding Activity 5, some students expressed difficulties with the concepts presented by the molecular biology expert but acknowledged the richness and necessity of a way of thinking that embraces the complexity inherent in genetics:

> The professor's lecture, I found it very interesting and it really conveyed the message that genetics is much more complex than we think . . . but sometimes I found it a bit too technical for our level. (A12)

> I was shocked . . . genetics isn't simple, it's not made of predefined things. (A9)

> Science isn't my strong suit. For example, penetrance and expressivity—I'm not sure I'll be able to explain everything again in two weeks. The concepts themselves were well explained though. (A3)

> Those terms (penetrance and expressivity) are worth exploring further. (A1)

These student reflections align with the perspective of the molecular biology expert, who emphasises that the questions raised – despite sometimes revealing confusion – are all relevant, as they help identify conceptual grey areas that can then be addressed. He insists on the importance of deconstructing preconceptions and revisiting definitions, sometimes repeatedly, to support a deeper appropriation of complex concepts such as penetrance and expressivity. The expert considers that his intervention came at the right moment in the framework and that the diversity of activities fosters attentive engagement and a cautious attitude towards knowledge – an essential skill in an information-saturated world. He believes that this kind of approach is necessary to help students think about the complexity of living systems within an educational vision grounded in citizenship.

Appropriation of the model for thinking about knowledge objects

The model for thinking about knowledge objects, which encourages moving beyond simplistic thinking, is perceived as a useful and transferable tool. This perception emerges repeatedly in the interviews:

> It helped us realize that we might need to think differently. The model is quite a useful tool for many things—even during higher education, when facing a problem, why not use it? (A4)

> This model helps analyse a problem, break it down, simplify it . . . but you also have to consider external factors at play . . . It's a model we could even use in everyday life. (A5)

The interviews reveal that students are beginning to think differently, integrating notions of uncertainty, interconnections, and emergent properties:

> If we don't have certainties, it means we're aware of unpredictability and emergent properties. And so, it's a good way of thinking because we make a lot of connections . . . there's really everything you need to get an overview and not just say: if we do this, then that will happen. (A8)

Discussion and conclusion

The analysis results show that the teaching intervention supports not only the development of a complex mode of thinking, but also the appropriation of complex genetic concepts.

Statistical analysis reveals a significant effect of the intervention on students' ability to mobilise skills that are constitutive of a mode of complex thinking, in particular their ability to nuance their responses by taking into account interconnections, uncertainty, and unpredictability. Additionally, the criteria related to the formulation of coherent and valid justifications, as well as critical thinking, which also represent essential dimensions of complex thinking, show progress, although statistical significance was reached only for one of the two question parts associated with each.

Regarding knowledge, the results also highlight a significant effect of the intervention on the appropriation of several key genetic concepts, including penetrance, expressivity, the links between epigenetic modifications and phenotype and hereditary transmission. The concepts of penetrance and expressivity, identified by students as particularly complex, are essential for understanding phenotypic variability and grasping genetic complexity. Within a reflective approach, the appropriation of these key genetic concepts contributes to the construction of complex knowledge.

The analysis of the interviews, based on students' verbatim excerpts, highlights learning processes that reveal an evolution in their modes of thinking. It complements the quantitative results by showing how the various activities of the framework supported the deconstruction of preconceptions, the integration of new concepts, and the recognition of uncertainty as an inherent feature of living systems. The reflective and socio-constructivist approaches particularly contributed to these processes by fostering questioning, dialogue, and awareness of initial representations. The systemic and emergentist approaches, in turn, enabled students to engage with knowledge objects in their complexity, highlighting the multiple interactions and unpredictable dynamics characteristic of complex systems. These four complementary approaches respond to the need, emphasised by Morin (2005), to cultivate a mode of thinking capable of grasping the complexity of reality. They reinforce one another and benefit from being integrated into a didactic framework that addresses complexity.

The specific contribution of each activity, as well as the order in which they were introduced, proved essential, as they gradually established the conditions necessary for transforming modes of thinking and appropriating complex knowledge. In this regard, the transfer activity (Activity 6), which mobilised the different approaches around a new complex situation, though appreciated for its richness, would benefit from being extended. Such an extension would better meet the expectations expressed by some students and the expert, by consolidating learning and deepening the application of the various approaches in a novel context.

A learning environment where students can explore, question, and discuss complex topics plays a key role in opening them up to new ideas and encouraging critical and nuanced reflection on their initial conceptions. As Hamant (2023) points out, the heterogeneity of interactions stimulates critical thinking. Recognising gaps in our knowledge and accepting that we cannot control everything are destabilising but essential experiences for developing complex thinking. The expert plays an important role in these learning processes, particularly in raising awareness of complexity, by introducing and illustrating key concepts that are often overlooked in education due to their contingent nature and the complexity of the multiple interactions they involve.

In light of the literature, our results extend and broaden previous intervention studies. We observe in particular a strong convergence with the study by Thörne, Gericke, and McEwen (2025), whose authors recontextualized the content themes identified in the Delphi study of N. Gericke and McEwen (2023) into a set of ten Big Ideas, which they then integrated into an innovative dialogic teaching design.

Although these Big Ideas (BI) were published in 2025, our intervention - implemented in 2024 -draws on these same ideas:

- Activity 2, which focused on the ethical issues of genetic testing, addresses BI 10 (ethical aspects).
- Activity 3, which adopts a systemic approach, covers DNA stability (BI 1), gene regulation (BI 2), molecular mechanisms (BI 3), cell differentiation (BI 6), and linkages between levels of organisation (BI 7), as well as, more briefly, inheritance (BI 5). These ideas are explored through several tools: a mind map (Appendix 2), the four-level model (Appendix 2), and the 'Some Figures' document (Appendix 3).
- Activity 4, which adopts an emergentist approach, addresses the reversibility of epigenetic marks (BI 4), gene – environment interactions (BI 8, nature – culture), and the impact of lifestyle (BI 9).
- Activity 5, which includes the intervention of a genetics expert, mobilises all ten Big Ideas and constitutes a key moment for engaging with the Nature of Science (NOS), a competency that Thörne, Gericke, and McEwen (2025) emphasise as essential.

Our intervention also aligns with the central importance of classroom dialogue highlighted by Thörne, Gericke, and McEwen (2025). Similarly, we observe that the socio-constructivist approach of our design is highly valued by students and fosters the co-construction of knowledge.

Consistent with the findings of Thörne, Gericke, and McEwen (2025), we also observe that epigenetics 'demystifies black boxes' of genetics by providing mechanistic explanations that make phenomena more intelligible rather than more complex.

Beyond these convergences, our design differs from that of Thörne, Gericke, and McEwen (2025) by articulating four complementary approaches – reflective, socio-constructivist, systemic, and emergentist – whereas their intervention primarily relies on the Big Ideas and a dialogic orchestration centred on epigenetics. This combination of approaches, together with a transdisciplinary transfer activity, enhances the effectiveness of our design in developing complex thinking and knowledge.

Echoing the Weldonian teaching implemented by Jamieson and Radick (2017), our intervention also made it possible to identify several key concepts to be addressed in order to grasp genetics in its full complexity. We thus address phenotypic plasticity, epigenesis, and phenotypic polygenism, as well as pleiotropy, penetrance, and expressivity - three key concepts explicitly highlighted in Lecture 8 of their course.

Finally, Activity 3, which draws on the four-level model, helps students explicitly connect different levels of organisation (from environmental factors to molecular and chromatin mechanisms). This tool aligns with the development of 'yo-yo reasoning', as described by Knippels and Waarlo (2018), that is, the ability to move back and forth between levels of organisation. This type of progression is also observed in the work of Thyberg, Schönborn, and Gericke (2024, 2025), which shows that understanding epigenetics relies precisely on these vertical connections.

Limitations

This study presents several limitations that call for a cautious interpretation of the results. First, the pre-test, post-test and analytical grid used were specifically designed for this research. Their validation and reliability therefore remain limited, as is often the case in exploratory studies in genetics education. Moreover, the small sample size limits the extent to which the results can be generalised.

Furthermore, it is important to note that the teacher who implemented the framework with the students was also the researcher. This dual role may amplify certain potential biases, such as a Hawthorne effect or a tendency for students to adjust their engagement or responses based on the perceived presence and role of the teacher-researcher, as reported in other studies conducted in authentic classroom contexts (Thörne, Gericke, and McEwen 2025). These factors may therefore have influenced the observed classroom dynamics beyond the effects of the intervention itself.

Finally, as highlighted by Jamieson and Radick (2017), research conducted in authentic educational settings must contend with methodological and institutional constraints that make it difficult to establish fully controlled experimental conditions. This study should thus be understood as an initial exploratory contribution that paves the way for future, larger-scale investigations with more consolidated methodological designs.

Implications

The findings of this research raise several implications for the teaching of genetics as well as for other complex topics. They may also inform ongoing reflections on the evolution of education frames of reference and secondary-school curricula, which are currently undergoing revision in various educational contexts (including in Belgium, where the study was conducted). Training future teachers in complex thinking therefore appears essential.

With regard to genetics education specifically, we observed that throughout the framework, students were encouraged to identify their misconceptions and the limitations of reductionist and deterministic approaches. They integrated new concepts to approach genetics in all its complexity, thereby constructing complex thinking and knowledge. These learning processes could be further optimised if they were also integrated into other complex subjects throughout schooling. Strengthening these processes would support a better integration of the new paradigm of emergence and complexity described by Atlan (1999). It would also address the challenge of learning new paradigms, which is often hindered by the persistence of existing ones, as noted by Rumelhard (2005).

Familiarising students with systemic and emergentist approaches could help them address any new situation in all their complexity. As mentioned by the interviewed students, the model for thinking about knowledge objects is useful and could be further exploited in various contexts. These approaches can help students remain open to being surprised by living systems. According to Hamant (2023), living systems are experts in turbulence, capable of navigating unpredictable fluctuations thanks to their ability to adapt and evolve. A reductionist view sees living systems as efficient, optimised, and selected for performance. In contrast, a systemic perspective reveals heterogeneity, randomness, and inconsistencies, offering living systems the flexibility to remain stable in the short term and viable in the long term despite unpredictable fluctuations. Embracing the complexity inherent in living systems could thus serve as a model for our societies in the face of uncertainty.

From the perspective of education frames of reference and school curricula, our findings indicate that the proposed didactic design can be mobilised during curriculum-revision processes by providing an operational example of how to integrate content related to epigenetics and the complexity of genetic mechanisms. Our design also aligns with the approach proposed by Thörne, Gericke, and McEwen (2025), whose Big Ideas build on the recommendations of the N. Gericke and McEwen (2023) Delphi study – namely, the importance of structuring instruction around Big Ideas and dialogic activities. It further highlights that the appropriation of key concepts such as pleiotropy, penetrance, and expressivity - also identified as essential by Jamieson and Radick (2017)- is crucial for enabling students to approach genetics in all its complexity. This combination may help reduce the delay in didactic transposition and support teaching practices that avoid reinforcing deterministic views of genetics. However, as suggested by McEwen, Gericke, and Thörne (2025), responsibility for integrating more contemporary scientific content (such as epigenetics) should not fall solely on researchers and teachers; it must also be shared with curriculum and framework developers.

Regarding teacher education, these results underscore the need to support the transition towards less reductionist and deterministic approaches. As shown by McEwen, Gericke, and Thörne (2025), resistance to the introduction of non-linear and multicausal perspectives remains common. Presenting this didactic framework to future teachers in initial training could help them engage with complex genetic concepts and the approaches needed to teach them. They could learn to use the iceberg tool as a basis for preparing a teaching sequence on a complex topic: identifying key concepts, examining students' preconceptions and modes of thinking, and designing activities aimed at developing complex thinking and complex knowledge within the chosen context. The involvement of an expert and a dialogic discussion activity could likewise be employed. Nonetheless, as McEwen, Gericke, and Thörne (2025) point out, this transition may encounter a dominant selective teaching tradition and certain inevitable forms of resistance. To support the appropriation of the didactic design and the iceberg tool, a gradual form of guidance is needed – co-design with a teacher educator or expert, opportunities for reflection on existing practices, and ready-to-use materials to secure implementation.

More broadly, these approaches constitute levers for developing responsible citizens – aligned with the aims of the *Code de l'enseignement fondamental et secondaire* (Fédération Wallonie-Bruxelles 2019) – capable of understanding the complex systems in which they live and acting within them with discernment. The more such approaches are mobilised throughout the educational pathway, the better equipped learners will be to develop essential competences for informed and innovative decision-making.

Notes

1. The concepts of **systemism**, **reductionism**, **emergentism**, and **determinism** present a range of nuances in the literature (e.g. Braccini and Finck 2023; Mossio and Umerez 2014; Sartenaer 2017), which will not be explored here. We will limit ourselves to the definitions provided within the theoretical framework, as they are used in the construction of the didactic approach aimed at developing complex thinking and knowledge.
2. The following benchmarks were developed by Cohen (1988) to guide the interpretation of **partial Eta-squared (η^2)**:

Around 0.01	Small effect
Around 0.06	Moderate effect
Around 0.14 and above	Large effect

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Ethics statement

Our University did not require the study to have formal ethics approval because it involved the design and implementation of a didactic framework in regular classroom settings. However, the research adhered to the Ethical Guidelines for Educational Research (Fifth Edition, 2024) published by the British Educational Research Association (BERA). All participants were informed about the purpose of the study, participation was voluntary, and anonymity and confidentiality were ensured throughout. No personal identifiers were recorded.

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