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UNCERTAINTY AND COMPLEXITY IN SCIENCE:
A CASE STUDY ON FUTURES-ORIENTED CLIMATE CHANGE EDUCATION

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Abstract

Il cambiamento climatico rappresenta la principale sfida che la società globale contemporanea si trova ad affrontare. L'educazione al cambiamento climatico è per sua natura sfaccettata e multidisciplinare e richiede una profonda rivalutazione del nostro quadro educativo. L'educazione scientifica riveste un ruolo centrale nell'affrontare questa problematica. Acquisire familiarità con concetti quali l'incertezza e la complessità è infatti fondamentale per sviluppare la capacità di diventare agenti rispetto al futuro e per esercitare processi decisionali consapevoli. Tuttavia, l'educazione scientifica spesso non riesce ad allinearsi alle sfide sociali ed ecologiche contemporanee.

La mia tesi analizza gli effetti di un approccio all'educazione scientifica orientato al futuro, sull'immagine di scienza insita negli studenti, osservando il caso studio di un corso di 20 ore intitolato "Verso nuovi scenari futuri: il ruolo della fisica nelle sfide del cambiamento climatico", sviluppato e condotto dai ricercatori Lorenzo Miani e Francesco De Zuani Cassina durante il loro dottorato presso il Dipartimento di Fisica e Astronomia "A. Righi".

I risultati indicano che il corso ha ampliato la percezione degli studenti riguardo alla complessità e all'incertezza. Inoltre, l'analisi mostra che l'esposizione alle prove degli effetti del cambiamento climatico durante il corso, insieme alla pratica della costruzione di scenari, ha contribuito a far maturare negli studenti un posizionamento più costruttivo nei confronti del futuro e, al tempo stesso, li ha aiutati a definire il proprio ruolo nel contesto sociale globale.

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Introduction

My thesis aims to observe the effect on students' image of science of a future-oriented approach to science education. The work focuses mainly on the themes of complexity, uncertainty and future, in the context of climate change education.
The thesis is divided into four chapters.
In the first one, I outline the transformation of the epistemology of science between Newtonian mechanics and science of complexity, focusing on the impact of the transition from the traditional view, which considered complexity as an obstacle to scientific progress, to that of post-modern sciences, that regard complexity and uncertainty as intrinsic aspects of scientific knowledge.
To begin I introduce the concept of complex systems and observe the instance of the climate system. I then discuss the difficulties of climate change education, describing the context, background, and research in which my work is positioned. Afterwards I move on to the concept of uncertainty, prediction and probability, with emphasis on Bayesian probability and the Bayesian didactic approach.
The second chapter presents the field of futures studies, its developments and the framework of future oriented science education, developed by the research group in Physics Education at the Department of Physics and Astronomy of the University of Bologna.
I then present, in the third chapter, the case study which my thesis is built upon. A 20-hour course titled “Towards New Future Scenarios: The Role of Physics in the Challenges of Climate Change”, developed and conducted by the researchers Lorenzo Miani and Francesco De Zuani Cassina, during their PhD.
I outline the contents of the lessons and the timeline of the course and the multiple moments of data collection, to then present the data analysis process, a comparative, thematic analysis.
In the fourth and last chapter I present the findings of the comparative analysis.
The analysis shows that the course and the game helped students gain new awareness towards science's intrinsic complexity. Although their image of science remains rooted to the concepts of evidence and demonstration, the students appear more open to embrace a nonlinear causality.
Moreover, the interviews show that being exposed to the evidence of climate change, during the course, together with the practice of scenario building helped them mature a more constructive positioning towards the future and, simultaneously, widened their perspective towards complexity.
Lastly, it appears that, although the students' understanding of uncertainty is partial, learning about the different types of uncertainties slightly reinforced their trust in science.
To conclude I then advance ideas for improvements and future implementations.

1. Uncertainty and complexity in science

The work presented in this thesis revolves around a specific course, “Towards New Futures Scenarios: the role of physics in the challenges of climate change”, developed by a group of researchers of the Physics Education Research group of the Department of Physics and Astronomy at the University of Bologna: Dr. Lorenzo Miani, who co-supervised this work, Dr. Francesco De Zuani Cassina, Dr. Emma D’orto and Prof Olivia Levrini, supervisor of the thesis. This first chapter aims to outline the cultural landscape in which the course has been designed.
To begin, I describe notable features of modern science, with a special focus on the concept, from Newtonian theory to the present. The dissertation does not aim to show the many achievements of modern physics, nor to determine the origins of modern science’s traits, but rather offers a justification for the structure and the pillars chosen for the course.
After this description, I zoom in on the concept of uncertainty, a really important aspect of the course.

1.1. Science between determinism and complexity

Pertinent, knowledge must confront complexity. Complexus means that which is woven together. In fact there is complexity whenever the various elements [...] that compose a whole are inseparable, and there is inter-retroactive, interactive, interdependent tissue between the subject of knowledge and its context, the parts and the whole, the whole and the parts, the parts amongst themselves. Complexity is therefore the bond between unity and multiplicity.
(Edgar Morin, Seven complex lessons in education for the future)

The history of science is complex and multifaceted, it can not be described as a linear or causal process. I will therefore zoom in on the short period of time in which Newtonian mechanics became prevalent, and subsequently jump ahead to the development of science of complex systems, in order to offer a brief overview of how both the epistemology of science and the concept of prediction changed across the centuries.

In the Seventeenth Century, Newton opens a new era of western science, one that pursues the rationalization of reality and values natural science not exclusively because of its importance to the development of new technologies, but as a means to understand reality and a source of certainty (Okafor, 2013).
Newtonian mechanics offers a reductionist approach, it studies bodies in motion reduced to material points in ideal environments.
In the paradigm of classical mechanics the state of a system can therefore be described by a vector. An example is the state of a point-like particle, which is

described by a six components vector X(t), representing the three spatial coordinates and the three components of the velocity.
Thus the future state of the system at a given time t can be predicted as a function of the initial state, using the equation of motion generally of the form

$$\frac{dX}{dt} = G(X(t)) \quad \text{(eq. 1)}$$

The result of the computation will be univocal and in principle, imposing the same initial conditions and repeating the prediction, the final state will always be the same. Classical mechanics offers a deterministic perspective, regulated by direct causal connections between causes and effects and in which the concept of prediction is linear (Parisi, 1999).

With the diffusion of Newton's theory, determinism permeated Western culture and can be identified as one of the pillars of philosophical ideologies, such as Positivism, as well as the Project of Modernity. And at its core, modernity bears the promise that scientific knowledge would be the starting ground for a new, progress-oriented societal order, with full comprehension and control of nature, and thus fed the hunger for objective, causal laws which would reduce the future to a never-ending present (Scambler, 1996, Levrini et al., 2024).

One could indeed imagine that once the locations of all objects and the forces acting on them in a physical system are known, the system's future can be predicted precisely. And, according to this perspective, through an approximation of the whole universe to a physical system, history and future could theoretically be fully predicted.
At the beginning of the Nineteenth century this issue is formalized by Laplace (1825) in a rhetorical exercise, referred to as Laplace’s Demon, that poses the question of whether an hypothetical demon with complete knowledge of all the laws of nature could predict the future.
However the practice of prediction relies both on an infinite ability to compute the evolution of the system and on the ability to measure its initial state with extremely high accuracy; which respectively add elements of epistemic and ontological uncertainty to the question (Parisi, 1999; Acquistapace, 2025; Israel, 2005).

Over the course of the Eighteenth and Nineteenth centuries, therefore, many scientists start to realise how Newtonian determinism can not be easily translated from a local feature to a universal one (Oestreicher, 2007).
Laplace, for instance, in order to study phenomena which can not be described purely through classical lenses, introduces a new probabilistic approach to the study of aleatory events (Zanarini, 2025; Van Strien, 2014). He indeed argues that probability theory is necessary in all cases in which our knowledge is less than perfect, not solely when dealing with fundamental chance or randomness (Van Strien, 2014).
This new paradigm keeps evolving throughout the century. In the meanwhile, social sciences adopt statistical models to identify consistent trends in the

behaviour of big populations, which allows them to predict the future of the system even if individual actions, arguably because of free will, can not be predicted (Goldstain, 2001).
And, at the time of Boltzmann and Gibbs, the field of thermodynamics developed a new probabilistic approach to study molecular interactions. Whereas the microscopical perspective bore the problem of needing to measure the positions and velocities of billions of particles, through a probabilistic, macroscopic lens, the state of the system can be studied as a whole.
Indeed, practically all the initial conditions (at fixed total energy) lead to the same macroscopic behavior of the system (Goldstain, 2001; Parisi 1999).
Furthermore, in the second half of the Nineteenth century, scientists realize that probabilistic arguments are not only necessary to study systems with a huge number of particles (or degrees of freedom), but also chaotic systems, of any size, that are too sensitive to initial conditions. This new framework is at the core of statistical mechanics. And it still allows one to predict at least the behavior of the system, represented by its probability distribution at large times, starting from its equation of motion (Parisi, 1999).

However, in the Twentieth century, the idea that the universe can be described by simple, causal laws, is opposed by the insurgence of science of complexity, which negates the principle that "the whole is the sum of the parts” and proposes the concept of complex systems as an integrated whole that cannot be broken down into simple elements (Israel, 2005, p. 492).

Complexity and complex systems

As M. Cannata writes in her thesis (2024, p. 5), the concept of complexity is particularly difficult to define, for one G. Israel addresses the dichotomy between what is complex and what is complicated, claiming that “complicated is what presents a web of interrelations that is difficult but not impossible to reduce to simple elements; while complex is what is intrinsically impossible to reduce to a simple description” (2005, p. 480). The term itself derives from the Latin *complecti*, to grasp, comprehend, embrace and is commonly used to oppose the concept of simplicity.
However, describing a system as complex implies the idea that its components interact in nonlinear ways, and thus the system cannot be understood simply as a sum of its individual parts: science of complexity is a field of study that aims at observing exactly this whole, centring on concepts such as holism and emergence (Mitchell, 2014; Israel, 2005)

As M. Mitchell describes in an article published in 2014, science of complexity stems from a variety of research fields, such as “the Cybernetics movement of the 1940s and 50s, the General System Theory movement of the 1960s, and the more recent advent of Systems Biology, Systems Engineering, Systems Science, etc.”, which all shared the aim to find an explanation for the emergence of system-level behaviour from the interactions of lower-level components.
If Newton, and Galileo before him, considered the world to be structured on the perfect ideas of physical objects and thus aimed at discovering the

mathematical laws behind the inner workings of reality, post-modern science embraces the idea that chaos, and later complexity, is an integral part of reality and renounces the idea of natural law (Israel, 2005).

Drawing fully from E. Estrada (2023), a possible definition is that a "complex system is a system where there is a bidirectional non-separability between the identities of the parts and the identity of the whole. Thus, not only the identity of the whole is determined by the constituent parts, but also the identity of the parts are determined by the whole due to the nature of their interactions" (p. 1143). In addressing the bidirectionality of this dynamic, this definition highlights how the distinctive trait of complex systems lies in the nature of said interactions, which "must be transformers of the nature of the interacting objects and of the whole formed by them" (Estrada, 2023, p. 1155). Whereas a classical system can be described as a sum of its parts and their interactions, but does not show any emerging quality of the whole.

In not as many words, P. Anderson claims that "the whole becomes not only more than but very different from the sum of its parts" (1972, p. 395).

This property of complex systems can be observed, for instance, in the behaviour of ant colonies. An army ant, when taken individually, is behaviorally one of the least sophisticated animals imaginable. For instance, if a large number of solitary army ants are placed on a flat surface, they will walk around and around in never decreasing circles until they die of exhaustion. Yet when half a million of them are observed together, the group as a whole behaves as a hard-to-predict superorganism with sophisticated collective intelligence (Franks, 1989).

Nonlinearity is fundamental to the characterization of complex systems.

For instance the shift of causality's conception from linear to circular, makes cause-effect relationships circular loops where an effect can amplify (positive feedback) or soften (negative feedback) the cause that originally led to this effect. An example of a circular loop is the Arctic feedback: diminishing ice cover reduces albedo (the reflective capacity of a surface), which leads to increased absorption of solar energy by the ocean. This, in turn, raises the water temperature and accelerates ice melting, forming a clear example of a positive feedback loop in action.

However, few mental models incorporate feedback processes, as shown by multiple studies over the course of last eighty years (Axelrod, 1976; Dörner, 1980; Dörner, 1996; Sweeney & Sterman, 2007), which found that people tend to think in single-strand causal series and had difficulty both in conceptualizing systems with side effects and multiple causal pathways and in recognizing feedback processes. People routinely assume that positive (negative) feedback is good (bad) and have difficulty understanding that feedback can be either beneficial or harmful depending on one's values and on which way the loop is operating (Sterman, 2011). This confusion is particularly frequent regarding climate change because, in many cases, positive feedback indicates the escalation of a harmful phenomenon. An example is how the negative feedbacks of black body radiation and CO_2 fertilisation help limit warming, while positive climate-carbon cycle feedbacks worsen it (Sterman, 2011).

Furthermore, “[...] nonlinearity highlights the fact that in a complex system there is no proportionality between magnitudes of causes and effects, with a small change in one factor or parameter of the system able to lead to large changes in the system. Nonlinearity thus leads to other characteristics like high sensitivity to initial conditions, self-organisation, and emergence” (Miani et al., 2025a).

The climate system: complexity and sustainability

The increasing prevalence of poly-crisis events, such as geopolitical instabilities, forced migrations, and biodiversity loss, attributed to climate change, is redefining the relationship between science and society, as well as the relationship between humans and nature and, lastly our perspective towards future scenarios (Miani et al., 2024).
The deterministic view that is still prevalent in science education is not suited to embrace notions of complexity and uncertainty, which are however intrinsic to post modern-science and to the science of climate (Rosenberg et al., 2022; Stevenson et al., 2017)

As Miani describes in his PhD thesis (2025, p. 9)

> [...] the field of Climate Change Education has expanded rapidly in recent years (Monroe et al.,2017), driven by increased interest from students and society (Anderson, 2013; Rodrigues & Shepherd, 2022), the rising frequency of climate-related events (IPCC, 2014, 2022), and institutional pressure to promote sustainability and environmental responsibility (https://sdgs.un.org/2030agenda). There is indeed an urgent need to look for effective ways to address Climate Change in school curricula and communicate it (Andrey & Mortsch, 2000). [...] Climate Change Education “can be a strategic and meaningful entry point for promoting the principles and practice of sustainable development through education” (Mochizuki & Bryan, 2015, p. 5).

The introduction of Climate Change Education and climate literacy in schools’ curricula, however, involves several challenges, from teaching practices to social implications. The inherent complexity of climate science can cause discouragement in learners, it is therefore crucial for science communication to be effective. Also in order to prevent and address common misconceptions both of the evidence and of the role of individual action in the context of climate change. I will expand on this further in the next section (Complexity in science education). In addition, climate change is highly multidisciplinary, thus an holistic, interdisciplinary approach is essential to fully understand climate change's scientific, ecological, political, and social dimensions (Mochizuki & Bryan, 2015).

In order to implement the educational applications of climate change education, it is crucial to introduce learners to complexity and specifically to the characteristics that define complex systems.

Jacobson and colleagues (2011, p.767) propose a subset of four formal scientific concepts at the core of complex systems teaching and learning:

- ❖ Agents and Rules (i.e., the behavior of a complex system is determined by the interaction of agents or elements in a system based on particular rules)
- ❖ Feedback (i.e., positive and negative feedback mechanisms operate in many complex systems, both within and across levels of the system)
- ❖ Self-organization (i.e., order in complex systems results from the interaction of agents with each other and with the environment, rather than being imposed or ‘‘caused’’ by a central control entity)
- ❖ Emergent Properties and Levels (i.e., macro levels of a complex system often have properties that are different from the elements or agents at a micro level of the system).

Understanding these concepts, learning to recognize a diverse array of feedback and their nonlinear interactions is thus relevant in order to discuss climate change problems and policies.

Other than with science of complexity, an interdisciplinary approach to climate science needs to be intertwined with sustainability in all its aspects, considering sustainability a multi-folded concept that needs to be taught at all levels.
The framework for sustainability competences used as a reference for my thesis, as well as for the research work which my thesis stems from is the European sustainability competence framework (or GreenComp). In it sustainability is described as the act of "prioritizing the needs of all life forms and of the planet by ensuring that human activities do not exceed planetary boundaries" (Bianchi et al., 2022, p. 12), emphasizing how it is rooted in the concept of humanity’s interdependence with nature.
The GreenComp, was developed by the Joint Research Centre (JRC) of the European Commission after a long process of analysis with experts, policymakers and stakeholders to understand the most comprehensive way to talk about sustainability in the field of education. The framework follows other policy initiatives issued by the European Community in recent years, in particular, the “European Green Deal” (European Commission, 2019), the “European Skills Agenda for Sustainable Competitiveness, Social Fairness and Resilience” (European Commission, 2020a), the EU biodiversity strategy for 2030 “Bringing Nature Back into our Lives” (European Commission, 2020b), and “Achieving the European Education Area by 2025” (European Commission, 2020c). And the aim of GreenComp is helping learners develop knowledge, skills and attitudes that promote environmental sustainability (Bianchi at al., 2022; Miani, 2025).
The GreenComp identifies four competence areas, each comprising of three competences:

- ❖ Embodying sustainability values (Valuing sustainability, Supporting fairness, Promoting nature)
- ❖ Embracing complexity in sustainability (Systems thinking, Critical thinking, Problem framing)

❖ Envisioning sustainable futures (Futures literacy, Adaptability, Exploratory thinking)
❖ Acting for sustainability (Political agency, Collective action, Individual initiative)

all the twelve competences are interconnected and together support the sustainability "ecosystem" (Figure 1).

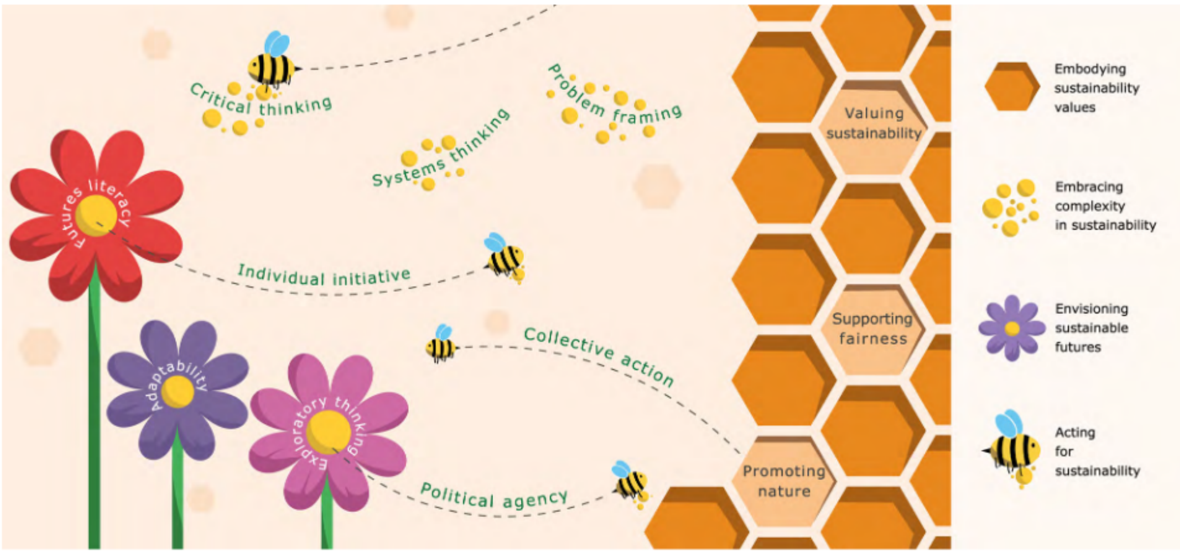

Figure 1. A visual representation of GreenComp. It builds on bee pollination as a metaphor for the framework where bees, flowers, nectar and beehives represent the four areas of the framework. As a simile of a highly-developed natural system, the metaphor highlights the interplay and dynamics between the four areas and 12 competences of GreenComp (Bianchi et al., 2022).

The exercise of personal agency and environmental sustainability requires adaptability: in the face of the complexity and the uncertainty that characterize the environment, learners are asked to reflect on the present as a series of interacting complex systems - the climate, society, the economy, to name a few - that interfere with each other's development, values and future trajectories (Bianchi et al., 2022, p. 23); a future-oriented approach to education will thus inhabit the boundary zones between multiple disciplines.

Complexity in science education

The resistance of learners to embrace the paradigm of complexity is multifaceted and deep rooted. Studies conducted on undergraduate university students who had not formally studied complexity, show that is the different understanding of complexity between experts and novices are related to epistemic and ontological ways of thinking (Jacobson, 2001; Jacobson et al. 2011) and Hmelo-Silver and colleagues (2007) documented that novices think about complex systems in terms of lower level attributes of structures, whereas experts focus on causal behaviours and functions of the system.

For instance, novices were prone to resolve problems about different types of complex systems with ontological commitments such as actions being linear, order resulting from centralized interactions, and system processes as being linear events. In contrast, complexity experts solved these problems with ontological commitments such as actions being nonlinear, order being an emergent property of decentralized interactions, and processes being in dynamic equilibrium (Jacobson et al., 2011).
Students' difficulty in understanding the behaviour of complex system models can be attributed to what Resnick and Wilensky (1998) refer to as Deterministic-Centralized-Mindset. A bias students have that compels them to assume firstly the behaviour of agents in a system to be predictable rather than random, and also order in a system to be centrally imposed by a leader or designed by a single entity, rather than a result of de-centralized interactions.
In order to understand expert perspectives about complexity, novices would need to experience a process of conceptual shift across ontological lines. Jacobson and colleagues (2011) describe it as a commitment to complexity ontologies, as opposed to implicit ontologies, in which students constructed ideas based on everyday experiences and generally reinforced in formal schooling.

1.2. The role of uncertainty: from science to climate science education

Within the classical framework of Newtonian Physics the ability to predict the future development of the state of a system is a corollary of linear causality - every phenomenon has one determinate cause - and is a pillar of determinism. With the emergence of complexity, though, the concept of prediction changes drastically.
Furthermore, a non-linear system shows high sensitivity to initial conditions, thus the smallest variation of the initial value of a variable, might alter the evolution of the whole system. This implies that in order to forecast the future of a system one would need perfect knowledge of its initial state.
What hinders prediction in this case is the measurement accuracy, an epistemic limitation (Acquistapace, 2025), however it is crucial to recognize that not all uncertainties are linked to the measuring process.

Uncertainty, in all its different forms, is an inherent aspect of science. And the way in which the field grapples with it delineates the essence of science and propels scientific progress (Kampourakis & McCain, 2020). Therefore science education should work on implementing methodologies to recognize and embrace complexity while addressing uncertainty (Miani et al., 2024).
However, in regards to uncertainty, science education still focuses mostly on concepts linked to the theory of measurement, statistics, probability or Heisenberg’s uncertainty principle (Pollard et al., 2021; Miani et al, 2025).

I will now take a step back and discuss the nature of uncertainty, presenting a categorization of scientific uncertainties suitable for climate science and then zoom in on the role of uncertainty in climate change education.
Furthermore, I will discuss the different approaches to uncertainty in science education, the traditional one and the Bayesian probabilistic approach.
The aim of this section is to show that uncertainty "is an essential component of the growing of knowledge, in the scientist's activity as well as in the science classroom activity" (Tiberghien et al., 2014, p. 934) and that it can help develop probabilistic thinking, a useful tool to inhabit and act in the present (Miani et al., 2025b).

Types of uncertainty

Although multiple different categorisations of scientific uncertainties are present in literature, I present the one described in Miani's PhD work, originated from the distinction made by Shepherd (2019) and simple enough to comprehensively map the different typologies of uncertainty present in climate change education.
Miani (2025, p. 77) distinguishes between reflexive, epistemic and aleatoric uncertainty.

> The first type of uncertainty - reflexive - is directly linked to human behaviour, due to the fact that humans have the specific characteristic of reflecting critically on their actions and changing them in the light of experience (Kahneman & Tversky, 1982). Unlike other systems, human systems are the only type of system sensible to information about the future enough to change their present behaviour, for example by using anticipatory techniques (Poli, 2017). This type of uncertainty is influenced mainly by social phenomena, like politics or the economy, and cannot be reduced. Instead, the approach used to address this particular uncertainty is related to the differences between future scenarios and the actual realisation of those predictions due to the variability of human behaviour. It can be used to create future possible or plausible scenarios differing for the type of decisions taken at the political and economic levels.
>
> The second type of uncertainty, the epistemic one (Kahneman & Tversky, 1982; see Helton & Davis, 2000, for a mathematical description of this type of uncertainty) is directly connected to the knowledge level and the scientific process itself. Indeed the word comes from "epistēmē", which means knowledge in Greek.
> As discussed earlier, even if we understand a certain phenomenon, our degree of knowledge might not be enough to fully comprehend it. Similarly, we may have a certain knowledge about a certain phenomenon, but future research or discoveries may change our level of understanding of it. In climate studies, this uncertainty is linked to our capability to understand and reproduce climate dynamics using climate models. As Shepherd (2019) notices, climate models are

“imperfect representations of reality and share many deficiencies; they may exhibit a collective bias and fail to explore important aspects of climate change” (p. 5).
Epistemic uncertainty is tied to understanding what kind of response the climate system will realise depending on possible external forcings since we don’t know how our knowledge represents the system's actual functioning.

The third type of uncertainty, the aleatoric one (Helton & Davis, 2000; Smith, 2002) from the Latin word “aleator”, dice player, is stochastic.
It is profoundly connected to the inner variability of the climate system, due to its complexity and chaotic nature (Lorenz, 1995). Climate can be described as a complex dynamic system (Dijkstra, 2013; Kirchner et al., 2021; Provenzale, 2014) due to several aspects, like nonlinearity, emergent properties, and dependence on the initial conditions.
This type of uncertainty cannot be reduced because its nature is ontologically very different from the epistemic one, but it can be quantified. In the case of climatology, aleatoric uncertainty can be quantified by taking coarser spatial and temporal averages (Shepherd, 2019) using statistical analysis methods. Even if this process can be very difficult, it can help understand what kind of climate will be experienced in the future using a frequentist approach.

Probability in science education: the Bayesian approach

Uncertainty is integral to science and scientific knowledge and can be considered the driving force of the scientific process, as it pushes scientists to continue their research to reach the ultimate goal of understanding nature and its functioning (Kampourakis & McCain, 2019).
Moreover, in the context of science education, addressing uncertainty through uncertainty-based and probabilistic thinking can help learners understand how the scientific process works, avoid adopting a fundamentalist approach and appreciate the provisional nature of scientific knowledge and its utility despite inherent limitations (Covitt & Anderson, 2022).
The Bayesian approach, also used by Shepherd (2019) and other colleagues in the Detection and Attribution research field, can support science learners to make sense of uncertainty and to build trust in science. It is based on Bayes’ theorem, a mathematical procedure useful to understand new evidence in light of prior information (Rosenberg et al., 2022, p. 1247), and which helps recognize the roles of different causes connected to scientific phenomena (Miani & Levrini, 2024).
The approach is indeed grounded in the idea that scientific knowledge is not assessed in a dichotomous correct-incorrect or true-false base, but rather considering the degrees of belief that one might express according to prior information and new evidence. Thus, it encourages viewing uncertainty

probabilistically and introduces the language of relative probability to express the degree of uncertainty in scientific knowledge.
Bayes' theorem states that at any point in time our knowledge about the world after observing new evidence, the posterior knowledge, can be obtained by multiplying our prior information, the prior knowledge, with something called a predictive updating factor (Rouder & Morey, 2019; Wagenmakers et al., 2016):

$$Posterior = Prior \times Predictive\ updating\ factor \qquad \text{(eq. 2)}$$

where the predictive updating factor holds the relation between the present knowledge of the system and the uncertainty that characterizes a future prediction.
Mathematically the theorem can be expressed as:

$$P(\theta|data) = P(\theta) \times \frac{P(data|\theta)}{P(data)} \qquad \text{(eq. 3)}$$

It shows that the prior probability, $P(\theta)$, represents the uncertainty about some knowledge θ, which can take the form of a theory, a proposition, a claim, a hypothesis or a parameter value, prior to observing the outcome. The posterior, $P(\theta|data)$, is instead the probability that said knowledge θ is correct after observing the outcome and gathering data (Cowan, 1998; Rosenberg et al., 2022).

Lastly, the predictive updating factor is the ratio between:

- $P(data|\theta)$, the likelihood of the observed outcome, under the assumption of the prior knowledge θ;
- $P(data)$, the extent to which the observed data were expected across all possible outcomes.

As a consequence, if θ predicts the data better compared to the average across all possible values, then the factor is larger than 1 and by multiplying it with the prior probability, the posterior probability increases, representing reduced uncertainty.
For instance, I will consider the application of Bayes' theorem presented by Rosenberg and colleagues (2022). They observed the proportion of Easter Hemlock trees, a tall-growing pine tree found in the Eastern USA, within a specific area that exhibit signs of infection by Hemlock Wooly Adelgid, an invasive insect that feeds on the tree (National Park Service, 2021).
An observer, who has learned to recognize the signs of infection, walking among the trees in a certain area, might guess that about half of the Eastern Hemlock trees are infected. In this case, the prior information is the relative plausibility of the different values for the proportion of affected trees.
The observer would not be surprised if the proportion of affected trees was between 30% and 70%, but, based on what they learned and observed, they would be somewhat surprised to find either no affected trees or that all the trees were affected. The background knowledge of the observer, which constitutes the prior, stems from direct and indirect experience and is

represented in Figure 2 as the dome-shaped distribution traced by the dashed line.
Now the observer starts to collect data regarding the trees in their area, and they establish that the first ten observations result in six infected trees and four not infected trees: with Y representing infected and N representing not infected, the result is {Y, Y, N, Y, N, Y, Y, N, Y, N}.
Bayes' theorem explains (Rouder & Morey, 2019; Wagenmakers et al., 2016) how this data can be used to inform the knowledge about the proportion of trees that are probably infected, with the relation:

$$Posterior = Prior \times Predictive\ updating\ factor. \qquad \text{(eq. 4)}$$

Now, if $P(data|\theta) > P(data)$, thus the predictive updating factor is larger than 1, the value of the *posterior* $p(\theta|data)$ increases. And in turn this indicates that the data have sharpened the knowledge about θ (Figure 2) and the posterior distribution is more peaked than the prior distribution. In addition, the posterior distribution is higher than the prior distribution for values of θ between approximately 0.4 and 0.75 which predicted the data relatively well and have therefore gained credibility. In contrast, values of θ lower than 0.4 and higher than 0.75 predicted the data relatively poorly, which is why they have lost credibility compared to the prior.

Furthermore, when the updating process is executed sequentially, for instance observing one tree at a time, at every stage the posterior distribution based on the observations seen so far becomes the prior distribution for incorporating the information from the following observation.
In Figure 3 the first observation is a Y, and in light of the prior, this makes the proportion of infected trees a bit higher. This slight change in knowledge is reflected in the difference between the distributions on the top two lines. The line "0" represents the dome-shaped prior distribution, and the line "1" represents the posterior distribution after the first observations. Note that observing a Y has nudged the distribution a little to the right. Crucially, the "nudged" posterior distribution after the first observation now takes the role of the prior distribution ready to be updated by our second observation. The second observation is again a Y, and line "2" shows that the resulting posterior distribution is nudged to the right once more.
Bayes' theorem thus shows that scientific knowledge about the world is subject to constant change, by making observations and integrating incoming information with current knowledge.

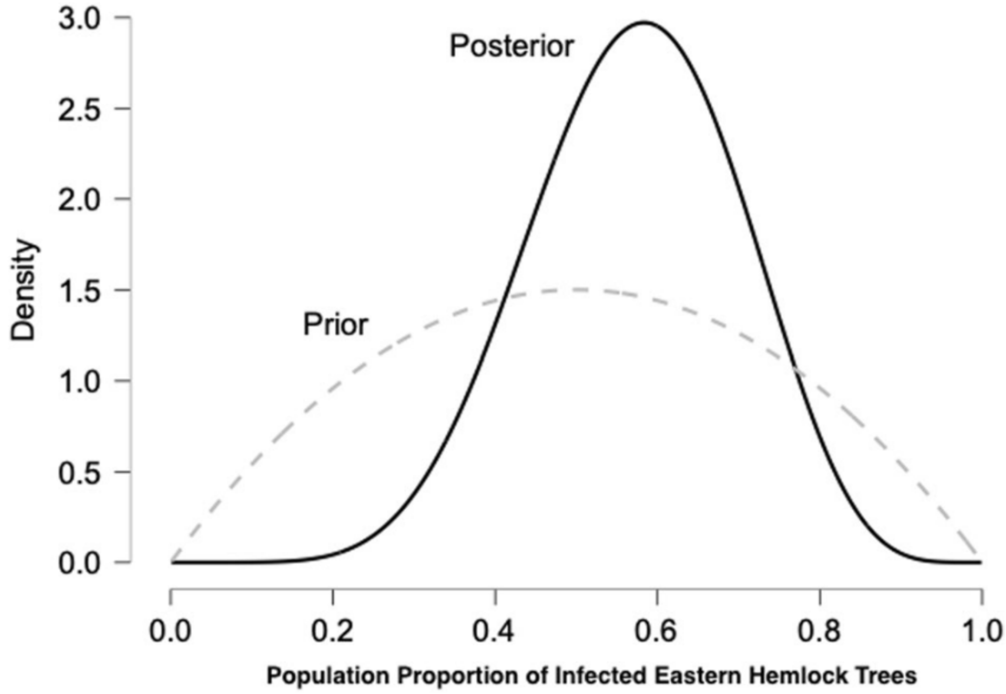

Figure 2. Example of using Bayes' theorem to update prior information in light of new evidence. (A dome-shaped prior distribution captures the background knowledge concerning the pro- portion of affected trees. Observing ten trees (six affec- ted and four not affected) drives a knowledge update that results in a bell-shaped posterior distribution. Figure based on the Learn Bayes' module in JASP.) (Rosenberg, 2022)

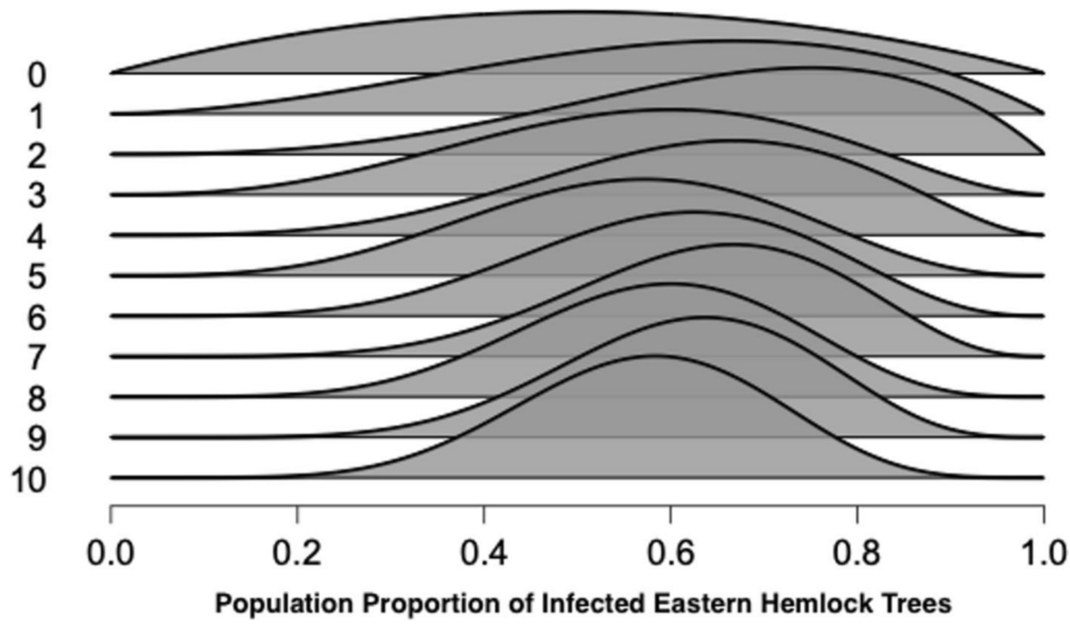

Figure 3. Example of sequentially updating what is known using Bayes' theorem. Note. A dome-shaped prior distribution (line 0) captures the background knowledge concerning the proportion of infected trees. Each new observation results in an update to a posterior distribution, which becomes the prior distribution for the analysis of the next observation. Figure based on the Learn Bayes' module in JASP. (Rosenberg, 2022)

Similarly, a Bayesian approach to science education, or Bayesian reasoning, is rooted in the idea that “scientific knowledge always comes attached with a degree of belief that can be updated following Bayes’ theorem’s rules when new evidence becomes available” and is contextual and open to revision (Rosenberg et al., 2022, p.1250).

Rosenberg and colleagues (2022, p. 1250) indicate the three main principles of Bayesian reasoning:

1. Scientific knowledge always comes with some uncertainty, and priors that denote absolute certainty (or impossibility) prevent scientific progress. And because of this, scientists should not make absolute or certain claims.
2. Scientific knowledge is not constructed in isolation but built upon earlier information and evidence, so new data should be evaluated in light of prior information.
3. Evidence should be evaluated taking into consideration the extent to which it supports the range of possible explanations for the data. This principle is referred to as the Simple Principle of Conditionalization (Adams, 1965) and highlights the importance of counterfactuals.

The exercise of Bayesian reasoning in the context of science education provides tools to address learners’ prior beliefs, before introducing new concepts, ideas, data, and to identify their relation to the claims learners make.

Cognitive science research has indeed demonstrated that one’s initial familiarity with a topic or phenomenon does impact their way of reasoning about it (Klahr & Dunbar, 1988; Masnick et al., 2007, 2017; Schwartz et al., 2007). And an uncertainty-based, probabilistic approach may aid learners to transition from their conceptual understanding of scientific knowledge to understanding data.

Furthermore a Bayesian perspective, by emphasizing the tentative nature of science, can help view uncertainty in terms of the degrees of belief that a person holds toward prior information in light of new evidence (Rosenberg et al., 2022).

2. Towards Future-Oriented Science Education

Reaction might be possible without futures thinking, but not action, because to act requires anticipation.
(W. Bell, An Overview of Futures Studies)

E. Masini claims that “thinking about the future has been a central activity of men and women since the beginning of civilization. People become human the moment they think about the future, the moment they try to plan for the future” (2006, p. 1158) and in the framework of Newtonian mechanics, science gave the illusion that the future could be knowable, through scientific and mathematical progress. However, the development of scientific knowledge brought to light both epistemological and ontological characteristics of reality that forbid trespassing the barrier between the present and the future.
Nonetheless, since the end of World War II, mankind has sought to tackle the ever-accelerating and increasingly interrelated transformations taking place and to identify the future consequences of present actions, in order to avoid being overwhelmed or taken unaware by events. The endeavor to anticipate events through scientific analysis of trends and indicators of change - the technological forecasting component of modern futures studies - developed first in the United States during and just after World War II. Soon thereafter, Bertrand de Jouvenel and others in Europe began addressing the philosophical and sociological dimensions of futures studies, stressing the importance of forecasting alternative possibilities and considering in detail the long-term consequences of current policies and actions. With time, it became apparent that foresight was important not only in order to know where one was going and how, but also to choose where one wanted to go. That is, by identifying futures that were possible and perhaps the most probable, futurists could progress to think about desirable ones (Acquistapace, 2025; Levrini & Miani, under review).

In this chapter I will start by outlining the evolution of Futures Studies through the second half of the Twentieth century, and then move on to the application of futures thinking and forecast in science education.
Lastly, I will discuss some of the tools science education borrowed from the field of Futures Studies.

2.1. The development and pillars of Futures Studies

Futures studies does not – or should not – pretend to predict "the future." It studies ideas about the future – what I usually call "images of the future" – which each individual (and group) has (often holding several conflicting images at one time)
(Dator, 1995)

As shown in the first chapter, until the Nineteenth century, the future was tied to a deterministic framework, according to which it was ontologically equal to the past and could thus be predicted and known.
However, after the scientific discoveries that occurred at the beginning of the century and especially after World War II, which emphasised the importance of planning, strategies, calculations and management of complex situations, the way of looking at the future changed (Kuosa, 2011).
The new paradigm rejected the idea of predicting the future as something that already exists, instead developing a new concept of the future as a multiplicity of possible futures that can be forecast, envisioned and invented (Kuosa, 2011).
The transition was however gradual. At first, during the 1950s, the focus was on long-range planning, trend-extapolations and technological foresight and assessment in general (Kuosa, 2011).

The key advocates of this new problem-based future research were governments, such as the US and the Soviet Union.
At the dawn of the Cold War, the US government founded many think-thanks, uniting scientists and technicians from different fields, that would develop methods and techniques for military and strategic planning. One of the most influential was the Research and Development Unit of the US Army, or RAND Corporation, which gained relevance right after the war, in 1945, and produced policy alternatives, designs, suggestions, warnings, long-range plans, predictions, and new ideas to deal with the problems of war management (Bell, 1996). The theoretical foundations of the research were primarily found in game theory and cybernetics, and the intertwined interest of researchers and policy makers in modernisation and planning spurred the development of a new approach to thinking about, forecasting and planning the future.
But post-war future research had, at its core, the aim of knowing the future in order to control the present, and saw science and policy as tools (Bell, 1996; Kuosa, 2011).

In the same fashion, Socialist countries considered future research as a crucial process preceding the formation of a socioeconomic plan, in accord with their view of the future as stochastic but only partially determined by the past, and instead a result of present action and policies. Therefore, their research was focused on the analysis of scientific and technological process and on the consequences thereof as elements of social progress (Masini, 2006).

During the same years, French political scientist Bertrand de Jouvenel, inspired by the circulating knowledge of US intellectuals, gave the futures movement an extremely important boost with his studies on power, methods of governing, and political choices. He founded the Association Internationale de Futuribles, combining the words *future* and *possible*, to highlight the central principle that many possible futures exist to think about and create. The French approach to future research, indeed, focused on the concept of alternative futures and on the idea that there are multiple possible futures and the one that will come to be is determined by human choices (Masini, 2006).

European researchers and theorists, who were much less affected by the Cold War than their American and Soviet counterparts, broadened the focus of research from military and economic issues to the spheres, for instance, of public health and the environment and on enemies such as urban sprawl, hunger, lack of education and growing alienation (Acquistapace, 2025; Bell, 1996). And, as a negative reaction to RAND Corporation's focus on military issues and related industrial goals, some futurists, such as Johan Galtung, I. Bestuzhev-Lada, de Jouvenel, Robert Jungk, and John McHale explicitly turned to peace research.

In Norway, the International Peace Research Institute was founded, and in 1967 organised the First International Future Research Conference, dedicated to peace and development. This event led to the founding of the World Futures Studies Federation in Paris, in 1973.

This wave of wider research spread through Europe and eventually reached the US, as shown by the fact that in the 70s RAND added non-military projects to its agenda developing scenario-writing, computer simulations, technological forecasting, program budgeting, cost-effectiveness and system analysis (Bell, 1996).

Moreover, the idea of the future as a multiplicity of possible futures gained popularity among the vast community of researchers and intellectuals, leading to a mutation in the ontological conception of the future that no longer became determined and singular, but plural and open, and ontologically distinct from the past.

The introduction of this new paradigm, entailed the need for new concepts and tools to talk about the future.

An example is the coinage of the broader term Futures Studies, to indicate the field of future research, in place of the term Futurology, more widespread during the first half of the century.

The use of the plural futures represented the peculiar confidence of Western research in the idea that the futures were open and could be planned and steered, as well as the positive understanding of technological progress, which was regarded as the key to build not only a possible but a desirable future (Seefried, 2014).

In Italy, a unique approach to futures studies was developed by the Club of Rome, founded in 1968 by the industrialist A. Peccei, with the aim to alert the world to what they referred to as the global problematique. It was a cluster of interrelated world problems including hunger, environmental degradation, violence, overpopulation, and increasing alienation of the working classes. At the core of the new view was a sense of fear and urgency, in the face of the global problematique, and the Club developed and proposed a holistic, global and multidisciplinary approach that then became characteristics of the field as a whole.

Even though future research acquired different traits in different regions and evolved greatly between the Fifties and the Seventies, ultimately future studies engage in perspective thinking and they try to create new, alternative images of the future, visionary explorations of the possible, systematic investigation of the probable, and moral evaluation of the preferable. And researchers in this field attempt to clarify goals and values, describe trends, explain conditions, formulate alternative future scenarios, and invent, evaluate, and select policy alternatives (Bell, 1996).

2.2. Futures-Oriented Science Education

The approach introduced by Futures Studies redefines the concept of future and future prediction. The past and the future became ontologically different because the latter can no longer be known or measured and opens into a multitude of possible futures, whereas the past is knowable and thus singular.

Moreover, "the Futures Studies approach draws upon the science of complex systems and, consistently, questions the common belief that futures are only matters of making predictions from the present towards, instead stressing futures as ways to open a fan of possibilities, whose evolution follows (in the medium and long term) the non-linear dynamics of complex systems" as observed by Levrini et al. (2019, p. 2654).

This plurality introduces an aspect of unpredictability, since science can not provide accurate predictions, and the need instead is to imagine the future in a creative, active manner.

As a corollary of the new perspective on future research, new terms and tools are needed. In regard to future projection, three main approaches emerge: forecasting, foresight and anticipation (Poli, 2017).

Forecast (in Italian *previsione*) is defined as the attempt to determine future trends from the present state of a system. It is predictive and data-based and is used predominantly in meteorology and economics.

Whereas the words *Foresight* and *Anticipation* indicate the ability to build a vision by detaching from the current situation, for instance, imagining a desirable future and, in light of it, evaluating present actions, trends and their future consequences (Acquistapace, 2025, p. 27; Levrini et al., 2019, p. 2654).

Both are non-predictive, and rely on scenario building and back-casting, proceeding backwards from the desired outcome and attempting to trace actions and decisions in the present that may lead to the chosen scenario.

Anticipation can be considered as the emphasis on transforming foresight into action through decisions, thus it is an important tool in education, to develop learners' future agency (Miani, 2025, p. 17; Poli, 2017).

Moreover, when the idea of a series of possible futures is introduced, even the concept of a linear timeline is found lacking; within this possibility perspective, indeed, multiple kinds of futures can be imagined: possible, plausible, probable and preferable. The relationship between them is often represented with a "future cone" (Hancock & Bezold, 1994), elaborated by Voros (2003) (Figure 4).

The cone shows how the wide variety of possible futures, the largest range, comprises plausible futures, with a higher likelihood to happen based on present knowledge, as well as unplausible ones. Furthermore a subclass of plausible futures is that of probable futures, determined as a continuation of present trends. This distinctions are based on informational of cognitive knowledge but, as I previously argued, the subsidence of determinism led to the development of an imaginative and creative trait of futures research, preferable (or desirable) future scenarios can indeed depend, with high sensitivity, on contingencies or unexpected choices and compel individuals to develop foresight, reflect on their desires, values, competences and cultural point of view.
In order to develop future agency, "it is socially, economically and personally important to develop skills for thinking about possibilities and ways to realise possible futures rather than predicting exactly what will happen" as Levrini et al. (2019, p. 2654) observe.

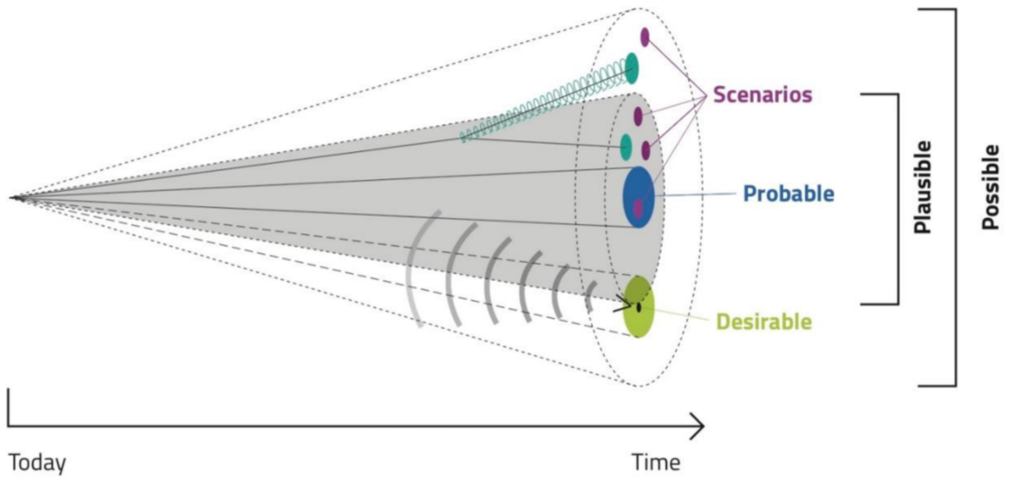

Figure 4. The futures cone of the Erasmus+ project I SEE 'Inclusive STEM Education to Enhance the capacity to aspire and to imagine future careers' (The I SEE project (https://iseeproject.eu)) (re-elaboration from the Voros' cone – Voros, 2003).

Another important tool of Futures Studies is scenarios. Voros' cone highlights how each scenario is a coherent, internally consistent and plausible description of a possible future state of the world: all the scenarios are possible, none is certain (Levrini et al., 2019, p. 2650).
This is one of the reasons why a science education that is Futures-Oriented can prepare citizens to deal with uncertainty and probability, practise creativity and take agency, offering them a deeper understanding of the role of science and scientists.

Future-Oriented Science Education

Future-Oriented Science Education, or FOSE (Levrini et al., 2019, 2021; Laherto et al., 2023; Rasa, 2024; Rasa & Laherto, 2022), is a model that focuses on the role of the future in science. Although the role of futures literacy occupies a central role in the discussion regarding science education, this approach considers the future not only as a topic but as a core concept that shapes many aspects of the relationships we have with science and our society (Miani, 2025).

The FOSE model has been developed inside the European Union funded projects I SEE (2016-2019, https://iseeproject.eu/) and FEDORA (2019-2022, https://www.fedora-project.eu/), both led by the research group in Physics Education of the University of Bologna and participated in by other partners in Europe.

The ISEE project, was founded in 2016 in the context of the EU ERASMUS+ KA2 programme, and stems from the collaboration between eight partners: three secondary schools, two universities, an environmental NGO, a teachers' association and a private foundation from Finland, Iceland, Italy and the United Kingdom (Levrini et al., 2021, p. 8).

I SEE stands for Inclusive STEM Education to Enhance the capacity to aspire and imagine future careers. And the aim of the project was to address the issue in science education posed by global unsustainability and future uncertainty, designing innovative approaches and teaching modules, in order to foster students' identities as global citizens, while also developing professional skills through science education in and out of the school.

The I SEE modules focus on so-called future-scaffolding skills, or "the ability to construct visions of the future that empower action in the present with an eye on the horizon" (I SEE, 2016-2019, https://iseeproject.eu/), with the aim to make STEM education personally, socially and professionally more relevant for the future of younger generations.

FEDORA is instead a EU-founded project, which ran between 2020 and 2023 and gathered six partner institutions from five European countries.

FEDORA stands for Future-oriented Science Education to enhance Responsibility and Engagement in the society of acceleration and uncertainty (FEDORA, 2020-2023, https://www.fedora-project.eu/). The project conducted research and practice towards the regeneration of the ecosystem of science learning, by developing a future-oriented model to enable creative thinking, foresight and active hope, as skills needed in formal and informal science education.

The core of FEDORA is the belief that in today's fast-paced, changing world science education should adopt new open, collaborative, imaginative and curious approaches. Three main aspects of education that appear outdated are:

- the dissonance between the hyper-specialized organization of science teaching and the inter-multi-transdisciplinary character of innovation;
- the a-temporal character of teaching approaches, which should instead help learners develop future agency;
- the use of formalized and exclusive languages in schools that are inadequate to talk about complex and inter-multi-transdisciplinary challenges.

The project produced many relevant documents that oriented the research field, and a manifesto to regenerate science education (Levrini et al., 2021; Miani, 2025).

Furthermore, the European Union co-founded the FEDORA Academy, a network of schools, researchers, teacher educators, and communities across Europe working together to reimagine teacher education from the ground up, supporting educators in co-creating new approaches to teaching and learning
The Academy builds directly on the insights, methods, and findings of previous European projects and recognises that a regenerative approach to education is needed, one that is collaborative, contextual, and capable of responding to complexity (The FEDORAS Teacher Academy, https://www.fedoras-academy.eu/).
All these projects, and more, focus on the futurization of science education with the goal of “integrating problem-solving and critical thinking into science education to effectively tackle future uncertainties, including environmental challenges” (Miani, 2025, p. 20) and provide the foundation for the development of the FOSE model.
Typically, in future-oriented science pedagogies, learners are asked to imagine and examine various scenarios about possible, plausible, and preferable futures, to develop agency and detect otherwise unforeseen risks, especially regarding scientific and technological progress.
In the context of risk society, climate change is undoubtedly the greatest threat, because of its extensiveness and potential consequences; thus future-oriented approaches to science education often face concerns, fears and hopes related to sustainability issues.
While there are multiple pedagogies that incorporate the GreenComp framework, by focusing on one of the competence areas, at the core of FOSE is the idea that “science education could find more coherent approaches to sustainability education by interconnecting all four GreenComp areas” (Laherto et al., 2023, p. 93), reinforcing the claim that the future is inherently complex, and sustainability issues can not be solved simply through scientific innovation, but require systemic change, trade-offs and compromises across multiple fields.
This approach to education integrates and enhances future imagination, values and complexity, and the concept of a future that is built by present decision making facilitates acting for sustainability.
Thus FOSE, through developing desirable scenarios and the practice of backcasting, fosters individual and social agency (Laherto et al., 2023; Miani, 2025).

3. Case study: Towards New Future Scenarios: The role of Physics in dealing with the challenges of Climate Change

My thesis is grounded in the research work conducted by the research group in Physics Education at the University of Bologna through the European projects I SEE, IDENTITIES, FEDORA, CLIMADEMY, and FEDORAS, together with the national project Piano Lauree Scientifiche PLS. In this frame, my thesis looked closely at the work conducted by the researchers Lorenzo Miani and Francesco De Zuani Cassina, which during their PhD developed a 20-hour course titled "Towards New Future Scenarios: The Role of Physics in the Challenges of Climate Change" (https://pls.unibo.it/editions/498), organised in seven lectures for secondary school students as part of the PCTO activities. The course has been fully implemented two times, between October and November 2023 with 34 students and between November and December 2024 with another 33 students. A third edition of the course is currently undergoing. The second edition of the course saw the participation of the two main authors, Lorenzo and Francesco, together with their colleague Emma D'Orto.

The course has been offered as part of the "Piano Lauree Scientifiche" (Scientific Degrees Plan) (PLS), a project started in 2004 following the initiative of different organisations, the Italian Minister for Education, University and Research (MIUR), the Conference of Science and Technology Deans and Confindustria, an organisation representing companies producing goods and/or services in Italy (Miani, 2025).

The course has been designed, in accord with the core ideas of the PLS, with the goal to introduce students and teachers to scientific disciplines, through innovative tools and methodologies. The four main aims of the course are:

1. exploring the different types of uncertainties addressed in international reports on climate change, such as the Intergovernmental Panel on Climate Change, IPCC;
2. recognizing uncertainties in science, as well as their root sources, with particular focus on physics and in the context of climate change so called "wicked problems";
3. developing future thinking skills to reflect on the differences between possible, probable and desirable future scenarios, along with concepts such as backcasting and anticipation;
4. discussing the impact that both individual and collective actions have on the climate, analysing future scenarios as regards the social, economical and political contexts.

In this chapter I will begin by outlining the contents of the lessons and the timeline of the course and the multiple moments of data collection, such as questionnaires and interviews. I will then analyse the data.

3.1. Structure and contents of the course

The course, led by Dr. De Zuani Cassina, Dr. D'Orto and Dr. Miani, was organized in seven lectures. During the first one, titled "Introduzione al corso e alle incertezze in fisica" (Introduction to the course and to uncertainties in physics), Dr. De Zuani Cassina presented the three different types of uncertainties associated with physics.
In the first part of the lesson he introduced students to epistemic uncertainty, describing the deterministic perspective of classical physics and the Laplace demon.
After the discussion on the Laplace Demon, Francesco used the kinetic theory of gases to discuss an example of how the deterministic paradigm can be used in some cases to explain the behaviour of specific systems, although through a high level of modelling.
He then proceeded to introduce ontological uncertainty, which depends on the nature of the system itself. An example of ontological uncertainty is present in quantum physics, in the form of the Uncertainty principle, which discusses the ontological impossibility of knowing the exact value of non-commutable observables (such as the spin on two different dimensions) regardless of our capability of measuring.
Moreover, Francesco presented some basic aspects of the physics of complex systems, such as non-linear relations between the system elements, emerging properties, positive and negative feedback, in order to introduce the concept of aleatoric uncertainty. He used the double pendulum, as a simple example of the difficulty of making predictions when dealing with systems that are highly sensitive to initial conditions and dynamic behaviour.

The second lecture, titled "La storia dei cambiamenti climatici e il ruolo della climatologia" (History of climate change and the role of climatology) opened with an introduction to the field of climatology and the history of research on climate change by Paolo Ruggieri, a climatologist at the Department of Physics and Astronomy of the University of Bologna.
His lecture focused on four main aspects:

- ➢ Climate and the science of climate;
- ➢ Predicting the future climate;
- ➢ Uncertainty;
- ➢ Adaptation and mitigation.

Paolo Ruggeri started by presenting methods used to gather present and past climate-related data. He then moved on to define the differences between weather and climate and the development of climate studies, addressing for instance the Charney report (1979), the first official assessment of the effect of CO_2 on our atmosphere, and the first report of the IPCC (IPCC, 1992).
The IPCC (Intergovernmental Panel on Climate Change) is the United Nations body created to provide policymakers with regular scientific assessments on climate change, its implications and potential future risks, as well as to put forward adaptation and mitigation options.

The lecture then focused on the necessity of modelling in climate science and the difficulties connected to this practice (epistemic uncertainty), opening to the concepts of chaos and chance (aleatoric uncertainty) and the uncertainty connected to future climate forcing (reflexive uncertainty).
In the last part of the lecture, Paolo Ruggieri discussed the state of the art in climate change predictions and presented the concepts of adaptation and mitigation.

The third lecture of the course, titled "L'incertezza dei Cambiamenti Climatici e i future studies" (The uncertainty of climate change and future studies), revisited the discussion regarding uncertainties, focusing on the specific types of uncertainty connected to climate change.

Lorenzo discussed feedback mechanisms and presented the Arctic feedback, an example of positive feedback I described in a previous section Complexity and Complex systems). He then introduced the three types of uncertainties addressed in the context of climate change: aleatoric, epistemic and reflexive uncertainty, which I discussed at length in chapter 1.2 and he showed how each type derives from different aspects of the issue and, therefore, must be treated differently (Figure 5). The discussion on reflexive uncertainty served as an entry point to explore several aspects involved in climate change, such as the concept of risk connected to extreme events and the need to make decisions about adaptation and mitigation measures.

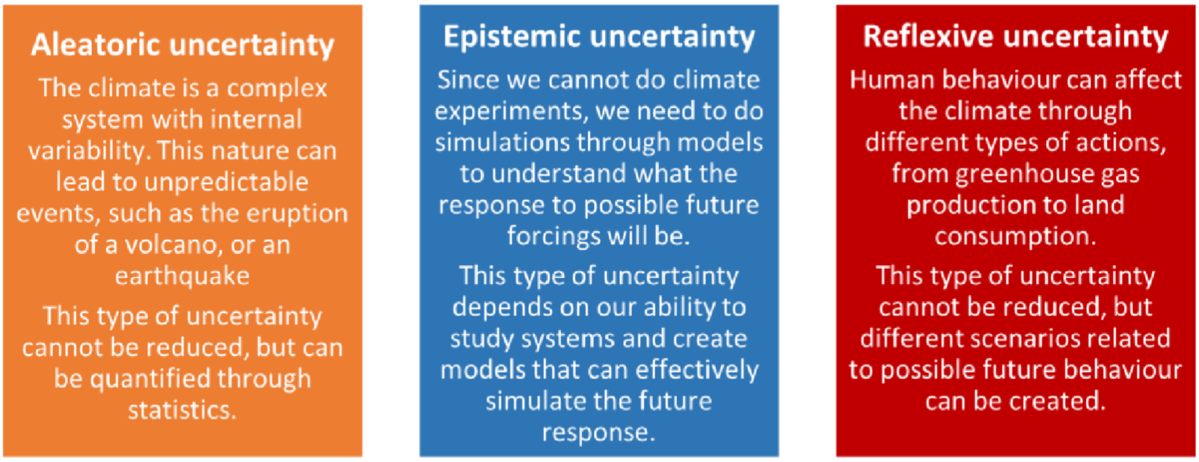

Figure 5. Different types of uncertainty connected to climate change, as described in Shepherd (2019) (Miani, 2025).

In the second part of the lecture, Lorenzo presented the field of futures studies, their origin, methods and aims. He began by defining the different ways in which the future has been addressed in general literature, referencing the concepts of utopia, dystopia and uchronia, and then he focused on future positioning and introduced the future cone.
Lastly, Lorenzo addressed the consensus-building process of climate change knowledge, and its role in policymaking, zooming in on the history of the IPCC

and on the process leading to the creation of an annual summary for policymakers (SPM).
During the fourth lecture, titled “Decision making e costruzione di scenari” (Decision making and scenario building), Lorenzo and Francesco joined by Micol Todesco, the director of the Bologna section of the Italian National Institute of Geophysics and Volcanology (INGV), and her colleague Barbara Lolli. They led an activity connected to risk management in case of extreme events, named “explosive uncertainty”, aimed at simulating the process of deciding when it is necessary to evacuate the population following specific warnings such as seismic tremors or symptoms of future volcanic eruptions. This activity addressed the inner uncertainty of complex phenomena and highlighted its role in decision making.
The remainder of the lecture focused on the concept of scenario and introduced the five narratives produced by the IPCC to describe the Shared Socio-Economic Pathways (O’Neill et al., 2017) and the idea behind what can be considered a sustainable future.

The so-called Socioeconomic Pathways are a set of possible paths, which describe different future evolutions of society (O’Neill et al., 2014, 2017).

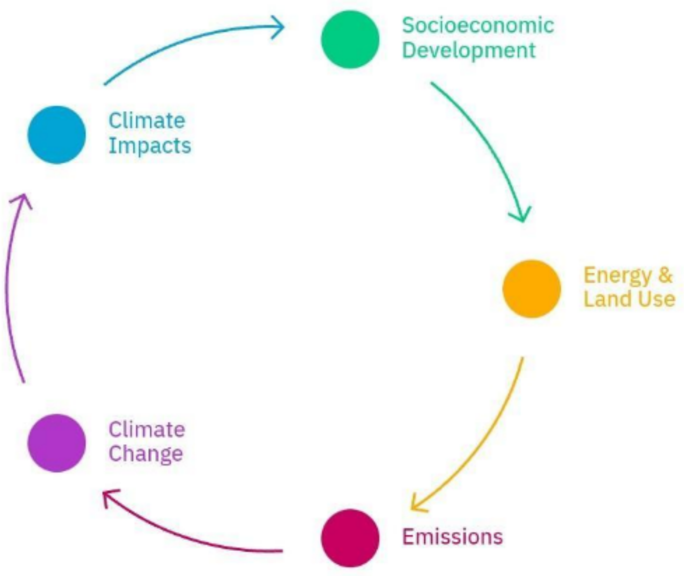

Fig. 6 Different types of scenarios developed by climate scientists to explore possible futures. The five types pertain to: Socioeconomic Development, Energy and Land Use, Emissions, Climate Change, Climate Impacts.

FyouTURES: how to build a sustainable future

In the fifth lecture, titled “F*you*TURES: come costruire un futuro sostenibile” (FyouTURES: how to build a sustainable future), the students were introduced to the board game F*you*TURES, created by Francesco and Lorenzo during the first implementation of the course.

As described by Miani and colleagues (2025), F*you*TURES is an educational tool designed to make students adopt a systemic perspective (Evagorou et al., 2009; Jacobson & Wilensky, 2006) on complex issues such as producing a climate scenario considering different variables at the same time and negotiating decisions with different stakeholders. I will now refer to F*you*TURES with the term 'game'; in the game, players (in this particular case the students) take the role of decision-makers forming a "government council", with the aim of making decisions to reach climate-related goals, such as decreasing sea-level rise and limiting global warming, by 2100 (De Zuani et al., 2024).

To make decisions, students were asked to use the simulator En-ROADS, delivered by MIT and Climate Interactive (https://en-roads.climateinteractive.org/scenario.html?v=24.7.0). En-ROADS is a system dynamics model which exploits several datasets as input information and by integrating (up to 2100) a diverse set of differential equations it produces future scenarios. The user can create by themselves the projections by acting on the available sliders, which represent possible actions such as the increase in carbon price and energy sources taxation or the increase of deforestation. This will show quantitatively the impact of such actions with respect to global temperature warming, sea-level rise and many other indicators. All the mechanisms are ruled by a non-linear and complex causal aggregated model created by the developers, in which specific assumptions have been made to make it usable, like for example the homogenisation of all the regions. This technique makes it harder to understand what happens at the local level, but gives a clear idea of the bigger trends connected to macrovariables. Furthermore, the simulator is constantly updated, both in the available sliders and in their calibration and settings options (Figure 7).

The game (Figure 8) is structured into three rounds, corresponding to three years (2030, 2050, 2100). Each player is responsible for one of the six areas of intervention (green areas, emission control, green energies, conventional energy sources, energy efficiency, and electrification) according to the sliders of the En-ROADS simulator.

For each area, players choose through investment and taxation opportunities for each round, and apply those decisions by moving the sliders in the simulation to reach the desired consequences. The final scenarios are therefore shaped according to each slider's final level and consequences. The game board is composed of four main parts: a description of the areas of intervention, directly taken from the En-ROADS simulator; a space for placing the wildcards, to be drawn in each round; a grid to represent the budget of each group; a big multi-sector circle, representing a big ensemble of futures cones, where players can visualise their choices by drawing lines connecting different points for each round.

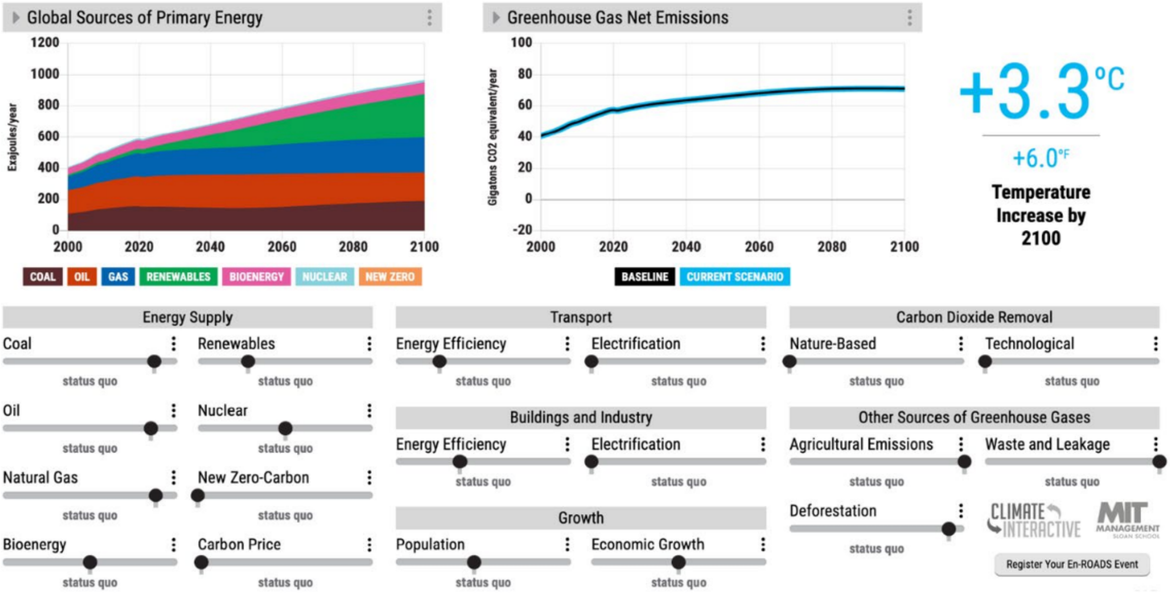

Figure 7. A snapshot of the En-ROADS simulator (https://en-roads.climateinteractive.org/scenario.html?v=24.7.0)

To introduce the need to deal with uncertainties, as discussed in the course, the teams that partook in the first implementation created a set of wildcards for the game, to be drawn at the beginning of each round (3 wildcards for each round). The wildcards (Figure 9) act as proxies for reality in scenario-building processes, are equally balanced in number between epistemic, aleatoric and reflexive uncertainties (Dessai & Hulme, 2004; Shepherd, 2019) and represent a plausible event that has practical consequences in the game. It is noteworthy to mention that only a few examples of wildcards were suggested before playing the game, and during the first implementation of the course students were asked to create others in the same style.

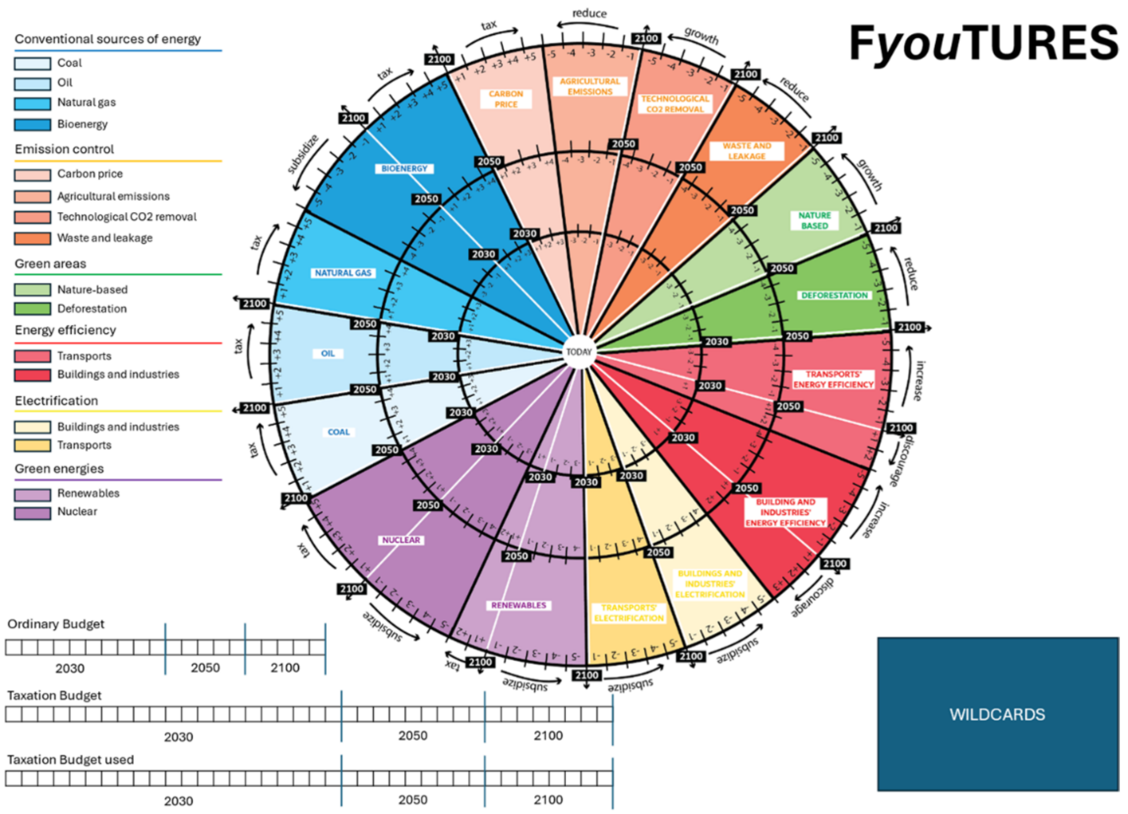

Figure 8. The game board used in the implementation. It comprises the list of areas and sliders, a space for wildcards, a grid for keeping track of the budget and a panel for keeping track of the changes for each sector (tesi o articolo) (Miani et al., 2025b)

Their creations were shared with the class, and some were collectively selected to be included in the official wildcards set. The full list of cards and game rules are available at https://zenodo.org/records/13820082.

Lastly, over the course of the sixth lecture, titled "Narrare il cambiamento climatico" (Narrating climate change), each group was asked to describe their gameplay from the previous lesson. They had to write down a report of the state of the world in 2100, according to the projection created by En-ROADS and to imagine the future scenario they had developed.

IT'S WAR	FLOOD	EUREKA!
Extreme political event: a war breaks out with a neighbouring country. Energy costs increase significantly, capital is strongly redirected towards the military industry and armaments in general. No technological development actions can be taken for a round, you are forced to reduce taxes on fossil fuels because gas pipelines are cut, and power plants bombed. You must spend 4 coins to reduce 4 notches in total on conventional energies.	Extreme weather event: a sharp increase in rains causes numerous rivers in the surrounding areas to overflow, leading to extensive damage to structures and a consequent expenditure of funds for repairs. You have 4 fewer coins to spend on the next turn because you will have fewer funds available.	Cold fusion is finally achieved: energy costs drop significantly and technological development accelerates. Thus, from now on in the game energy efficiency actions can be done at half the cost (2 notches cost only 1 coin).
GO VEGAN	YOU? AGAIN?	I-HELP
Awareness of the need for a different diet increases extensively: there are fewer livestock farms and more crops, and the net balance results in a reduction of methane gas produced. Thus, 2 notches can be scaled down without spending coins on the methane slider, corresponding to a decrease in methane emissions from livestock farming. 1 notch corresponds to -20%.	A pandemic breaks out. People, unable to leave their homes, cause damage to the economy, generating a crisis. Reduce economic growth by 4 notches. Modify the sub-variables (opening the dropdown menu) of consumption by 10% in oil, coal, and natural gas use. A side effect of the pandemic increases ecosystem well-being: the "Afforestation and Reforestation" sector is increased by 1 notch for free.	Artificial intelligence escapes human control and takes over the codes of nuclear warheads, deactivating them forever. Wars decrease, trade increases and the prices of many goods decrease. You have 5 more coins to spend in your budget.

Figure 9. A selection of two wildcards for each uncertainty embedded in the climate change discourse: aleatoric uncertainty (red), reflexive uncertainty (blue), and epistemic uncertainty (green) (Miani, 2025).

In the seventh and last lecture, students were asked to present the scenarios they had created while playing. Each group presented their work using the screens of the simulator through the rounds and described the type of world they ended up building. Each group was then asked about their play, the group dynamics, their main strategies, and their thoughts on the final scenarios.

3.2. Data collection process

Throughout the course diverse types of data were collected, in the form of two questionnaires, one at the beginning of the first lecture and one during the last one, recordings and gameplay group reports.
At the end of the course, Lorenzo, Francesco and I used the data collected to design a semi-structured interview.
Figure 10 shows the overall timeline of the course and of the data collection process.

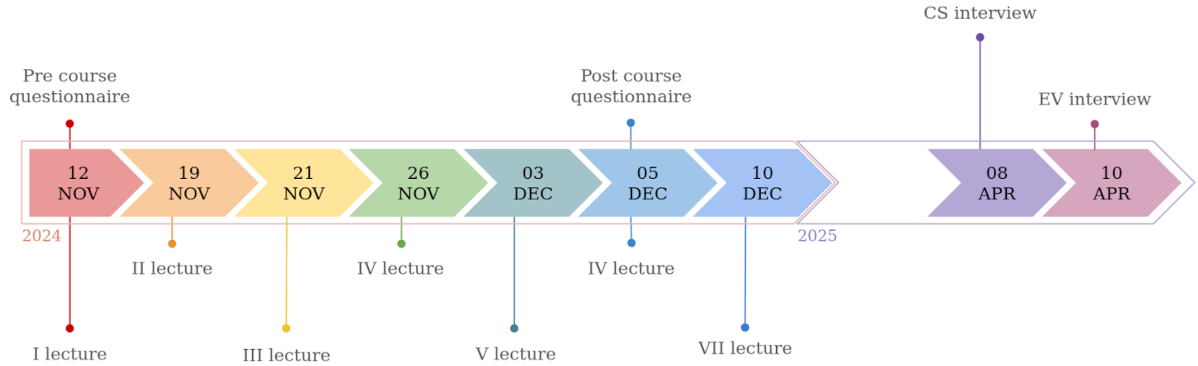

Figure 10. Timeline of the course and the data collection process (created with Google Slides).

The different phases of data collection include:

- ➔ Questionnaires on sustainability competences, future scenarios, and the students image of science, administered as a pre/post survey.
- ➔ Recordings: all the lectures, the gameplay of each group and the final discussion were all recorded.
- ➔ Reports: during the game, each group of students was asked to write a report of the evolution of their scenarios for every round (including a screen of the En-ROADS situation in 2030, 2050, and 2100), describing the wild cards drawn, recounting the decisions made, describing in which area the budget was spent, and specifying the rationale behind each choice. The team asked to give a quantitative description as well as a possible qualitative description of the world they were creating.
- ➔ Interviews: four months after the end of the course, in April 2025, the students were offered to take part in a follow-up interview that spanned through the different themes discussed in class.

Similarly to the first implementation, the recordings and the reports proved to be very useful to keep track of the students' work and their approach to the game, and served as the basis for a final discussion and comparison among all groups that took place over the course of the last lecture.
When it comes to the interviews, in this implementation only two of the students agreed to partake in the follow-up, whereas in the previous implementation a total of nine students were interviewed.
Because of the limited number of surveyees, I opted for a comparative approach rather than the qualitative approach previously used.

We designed each interview according to the answers given by the student in the questionnaires and their eventual intervention recorded during the lessons and the gameplay. Our aim was to explore the effects of the course on their positioning in regards to science and climate change, focusing on their idea of physics, their sense of agency and hope towards the future and their level of understanding of uncertainties in science before and after the course.
Each interview was structured in seven sections:

1. Warm up
2. Your perception of climate change
3. Future and sustainability
4. Uncertainty and decision making
5. Uncertainty in regards with the game
6. Scenario building
7. Identity

The full script of the interview can be found in the Appendix. In this implementation we chose to include, in section 4. and 5., multiple questions regarding uncertainty due to it being the main focus of my thesis.

For instance, the previous implementation included questions 4.1. and 4.2., but we added the follow up questions 4.2.a and 4.2.b. to address the students positioning towards the different types of uncertainties.

4.1. If you were to describe the differences between the three types of uncertainties in climate change, what would be the main characteristics you'd use to describe them?

4.2. What kind of vision of the scientific world emerges? How do the contents covered in the course—particularly the uncertainties—relate to your way of seeing science?

   a. Prompt: Did one or more types of uncertainty studied (or the differentiation among them) generate a tension or dissonance in your way of seeing science?
   b. Did these uncertainties challenge what you think about science?

Moreover, we added question 5.2.a. and 5.2.b. to inquire about the effect of uncertainties on their decision making.

5.2. In your opinion, what form of scientific knowledge and what way of doing science can help in making informed decisions and managing complexity?

   a. If so, does the presence of uncertainty in the data undermine the decision-making process?
   b. How would you approach the decision-making process in such a case?

Lastly, at the end of each interview we asked the student to reflect on their positioning towards the future through Polak's game. The latter consists in determining one's stance according to the board in Figure 11, which shows individual expectations on the vertical axis, spanning from an optimistic to a pessimistic view, and individual influence on the horizontal axis, spanning from the belief that one can influence the future to its negation (Hayward & Candy, 2017).

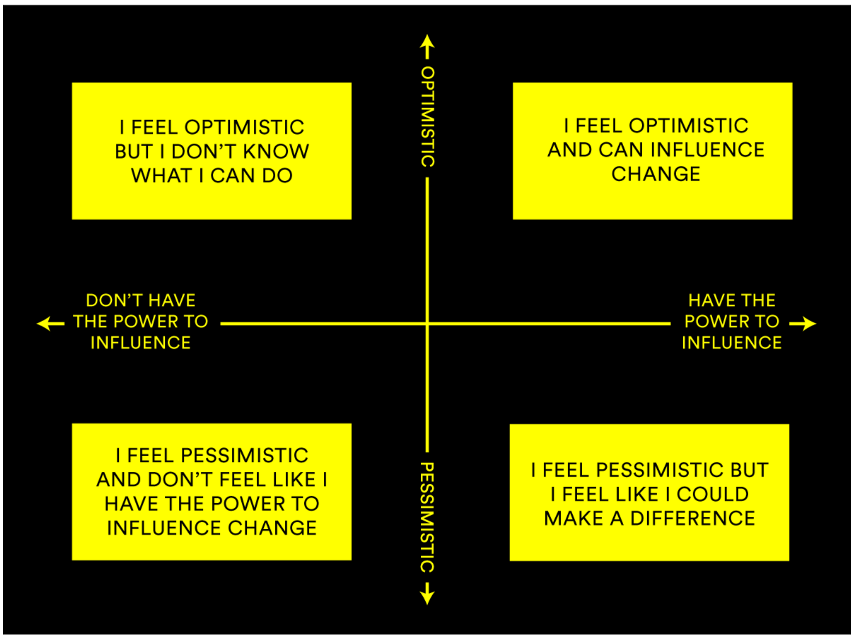

Figure 11. Polak Orientations matrix.

3.3. The data analysis process

Now that I presented an overview of the course and the data collection process in Chapter 3, I will proceed going over the research conducted to write this thesis. This chapter is divided into three main sections. To begin I will give a birdseye view of the approach used by Francesco and Lorenzo to analyze the data of the first implementation of the course. Subsequently, I'll move on the approach I chose, influenced both by the fewer number of interviewees and the research focus of my thesis.
In the third section I will then discuss the outcome of the data analysis.

Methodology of analysis and results of the first implementation

In order to analyse the data collected during the first implementation of the course, because of the nature of the data and the aim of the research, the team chose a qualitative approach. First, following the thematic analysis approach (Braun & Clarke, 2006; 2012), they identified the general themes from their conversations with students during the course and from the questionnaires. The themes were then refined and defined through triangulation in order to transform them into operational codes for use in NVivo, producing the following list of themes and sub-themes:

1. Image of science and climate change
    a. Naïve vision of science and climate change's inner complexities
    b. Awareness of the complexity of science and climate change
2. Sustainability dimensions

    a. Naïve approach to sustainability
    b. Balance between sustainability's dimensions
3. Decision making and the relation between science and politics
    a. Ingenuity about the science-politics link (mistrust)
    b. Awareness of the complexity of the decision-making process
4. Agency and reality shock
    a. Personal agency
    b. Collective agency
    c. Political agency
    d. Lack of agency

The nine interviews were then coded using a top-down approach, independently by the first two authors in a double-blind process. The references for each code of the two analysers were then discussed (Morrissey et al., 1974) until a final and full codification agreement was reached. Francesco and Lorenzo decided to create a "spectral representation" from each of the nine interviews, in order to create a representation that simultaneously pictures the ratio of each theme for each interview, and the phase of emergence for each theme, as visible in Figure 12. They associated every entry from each speaker (either interviewers or interviewees) with a column and used four different colors to highlight the entries that have been coded during the analysis phase (Miani et al., 2025).

The findings of the study show that "the game enhanced students' awareness of the complexities in policy negotiation [...]. This awareness fostered the development of a more nuanced, conscious and multidimensional attitude in students toward climate change. At the same time, it demonstrated how, for some individuals, exposure to the complexities of climate change decision-making can result in a sense of hopelessness that must be addressed to encourage a willingness to act for a better future" (Miani et al., 2025, p. 873).

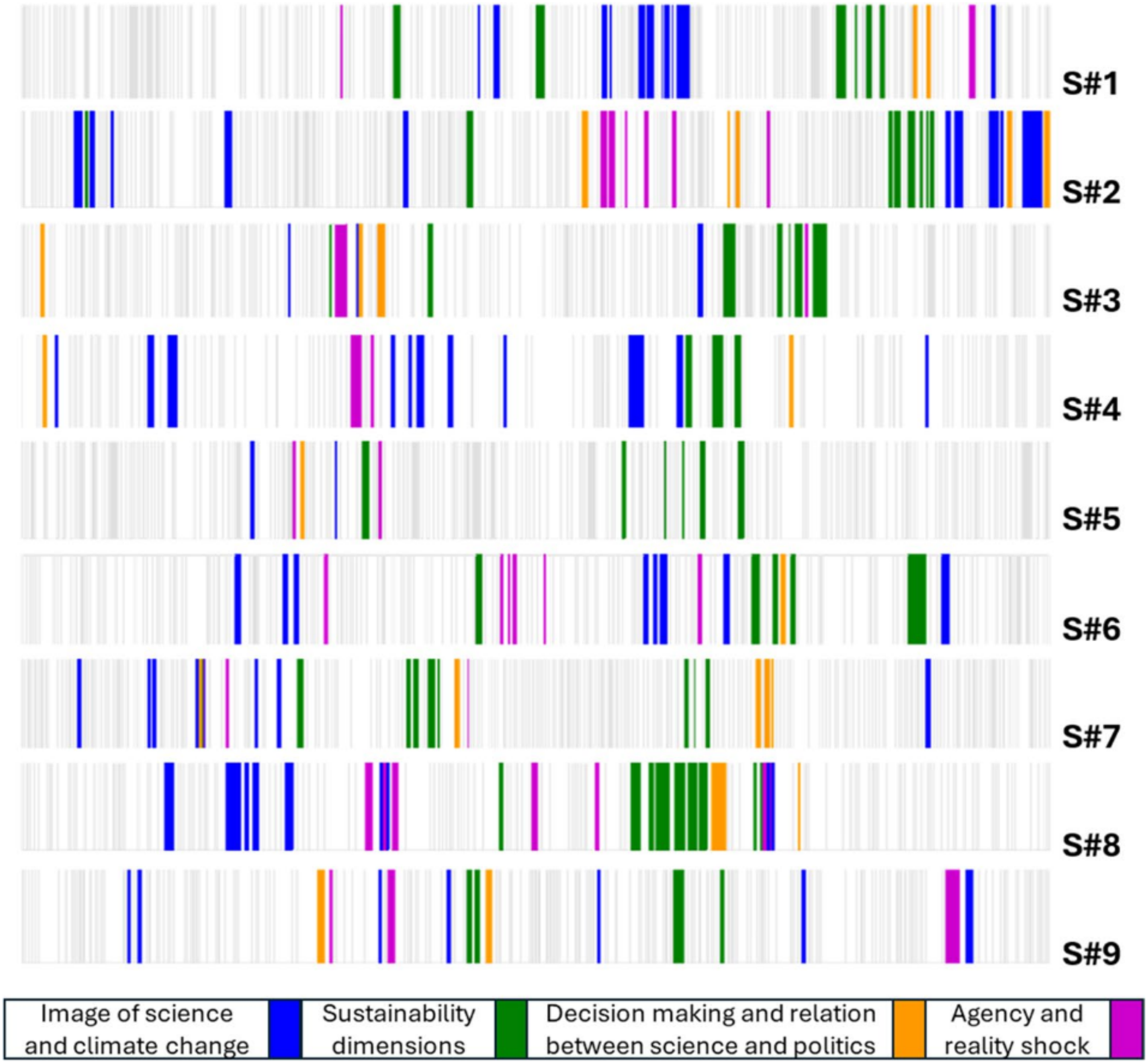

Figure 12. Spectra of the interviews. The coloured columns are the lines that have been coded to the four main dimensions (image of science and climate change, sustainability dimensions, decision making and relation between science and politics, agency and reality shock) (Miani et al., 2025a)

Methodology of analysis of the second implementation

To analyse the data collected during the interviews I used a qualitative approach. The process is divided into three steps:

- Revision and first examination of the interviews' transcripts.
- Coding and translation of selected excerpts.
- Comparison of the two interviews section by section.

To begin I edited the transcriptions, generated using the software NVivo, to correct misspellings and eventual mistakes. I started highlighting the parts of our discussion that showed the interviewee's positioning towards each theme and then proceeded with a mostly inductive thematic analysis (Braun & Clarke, 2012). The themes set the chronological structure of the conversation, but we conducted semi-structured interviews, in order to let the conversation flow and grasp what had interested each student the most during the course, therefore the discussion did not strictly follow the scripted questions.
To observe the effect on students' image of science and perception of complexity, uncertainty and future of a future-oriented approach to science education, I selected the excerpts that expressed the students' perception of these themes both pre and post course, conducting a more detailed analysis of the material. Also, following the analysis conducted in the similar set of data from the year before, I looked for patterns of meaning between the highlighted sections. This helped me refine the themes and transform them into operational codes:

- Core values of science and personal positioning
- Images of sustainability
- Uncertainty-Certainty tension

In order to quote the excerpts I translated them from Italian, in which the interviews were conducted, to English. To maintain the students' anonymity, I use the code S#1 and S#2 to quote them, whereas I will use the code FDZ, LM and MAZ to quote Francesco De Zuani, Lorenzo Miani and myself respectively.
Before entering into the presentation of the themes, I present a portrait of the two profiles according to the info shared during the interviews, so as to introduce them and better collocate their answers.

Portraits of the students

The two students are both 18 years old, attending their senior year of high school at the time of the interviews and were in the same team during the game.
I will use the pronoun they to refer to both students so as not to disclose any personal information.

S#1 is attending a scientific high school, oriented towards mathematics, physics and computer technology, and they expressed interest in physics, especially in its practical applications. They come from a town in the mountains and have personally experienced the effects of climate change in the pasts, thus showing particular interest in the way it affects people's lives and in the way it transforms the natural landscape:

> *S#1: My parents used to tell me about how twenty years ago they could see the white peak of the glacier from our house and so, I don't remember how it was when I was*

little, but as time went by in the last few years I noticed that the peak was grey.

They were already familiar with the concept of extreme events and claim that their perception didn't change after the course, which reaffirmed the belief that even if most extreme events are caused by human behaviour, they can not be reversed in the short term, but only contained.
However, the game helped them embrace the idea that taking individual actions can be more effective than waiting for nations and corporations to act on a greater scale.
Before the course, they had envisioned that it would focus more on analyzing climate change through statistical and probabilistic lenses and that the physical applications would pertain to observing natural phenomena.

S#2 is also attending a scientific high school oriented towards mathematics, physics and computer technology. They claim to have chosen to follow the course "because I'm passionate about physics and I have always been interested in fights such as that of climate change and the environment in general" and that beforehand they expected to learn more about the atmosphere and about the different factors that affect the environment.
Like S#1, S#2 is passionate about physics, especially when it comes to experiments and solving problems, which they describe as playful, as well as to its application to the production of green energy.
Now that we have determined that the students present similar backgrounds and share both an interest for physics and an initial understanding of climate change, we are going to go over their positioning towards the different themes.

Core values of science and personal positioning

During the analysis of the pre and post-questionnaires, we detected a common inclination among the students to identify scientific knowledge with the concepts of certainty and evidence. Therefore, we asked S#1 and S#2 to describe what they believed to be the core values of science.
As the following lines show, S#1's image of science is strongly linked to the concept of evidence.

FDZ: If we were to say "your vision of science is closely related to..." what? Let's complete this sentence.
S#1*: [...] For me science is everything that is rooted on evidence and hypotheses, that might be verified or not, and that thus have a demonstration, in the case that the thesis were true.*

This short excerpt indeed suggests that for S#1 the core value of science lies in its method to assess and demonstrate.
Whereas, when asked about the core values of scientific knowledge, S#2 replies by saying "objective and real", explaining that science is real because it is experimental and rooted in statistical evidence:

> S#2: “[science] is not just an idea, it’s experimented and analysed and has a probabilistic foundation”.

Suggesting that in their perception realness is a value linked to empirical and mathematical evidence.
S#2 believes that the role of science is that of providing a foundation for people to build arguments on, since without a scientific foundation discussions are rather hollow.

This shows that both students consider scientific knowledge to bear a description of reality that is somehow made more reliable by the existence of evidence.

We then asked what they thought the effect of scenario building had been on their perception of science.
S#1 describes the approach used to build scenarios as interesting because, whereas they had previously imagined future scenarios in a more "philosophical" manner, the course offered a “strictly scientific approach, based on evidence and on the true effects of one’s actions”.
They claimed to have acquired a “more rational point of view”, after the course.

> *S#1: My vision, now, is more rational than before, indeed I used to have this philosophical perspective, let's say, that the effects of certain decisions were more relevant, positively impactful, in reality it showed that they weren’t and it also depends on the fact that I hadn't yet researched all this evidence on the different effects.*

And, according to them, this shift partially depends on the fact that they previously hadn’t researched the evidence regarding said effects. In this case, we can see how the student gives values to the process they have been through during the course, specifying how for them data proved to be the primary source to distinguish between the impact and relevance of specific actions.

This emerges from the following lines of the previous excerpts:

> *S#1: More rational, meaning I relied more on what the data showed. Before, I hadn't looked into how much of an impact a certain decision could have, like reducing a type of energy production, but then, with all the different graphs and details on the website, it became clear how even a small decision could have a significant impact on the environment. So the scientific part of the data was missing, which said that if I do this, then I get this result. It was more of a popular way of thinking, in the sense that there were no more diesel cars, there were no more CO_2 emissions, but on the other hand, you also have to produce the batteries. So it was more of a popular way of thinking.*

The excerpt also introduces a new awareness towards the specific impact of certain decisions, showing in this way a reflection of climate's intrinsic complexity. When then asked whether scenario building had an impact on their perception of the future, they explain that the distinction between different types of future scenarios made their perception more pessimistic and simultaneously more realistic:

> *S#1: [...] It depends on the fact that I came in contact with the true effects, expressed numerically, of certain decisions and this has made everything more negative. [...] So according to me it has become more rational than before because there is this component of data that it's difficult to find, I struggled to find before.*

Here we can see how the student perceives the data emerging from the simulator during the game as "true effects expressed numerically". This position can be seen from one side as a possible correlation between the numerical form of a piece of information and its reliability.

It is also necessary to assess how, in facing the simulated version of reality coming from the simulator, the feeling of perceiving the effects of specific decisions more directly is associated with a perception of general negativity towards the problem.

When it comes to the positioning toward future scenarios, specifically during the activity of the Polak's game, S#2 indeed claims to be "A pessimist or maybe a realist" and that they'd always rely on science.

When asked to confront about this take during the interview, S#2 says

> *S#2: Yes, because most of the data that comes out—even news, let's say—is mostly bad, in quotation marks, but there is also positive data, and I look at that too. However, most of it is negative, so the outlook is a bit pessimistic.*

From these lines it appears that the students' positioning can be compared. The role of data and news have similar effects on the students, showing them a more complex reality that at the same time provides more understanding of the problems of climate change and that the space of action is large but also difficult to reach. In both cases, the role of the simulator helped them in visualizing and perceiving the future impact of certain actions, positioning reinforced by numerical evidence, and by the association of the mathematical representation of phenomena and relative effects.

To show the complexity of this positioning, we report here how S#1 explicitly elaborates on how this feeling of pessimism can have also its positive elements:

S#1: [...] This strongly rational approach and this pessimism I believe are more of a constructive pessimism, namely I don't delude myself of the fact that issues can be solved. I know that there are problems that will persist but through this awareness of the evidence and so on, I know how to work in order to mitigate, for instance, these problems.

Attending the course and coming in contact with evidence of the effect of certain decision making processes helped them to better frame their role in the social contexts, therefore acting towards the development of future agency competences.
As for S#2, their realistic perspective remained unchanged during the course.

LM: When you say realist, indeed, this perception of relying on facts… this perspective stayed the same?
S#2: Mostly.
LM: Were there any transformations?
S#2: No.

And, when asked whether this awareness of evidence changed his perspective during the gameplay, they claim that their approach changed and became more moderate. S#2 realized that operating solely in one area is not effective to influence the future of the climate system.
When then asked about the collective experience of the gameplay, S#2 states:

S#2: I really enjoyed the teamwork that took place and I was fine even if we didn't follow my initial idea. I really liked the confrontation with others and finding a common path that I ultimately believe was also very important.

This small excerpt allows us to understand also how the activity gave space to confrontation and reflections on the collectivity of actions that can affect our society as a whole. The mechanisms activated through the group discussions are perceived, as S#2 states, as a valuable learning moment for dealing with differences and alternative perspectives.

Images of sustainability

Regarding the images of sustainability emerging from the interviews, both students present a picture of sustainability as a complex concept.

In this first excerpt, S#1, talking about their personal choices regarding means of transportation, claims that sustainability is a compromise:

S#1: [...] Sustainability in function of one's needs. [...]
MAZ: So, finding a balance.

S#1: Exactly. That's what matters the most.
MAZ: Between what's sustainable for the environment and what's sustainable for you and your family?
S#1: Yes, obviously to a point, because if there's a [temporal] difference of 20 minutes, for instance, to go home than no [I wouldn't use private transportation], but if there's a 2 hours gap I'd rather go by motorbike or by car, than take the bus.

This position is in accord with the idea of sustainability that emerged during the reading of the gameplay report. In the report, where students were asked to describe the 2100 scenario developed by their team, the students and their group presented a world that plummeted into global crisis between 2030 and 2040, in order to reduce air pollution, and where society has made huge sacrifices for the environment, undergoing heavy taxations that led 90% of businesses to bankruptcy and paved the way for the centralization of power.

To explore this perception, we asked directly some questions about the scenario.

LM: Would you live in this world [you developed during the game play]?
S#1*: No, no, because if it's true that it is important to protect the environment and in some way fight and find a solution to climate change, however human life revolves around money, sadly, in the sense that even environmentalists, those that devote their whole life to the fight for the climate, in some way have to survive, and need economical stability.*

According to the student, a compromise between what would be the best choice of action for the environment and what is needed to live comfortably is necessary.
Their positioning towards sustainability is moderate, they state that it is an important value to follow but not when it would disrupt one’s economical stability.
This perspective reflects S#1’s positioning: they are not ready to sacrifice their life for the environment because they do not believe it would be worth it, when evidences, in this case produced and explored through the simulator, suggest that it would not be enough to save the world.

The perspective is different when we read the same gameplay report to S#2 and ask them to imagine and describe the world they had created in the 2100 projection.

S#2: We would be able to manage the issue of future climate change. Energy produced in this hypothetical *future would be cleaner and thus there would have been [scientific and technological] progress on every front.*

Their scenario has, in S#2's opinion, some positive aspects. However, they too doubt that solving problems linked to the environment, in the way they did during their gameplay, would have a positive effect on social issues.

We therefore asked them to imagine the effects on the population of a heavy taxation aimed at limiting climate change in the span of the next 25 years:

LM: [...] even if it seems desirable, it's not truly sustainable.
S#2*: Even for the future?*
LM: The future, and in the meanwhile? In what system can one operate a huge change, guaranteeing a better future in the span of 20, 30, 50 years?
S#2*: With scientific evidence [to support the taxation].*

The exchange demonstrates that S#2 holds a more radical view of sustainability; for them, sacrifices are necessary and justifiable to achieve climate goals, rather than seeking compromise.

As directly shared by S#2, they have been interested in sustainability for most of their formative years and attending the course reaffirmed their belief that individual action is very relevant but is ultimately not enough to fight climate change. Learning about extreme events during the course, they felt fear for the future, but denounced a general disinterest in their peers regarding the environment.

Uncertainty-Certainty tension

Multiple times throughout S#1's interview, a link between certainty and mathematical evidence has come up. For instance, when asked to compare a scientific theory supported by plenty of evidence, but in contrast to previous well established theories, and one consistent with previous knowledge, but supported by limited evidence, they state that

S#1: If there is more evidence, there is certainty or a greater probability that [the theory] is correct, [...] however if it goes against other theories I would consider it carefully.

Here S#1 generalizes an epistemological concept, that of minimizing uncertainty by gathering more evidence, and applies it to all uncertainties. This shows that they are not used to taking into consideration the differences between epistemic and aleatoric uncertainty and thus are led to think that all uncertainties can be reduced.

We then asked the student to list the different types of uncertainties. S#1 defines aleatoric uncertainty as the effect of multiple causes of a phenomenon, which are not fully predictable and thus cause the uncertainty. He then cites the uncertainty related to the measuring process, but doesn't remember that it's referred to as epistemic.

He doesn't indeed remember the difference between the two types of uncertainty, but says that maybe aleatoric uncertainty could be reduced "if we study and discover possible links between the different phenomena that cause it" and that "we would be able to foresee with more accuracy".

This statement reiterates the idea that, even if the uncertainty is not caused by the observer's epistemologic limits, gathering knowledge about the subject could diminish the uncertainty.

Similarly, when it comes to reflexive uncertainty, S#1 doesn't remember it nor remembers what it is linked to.

The student shows a difficulty towards perceiving the typologies of uncertainty as different and not only related to the measuring process. This difficulty, common also between other students, even after attending the course, suggests how prior exposure to an idea of uncertainty exclusively linked to measuring, such as the one to which they are exposed in schools, can influence their learning process, making it more difficult to embrace concepts in conflict with a prior framework.

Furthermore S#1 claims that during the course their perspective towards uncertainty has changed, but their perception of science was not transformed.

> S#1*: Maybe I consider even more elements of some complex phenomena, but in my opinion [the course] didn't change my way of reasoning, because I generally try to see [...] all the effects that an action may have and so I believe that yes, maybe I am even more stubborn in studying this phenomenon.*

We then asked about their perception of the simulation generated by En-ROADS, whether it changed taking into consideration the uncertainty associated with the data.

> *LM: [...] This thing, so on one hand the role of evidence, on the other the role of uncertainty, does it cause a conflict for you? Do you keep them separate so there is no problem, you consider the evidence for what it is? Or does it change your way of perceiving the evidence?*
> S#1*: So, I personally don't consider uncertainties, when there is evidence I know that it can be associated with a margin of error but I don't consider the magnitude [of the error], I do know that they are not absolute. [...] This reflection on uncertainties of the evidence certainly comes later, when I reflect back on it.*

> *[...] I know that the uncertainty exists but I don't, for instance in this case [of the simulator], ask myself how big the uncertainty is.*
> *LM: So there is a level of reliability, let's say you took the evidence at face value.*
> *S#1: Yes. Because the simulator is [made] by an important institution.*
> *LM: Yes, MIT.*
> *S#1: Yes exactly, yes, it matters the source because if it is not a reliable source I'm more careful. Instead if it is reliable it doesn't mean that it certainly did well, but it's more likely.*

S#1 claims that the existence of uncertainty does not change notably their perception of the evidence, and they give more importance to the source, adding that “The more evidence, the less should be the uncertainty”, which leads back to the idea that S#1 perceives uncertainty as a measuring error: “[...] can be associated with a margin of error”.

This idea is reinforced when they describe reflexive uncertainty.

> S#1*: Reflexive uncertainty is the most unpredictable, because in a way we can't see [...] it in the form of a number or a formula. Therefore reflexive uncertainty, surely regarding climate change, but in general in my opinion does not [pertain to] mathematical or physical or scientific problems. So all problems in which human action plays a role, as an effect, reflexive uncertainty is the most complex to foresee, because emotions and thoughts can not be foreseen. One could say that epistemic uncertainty is linked to evidence and reflexive uncertainty can not depend on anything that can be foreseen. [...] It's the most susceptible to any singular change.*

The student associates the concept of predictability with the mathematical representation of a piece of evidence. Their claim that: “reflexive uncertainty [...] does not [pertain to] mathematical or physical or scientific problems” because of its complexity and unpredictability suggests that their idea of complexity is partial and biased by the common use of the term to describe what is instead complicated.

We investigated further, focusing on the divide between scientific knowledge and reflexive uncertainty.

> *LM: However here we are dealing with scientific elements, and still it is present [reflexive uncertainty]. What does it make you think?*

S#1*: It's true, it's a scientific approach, but in this approach an important factor is human behaviour. [...]*
FDZ: And why "but"? I mean, I see, "scientific" doesn't contain human behaviour, or can it?
S#1*: So, for me, a scientific experiment doesn't contain human behaviour, it can be in the activation of the machines, but it can't modify the conditions of the experiment. While, [...] the study of the environment is scientific, but, for instance, the interaction between humans and the environment is partially scientific, but it partially is not because there is this human interaction that can not be foreseen. And that features this reflexive uncertainty.*

S#1 categorically draws a line between what they consider to be scientific, or in their opinion what can be assessed and demonstrated, and human behaviour. This leads back to the student's perception of complexity and predictability, which they address further when asked to expand on the claim that they have a "rational point of view".

S#1: More rational, that is more reliant on what the evidence showed. I hadn't previously looked into the impact [of what] a certain action could have, for instance, regarding the reduction of a certain type of energy production and thus through the website [En-ROADS] with all the different plots and so detailed I understood well how even a small decision had an impact more of less relevant on the environment. So I lacked the scientific aspect of the evidence that showed that if I do a certain action I have a certain outcome, it used to be more of a popular way of reasoning, in the sense that, for example if there weren't combustion engine cars anymore, the CO_2 emission would be less, but we would have to produce the batteries [for eclectic cars].

That shows that after the course S#1 is more open to embrace the complexity of a system, and it also highlights the association between the concepts of rationality, scientific knowledge and evidence. However it shows that S#1 maintains the idea that scientific knowledge is somewhat deterministic and linear.
Indeed he claims that it is often difficult to interpret evidence because "[evidence] is shown in a non-scientific way, too articulate, that only experts understand".

When it comes to S#2, their positioning towards uncertainty presents some points of contact to that of S#1, but introduces an ulterior argument.

To begin we asked them to describe the different types of uncertainties discussed in the course. S#2 remembers that there is a reducible uncertainty linked to the measuring process, the epistemic uncertainty. And they remember that there is a more unpredictable, "absurd" uncertainty. S#2 also remembers that there is a third type, the ontological one, but doesn't remember what it pertains to. Also, they don't recall reflexive uncertainty.

After we again list and define the four types, S#2 states that before the course they had only studied uncertainty linked to the measuring process and that they still haven't fully understood the other types of uncertainty. However, S#2 claims that learning about them changed their image of science for the better.

> *S#2: [...] It widened my vision of how science can work and how it can be more accurate thus it made me [...] rely on science.*

This highlights how, in their perception, the idea of uncertainties is directly followed by that of reducing uncertainty to get more accurate scientific knowledge.

The student's perception of uncertainty is not just negative, but more nuanced. In another small excerpt, we can see how he values the role of uncertainty in science:

> *S#2: I don't think that science was 100% certain, [...]. However the fact we care about uncertainty is a great point in my opinion, because if we didn't consider uncertainty we wouldn't have evidence that is relevant and accurate enough.*

S#2 considers uncertainty as an integral part of scientific evidence and simultaneously as a tool that "[helps] to gain the realest evidence, so to be certain that it, with the tools we have at the moment of collecting evidence, is the most accurate possible".

As it emerges from these excerpts, in their perspective the aim of science is to reduce uncertainty as much as possible and this shows that, similarly to S#1, they don't make a distinction between the type of uncertainty that can be actively reduced and the ones that are not influenced by the measuring process.
In the questionnaire done at the beginning of the first lecture, to the multiple choice question "When you think of scientific theories, you believe that..." S#2 replied "True according to the perspective, therefore multiple opinions about a theory can be equally true".
The other possible answers were:

- "They are fixed and established with absolute certainty"
- "Proven true in light of collected evidences"

We then asked them to elaborate on their choice.

S#2: [The fact of] them being fixed for me absolutely not, because –
LM: Absolutely not? But you give much importance to scientific thinking, to the scientific process –
S#2: Yes, but seeing during the course that there also is uncertainty, some uncertainty, to say that they are absolutely certain would be wrong.

A point of attention emerges in the student pre-post perception of scientific theories.

S#2: [theories] are not all absolute and certain, and are not all demonstrated on the basis of gathered evidence, some scientific theories, in physics as well, are not [based on] true, actual evidence and are instead demonstrated, maybe, mathematically.

In this excerpt resurfaces the concept that, according to S#2, scientific knowledge is associated with both mathematical demonstrations and empirical evidence.

Comparing this with S#1's claim that: "science is everything that is rooted on evidence and hypotheses [...] and that thus has a demonstration [...]." shows that in both their perspectives the concept of evidence and the concept of demonstration are central in order for scientific knowledge to be reliable.

Focusing back on S#2's answer, I ask them to expand on the concept of truth.

MAZ: You used a term, that is truth. Even after attending the course, what do you think is the relation between the concept of uncertainty and the concept of truth? Scientific truth in this case.
S#2*: The relation between truth and uncertainty, right? The absolute truth, in my opinion, is unattainable. But uncertainty helps to get as close as possible to the truth.*

S#2 in this excerpt underlines how uncertainty can be perceived as a tool to get closer to the truth, which reinforces the argument that the validity of scientific knowledge resides in potentially offering certainty.

To expand on this we ask if in their opinion a new theory, supported by plenty evidence, but associated with uncertainty and in discord with a priorly affirmed theory such as Newtonian mechanics, should be nonetheless taken into consideration, he claims that:

S#2*: [...] We established that epistemic uncertainty is the type that can evolve and that can give us a truer result so, in my opinion, one should discuss the truthfulness of the*

new theory. And sometimes in physics it happens that the Newtonian case is a specific case of a wider thing.
FDZ: [...] How does that relate to your claim that *science is founded on values of objectivity and reality?*
S#2: I think that reality is that in Newton's case, for instance, Newton's theory is true in a particular context, frame of reference, while in many others this thing does not happen. Therefore both are true, but in different circumstances, and these things can coexist. So it is more flexible and it is how science is.

For S#2 uncertainty is not in opposition with truthfulness, however they stress the idea that, if uncertainty is reducible, it offers room to improve a theory as the epistemic limitations evolve.
We then asked them how they perceive the different types of uncertainties in relation to decision making.

MAZ: Uncertainties, even considering solely [...] epistemic, aleatoric and reflexive uncertainties, do you value them in the same scale? Or when you consider, for example during the game, your decisions and the choices you have to take, do all these uncertainties have the same value, are they all present or –
S#2*: I think I focus more on epistemic uncertainty, because it is the one we can do something about, theoretically, the one we can impact. However I wouldn't exclude the others, because [...] I see them as an investment for the future. And epistemic uncertainty instead in the short term or [...] if there wasn't epistemic uncertainty the others would be less accurate as a consequence, i think, because it is with the tools that you measure uncertainty. But the others are something more, they are an added value that can open different paths or close them.*

Here surfaces a new element of the student’s perspective, the hierarchy in which they pose the different types of uncertainties.

MAZ: Ok, in your image of science, how do uncertainties position themselves? All at the same distance? At different distances?
S#2*: I see them like a branch, epistemic, reflexive and maybe there are more from here.*
MAZ: So reflexive and aleatoric [uncertainties] descend from epistemic?
S#2*: Yes.*

Similarly to S#1, S#2 centers his idea of uncertainties around epistemic uncertainty, with particular focus on the fact that it can be actively reduced by the observer, and is thus perceived as more useful, by S#2, and scientific, by S#1.

Results on the second implementation

Discussion on the thematic comparative analysis

The comparative analysis highlights that the course helped the students define their role in the social context, acting towards the development of future agency competences. In particular, the gameplay activity offered space for confrontation and reflection, proving to be a valuable learning moment for students, who got to deal with different opinions and alternative perspectives.

Furthermore, through the simulator, the students got to visualize and perceive the future impact of certain actions. And, more generally, being exposed to data and news during the lectures they acquired a more complex perspective of reality, and a deeper understanding both of the problems of climate change and of its intrinsic complexity.

The analysis also shows that the students' images of science are centered on the association between the concepts of scientific knowledge, rationality, and evidence. For instance, both students consider scientific knowledge to bear a description of reality that is made more reliable by the existence of evidence.

When it comes to uncertainty, the findings of this study show that the students built their idea of it around epistemic uncertainty, with particular focus on the fact that it can be actively reduced by the observer, and is thus perceived as more useful, and scientific. A corollary is that the idea of uncertainty is directly followed by that of reducing uncertainty to get more accurate scientific knowledge.

In addition to that, both students tend to discard the concept of reflexive uncertainty in the context of scientific knowledge, because human interactions with the environment are considered too unpredictable and complex. And this might suggest that in students' perception, there remains a latent resistance to fully embrace the concept of complexity.

However, overall, learning about the different types of uncertainties reinforced S#2's trust in science on one hand, but did not particularly affect S#1's perception of it on the other.

The students' positioning towards the future also didn't change after the course. They connote their perspective as constructive pessimism, because it is an effect of their awareness and the latter allows them to make decisions on an informed basis and exercise their agency.

The concept that one's positioning is pessimistic based on their perception of the present, however, fits into the broader discussion that humans tend to assume that whatever is happening now will continue.

As Dator explains "[...] we know from years of working in the futures field that *the future* that most people have in mind when they are first asked to think about the future usually is that *whatever is happening now will continue.* Thus if times are currently good, most folks believe they will remain good and will not want to think about or plan for bad things. If things are falling apart now, then many people will feel that there is no way to put them back together – much less find a new way – and will ridicule attempts at envisioning a bright future” (2009, p. 4).

Ideas for improvements and future implementations

According to Shepherd & Lloyd (2021, p. 2) one of the main obstacles in climate change education is that usable climate science is usually interpreted as quantitative, typically as a best estimate with quantified, probabilistic uncertainties. Whereas the uncertainties involved in the response of the climate system to anthropogenic forcing are sufficiently deep that they cannot be reliably quantified in a probabilistic way (Dessai & Hulme, 2004) and represent objective measures of uncertainty, i.e. the likelihood to capture the true value of a parameter. Consequently, when misinterpreted as subjective measures of uncertainty, i.e. the confidence in the result, they convey a lack of knowledge.

Bayesian approach encourages viewing uncertainty probabilistically, and introduces the language of relative probability to express the uncertainty associated with scientific evidence. Therefore it is suitable to help learners shift from a primarily quantitative perspective to a qualitative perspective (Shepherd et al., 2019).

Moreover, the Bayesian approach encourages the evaluation of new evidence in light of prior information, both aiding the deconstruction of learners' biases and highlighting the innovative aspects of the evidence.

In this framework students could address their prior understanding of complexity, which this analysis found to be a point of resistance for the interviewees. The approach could be useful at the beginning of the learning experience, to set the foundation for the lectures to build upon. And it might be introduced in the form of an interactive, empirical activity, to allow for an open dialogue between the students.

For instance, an activity that both students found interesting and engaging during the course was “explosive uncertainty”, where experts from the Italian National Institute of Geophysics and Volcanology presented the risks connected to a volcanic eruption through an empirical model. Similarly, in order to address implicit ontologies in students’ perspective (Jacobson and colleagues, 2011), we could select a set of different complex systems to work on with the learners, in an open conversation.

Discussing examples of complex problems could help them contrast and compare aspects of the different complex systems and challenge their thinking about the behavior and properties of these systems.

The discussion could be divided into two parts. The first part would focus on the observation and description of the systems, aimed at identifying the core formal scientific concepts in students’ ideas of complex systems. As a base we could address the misconceptions highlighted in the Deterministic-Centralized-Mindset (Resnick and Wilensky, 1998):

- ❖ Assuming the behaviour of agents in a system to be predictable rather than random

- ❖ Assuming order in a system to be centrally imposed by a leader or designed by a single entity, rather than a result of de-centralized interactions.

And the second part would aim at helping the learners think in more ‘‘expert-like’’ ways, by prompting consideration of ‘‘how’’ and ‘‘why’’ issues rather than ‘‘what’’ questions.

Conclusions

This thesis investigated how a future-oriented approach to science education can act on students' image of science, with particular focus on climate change education. By situating the study within the context of the epistemological transition of science between Newtonian mechanics and science of complexity, and focusing on the role of complexity and uncertainty in the shaping of students' perception. The work highlighted the importance of futurizing climate change education, so as to help students develop future agency and literacy, essential to fully understand and discuss climate change. Climate change represents a particularly relevant context in which to explore complexity and to reflect on how students interpret scientific knowledge, uncertainty, and the future.

The thematic, comparative analysis of the follow-up interviews of two students who had attended the course "Towards New Future Scenarios: The Role of Physics in the Challenges of Climate Change" provided insights into how a futures-oriented approach to science education contributes to fostering students' awareness of the complexity of issues related to climate change and encourages them to reflect on their role within a broader social context. In particular, the gameplay activity created an environment for dialogue and confrontation of perspectives, as students were exposed to diverse viewpoints and were invited to negotiate and reconsider their own positions.
The use of simulation tools also played an important role in the learning process. Through the simulator, students were able to visualize the long-term consequences of different actions and policies and, more broadly, exposure to scientific data and news, during the course, helped students develop a more articulated understanding of climate change and of the complexity of the systems involved.

The analysis also shows that the students' images of science remain centered on the concepts of rationality and evidence and that they present a resistance towards the complexification of their perception of science. For instance, detected in their tendency to build their idea of it around epistemic uncertainty and simultaneously discard the concept of reflexive uncertainty in the context of scientific knowledge. Nevertheless, exposure to different types of uncertainty appears to have had a positive effect on students' trust in science, suggesting that presenting uncertainty as an integral and structured component of scientific inquiry can contribute to a more realistic understanding of how science operates. The practice of scenario making, and the exposure to the framework of Futures Studies helped students understand the role of individual and systemic action, decision making and policy making. Furthermore, regarding their positioning towards the future, the students connote their perspective as constructive pessimism, explaining that their awareness of the risks and the challenges of climate change allows them to make decisions on an informed basis and exercise their agency. The course, however, did not substantially transform their positioning.

These findings, in accord to previous research (Miani et al., 2025) highlight the importance of education in empowering students to confront the complexity of climate change, but also indicate that, in order to better understand the concepts of complexity and uncertainty inherent to scientific knowledge, students would have to further deconstruct the epistemological bias they hold towards complexity. And this could be obtained through the implementation, at the beginning of the course, of an activity centered on the students perception of complexity and structured according to the principles of the Bayesian approach. For instance, the students could be shown a set of exemplary complex systems to, firstly, observe their perception and description of the systems, gathering the core scientific concepts in their ideas of complexity, and subsequently addressing eventual biases in an open discussion.

Appendice

Protocollo intervista PLS

Introduzione

Carissimə,
Grazie mille per aver dato la tua disponibilità a partecipare a questa intervista.
Lo scopo di questa chiacchierata sarà quello di ripercorrere e discutere assieme alcuni momenti che hanno segnato il corso PLS “Verso nuovi scenari futuri: il ruolo della fisica nello studio dei cambiamenti climatici”.
Il motivo per cui abbiamo sentito la necessità di chiedervi questo momento è perché, come vi abbiamo accennato durante il corso, questo corso si fonda sui nostri progetti di dottorato, e attraverso queste interviste vorremmo ricavare ulteriori informazioni sul senso di ciò che è stato fatto e sulla potenzialità del corso di sviluppare delle competenze necessarie per affrontare le sfide sociali con cui siamo costretti ad interfacciarci giorno dopo giorno.
Per ripercorrere questi momenti ci serviremo sia delle risposte che avete dato ai questionari che avete compilato durante il corso che di alcuni momenti registrati durante le attività di gruppo, come il gioco o la costruzione delle wild cards. Ci teniamo a precisare che non c’è nessun tipo di giudizio su questi dati e queste informazioni, ma piuttosto ci piacerebbe aprire uno spazio di confronto e discussione sul senso di ciò che abbiamo fatto.

Parte 1 - Riscaldamento

Prima di affrontare i vari argomenti trattati nel corso, vorremmo fare qualche domanda di contesto, per capire meglio il motivo di questa chiacchierata. Innanzitutto vorremmo chiederti:

1. Come mai hai scelto questo corso?
2. Cosa ti aspettavi da questo corso quando hai fatto l’iscrizione?
3. Hai trovato cose che non ti aspettavi?
4. Che tipo di rapporto hai con la scienza, e in particolare con la fisica?
5. Affrontando argomenti legati al mondo scientifico hai trovato qualcosa di interessante per te da una prospettiva personale?
6. Rispetto alla tua visione di scienza, come hai percepito il modo di trattare la fisica all’interno del corso?

Parte 2 - Come percepisci i cambiamenti climatici

Passiamo ora ai questionari che vi abbiamo chiesto di compilare nella prima e nell’ultima lezione. Il questionario aveva uno scopo comparativo, ovvero volto a rilevare eventuali differenze tra il vostro posizionamento prima e dopo il corso, rispetto alla visione della scienza, dell'agency e nell'area valoriale.

1. Il tema dei cambiamenti climatici è molto vasto, come abbiamo visto nel corso. Se pensiamo alla sua dimensione scientifica, ci sono temi/aspetti che ti hanno colpito e ti hanno fatto pensare?
2. Dalle tue risposte emergono alcuni esempi di effetti del cambiamento climatico. La tua idea di come possa influenzare ed essere influenzato dall'attività umana è cambiata seguendo il corso?
3. Nella storia descrivi dettagliatamente come, quando il ragazzo apre finalmente gli occhi e capisce che da solo non può fare molto, si impegna a sensibilizzare le altre persone e cerca in continuazione il modo o i modi più efficaci per salvare tutti...nessuno escluso. Che tipo di reazione hai avuto quando nel corso abbiamo affrontati temi che possono sembrare molto grandi o non raggiungibili (es. eventi estremi, catastrofi naturali, politiche internazionali)?

Parte 3 - Futuro e Sostenibilità

Spostiamoci ora sul tema del futuro e della creazione di scenari futuri

1. Il corso ti ha aiutatə a immaginare un futuro alternativo? Prima di partecipare avevi una visione diversa?
2. Ritieni di aver acquisito, durante il coso, strumenti utili e interessanti per pensare al futuro? Se sì, quali?

Parte 4 - Incertezza e decision making

Ora vorremmo parlare di uno dei temi centrali del corso, il concetto di incertezza. Come avrai potuto notare abbiamo utilizzato alcune terminologie specifiche per descrivere e categorizzare le diverse tipologie di incertezza che emergono quando si ha a che fare con argomenti come quello dei cambiamenti climatici.

1. Se dovessi descrivere le differenze tra i tre tipi di incertezza legati al cambiamento climatico, quali sono gli elementi principali che useresti per distinguerle?
2. Che tipo di visione emerge del mondo scientifico? Come si relazionano i contenuti visti nel corso, in particolare le incertezze, al tuo modo di vedere la scienza??
    a. Prompt: Uno o più tipi di incertezza studiati (o la differenziazione in sé) ha generato una tensione, una dissonanza, nel tuo modo di vedere la scienza?
    b. Le incertezze hanno messo in discussione ciò che pensi della scienza?
3. Rispetto alla domanda sulle teorie scientifiche hai risposto dicendo che possono esserci diversi modi di vedere la realtà, e quindi diverse teorie possono essere vere allo stesso modo. Sei ancora di quest'idea? Vuoi commentare questa risposta?

Parte 5 - Incertezza nel gioco

Concentriamoci adesso in particolare sul gioco. Se ricordi, il nostro obiettivo era quello di creare uno strumento che fosse capace di mettere assieme i diversi temi toccati durante il corso, come gli scenari di futuro, l'incertezza, la complessità dei fenomeni climatici e la relazione tra scienza, politica e società.

1. La struttura del gioco, ed in particolare la presenza delle wildcards, è volta a simulare anche solo in parte la complessa evoluzione del clima. Come hai/avete gestito questa complessità?
2. Secondo te quale forma di sapere scientifico e di modo di fare scienza può aiutare a prendere decisioni consapevoli e a gestire la complessità?
    a. Se sì, il fatto che ci sia incertezza nei dati inficia il processo decisionale?
    b. Come ti approcceresti al processo decisionale in tal caso?

Parte 6 - Scenario

Passiamo ora alla fase principale del gioco, la costruzione di scenari futuri.

1. Che tipo di scenario è emerso dalla vostra giocata?
2. Se potessi scegliere, vivresti in quel mondo lì?
    a. se sì/no quali aspetti influiscono maggiormente sulla tua decisione?
3. In quale modo avete proceduto durante l'arco della giocata?
    a. Prompt: vi siete posti degli obiettivi da raggiungere e avete preso decisioni di conseguenza o siete partiti da una scala di valori su cui fondare le vostre decisioni?
    b. cambieresti approccio col senno di poi?

Parte 7 - Identity

In ultimo vorremmo farti domande un po' più generali. Uno dei nostri obiettivi di ricerca è quello di capire se e come il cuore epistemico della disciplina, ovvero i contenuti, i metodi, le pratiche e i valori messi in campo dalla scienza, entrano in consonanza o dissonanza con le identità degli studenti. In particolare ci stiamo interrogando sulla potenzialità che argomenti di fisica come l'incertezza e la complessità hanno rispetto ad altri argomenti, per attivare una risposta di tipo personale.

1. Hai mai percepito che la scienza (a livello di contenuti, pratiche, metodi, valori) fosse in linea con alcuni tuoi aspetti personali? O al contrario fosse in opposizione ad essi?
2. Ci sono stati dei momenti nella tua esperienza del corso PLS in cui hai sentito che gli aspetti scientifici (a livello di contenuti, pratiche, metodi, valori) fossero in linea con alcuni tuoi aspetti personali? O al contrario fossero in opposizione ad essi?
3. Nel PRE e POST test ha risposto che il tuo atteggiamento verso lo studio delle materie scientifiche è razionale, logico e schematico. Questa modalità secondo te può essere applicata sempre? Sei riuscito ad

applicare questo schema anche durante il corso o ci sono stati momenti in cui non sei riuscito?

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