Reopening the future through science education

di Veronica Ilari, Paola Fantini, Olivia Levrini

Abstract

Contemporary crises have been interpreted as crises of imagination, rooted in dominant linear conceptions of time that constrain the ability to envision alternative futures. Within science education, these conceptions are reinforced by an almost exclusive focus on the Newtonian-Laplacian time of classical physics, which underpins clock time. This study explores how a complex systems perspective in physics education can expand students' temporal imagination. Drawing on two datasets from the FEDORA project, we conducted a qualitative analysis of students' writings to identify emerging temporal images. Results show a dominance of the "time of the clock" in future essays, while exposure to complexity science has opened space for the "time of experience". These findings suggest that integrating complexity science into secondary school science curricula can contribute to problematizing linear clock time, thereby broadening students' imagination of the futures.

Keywords: Science (physics) education; complex systems science; dinamical systems physics; temporal structures in physics; clock time.

The crises affecting the contemporary world – first and foremost the ecological crisis, but also crises of democracy, meaning, and social relations – have increasingly been interpreted as crises of imagination (Ghosh, 2016). From this perspective, the difficulty of responding to ongoing transformations lies not only in a lack of scientific knowledge, but also in a collective inability to imagine alternative futures.

Dominant narratives of the future often frame it as linear, inevitable, and governed by technological optimization, contributing to processes of de-imagination that narrow the horizon of possibilities (Paura, 2024). These narratives are grounded in deeper worldviews and conceptions of time, which are also shaped through scientific and educational languages.

This contribution draws on the experience of the Physics Education Research Group at the University of Bologna, developed through EU–funded projects, most recently the FEDORAS *Teacher Academy*, to argue that introducing the fundamental ideas of complexity science can help "loosen the chains" of the Laplacian conception of time and open up spaces for imagining alternative futures.

The problem

We are accustomed to thinking about the future almost exclusively in terms of technological innovation and scientific progress. As Roberto Paura (2022) observes:

> "Judging from the dominant iconography, the future is associated with enormous megacities, towering skyscrapers, ultra-fast and futuristic transportation systems, driverless cars, space colonies, virtual reality headsets, robots, touchscreen displays (perhaps entirely virtual). For some reason, futuristic aesthetics are associated with white…" (p. 175)

Within the dominant paradigm of technoscience, technological innovation is assumed to be intrinsically positive and the main – if not the only – driver of the future, as well as a privileged solution to complex social problems. Although with the end of modernity, the future has progressively shifted from promise to threat (Benasayag & Schmit, 2006), a linear conception of time persists, continuing to sustain these narratives. The future is thus still conceived as a projection of the present, guided by a teleological promise of progress grounded in the expansion of scientific and technological power.

The progressive disappearance of alternative images of the future is accompanied by an increasing retreat into the present, a dynamic further reinforced by the temporal structure of contemporary society, characterized by a permanent acceleration across technical, social, and existential dimensions. In the "society of acceleration", every dimension of experience is subjected to a constant pressure toward the "faster", the "more efficient", the "more performative". The present, saturated with urgency, takes the form of a succession of immediate moments that push toward continuous, frictionless functioning. Within this temporal regime, time is reduced to a quantitative and extensive dimension – something that can be "lost" or "gained", but not lived or inhabited.

The internalization and naturalization of clock time as the only legitimate form of temporality, together with the implicit belief that no alternatives are possible, has been conceptualized by the sociologist Hartmut Rosa (2009, 2013) as a form of temporal alienation.

Traces of this technocratic relationship with time also emerge in students' narratives. An emblematic example, drawn from a dataset previously analyzed by Barelli *et al.* (2022), is the following:

> I leave my apartment *at 7:45*, quite proud of having followed *my usual daily routine*. I enter the *ATS skyscraper (Aerial Transport Systems)*, and on the seventy-sixth floor I take the train that runs above the buildings. *As usual*, I find myself squeezed into a crowd of people busy talking on the phone, but I think that, after all, I just have to endure *3 minutes and 46 seconds. At exactly 8:00*, I am in the meeting room… then the meeting begins. Actually, the meetings.
> In case you are wondering about my profession, I am pleased to inform you that *I am a successful manager* in the fashion and design sector, now in my early forties*. I chose to prioritize my career* and, at a later stage in life, I found myself with a handful of money in one hand and absolutely nothing in the other. *For this reason, I regret my choice every single day.*

In these writings, the elements of the technocratic vision of the future clearly emerge, together with the assimilation of a logic of efficiency expressed through the linear temporality of clock time, which functions as a structuring framework for imagination.

Within this scenario, one of the central challenges is to reopen the future fostering, through science education, a process of widening the imagination beyond clock time. A crucial question for science education thus emerges: how is it possible to intervene within the school curriculum in order to problematize clock time and expand students' temporal imagination?

In what follows, we present a study conducted with secondary school students, aimed at exploring the transformative potential of complexity science in the teaching and learning of physics. The paper is structured as follows:

Context of the study
The activity
The study
Discussion and conclusions

Context of the study

Over the past ten years, the Physics Education Research Group at the University of Bologna has developed a Futures-Oriented Science Education approach aimed at regenerating school science contents so that they can serve as a foundation for developing temporal and futures competences, which are essential for navigating a complex, fragile, and fast-changing society (Levrini *et al.*, 2019, 2021).

Regenerating school science contents implies rooting the shift from Futurology to the Futures Studies in the ontological, epistemological and axiological shift that characterizes the establishment of the research field in the science of complex systems. The science of complex systems and the physics of the dynamical systems have historically represented an epistemological alternative to the Laplacian deterministic view of science and provided the framework to develop the modelling tools for simulating possible future scenarios. In our approach to science education, the science of complex systems is conceived as a context that provides the conceptual, epistemological, methodological, and modelling foundations for Futures Literacy.

The activity

Within the context of the Horizon EU-funded projects, first SEAS[1] (2019–2022) and subsequently FEDORA[2] (2020-2023), teachers from the "A. Einstein" Scientific High School in Rimini, in collaboration with the Physics Education Research Group at the University of Bologna, co-designed an interdisciplinary module focused on the physics of complex systems and creative writing. The module was implemented within the regular curriculum through a co-teaching approach involving Italian literature and history teachers alongside a physics teacher, with a Grade 9 class of 24 students (aged 14–15) during the 2020–2021 school year.

The core of the module, entitled *La fisica delle nuvole* ("The physics

[1] https://www.seas.uio.no/

[2] https://www.fedora-project.eu/

of clouds"), was based on the idea of introducing students, from an early age and in the physics classes, to the fundamental concepts of complexity science, encouraging them to "inhabit" these concepts and to transform them into lenses through which to interpret and address the major challenges of contemporary society.

In this context, the collaboration of the physics teacher with the Italian literature one led the project to focus on creative writing as a new language capable of fostering the appropriation of complexity concepts, through a continuous shift in perspective between the scientific and the literary domains. In the process of writing the stories – later collected in the dataset *The physics of clouds* – disciplinary knowledge thus came alive through the personal meanings attributed to it by students through the activity of creative writing.

In this section, we focus on the reflections developed during the physics lessons; in the following paragraph, we instead describe the study based on the analysis of the *The physics of clouds* stories, in comparison with a different dataset.

The activities on complexity science were carried out in class through interactive lessons structured around dialogue with students. The introduction to key concepts adopted a phenomenological approach, drawing on examples of complex systems from physical domains (such as Bénard cells or cloud formation), biological domains (bird flocks and ant colonies), and social domains (Schelling's segregation model).

The reflection began with the etymology of the words *complicated* and *complex*. While *complicated* refers to something that can be analyzed and eventually simplified, *complex* refers to something woven together in such a way that it cannot be reduced to the sum of its parts without losing something essential: the web of relationships. This idea of irreducibility was discussed through the metaphor of a bird's nest: if one decomposes it into branches and threads, what is lost is precisely the weaving that makes it a nest. In the same way, a complex system cannot be understood by isolating its components alone.

Attention then shifted to the formation of ordered and harmonious configurations such as clouds, bird flocks, and ant colonies. Here the role of the observer's perspective emerged, especially the importance of the spatio-temporal scale of observation. Students were invited to recognize that structures such as a flock exist only at a global level: simple local interactions can generate coherent collective forms that are invisible at the level of the individual. In the case of bird flocks, for instance, ordered behavior does not depend on central coordination but on a few simple interaction rules – separation, alignment, and cohesion – from which global spatial patterns emerge.

Building on this reasoning, students explored complex systems through agent-based simulations in NetLogo. By manipulating parameters and interaction rules, they could observe a plurality of emerging scenarios in both biological and social systems, such as flocking and segregation (Fig. 1). This made it possible to highlight analogies across apparently different systems and to give concrete meaning to key concepts such as multiplicity, emergence, and levels of observation. In all these cases, many interacting elements at the microscopic scale give rise to new ordered structures observable only at a broader spatio-temporal scale.

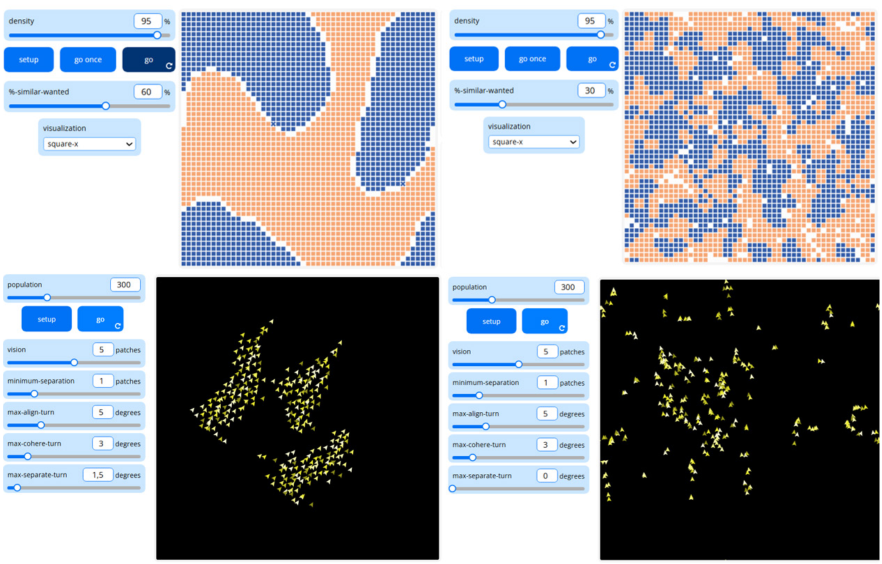


Figure 1. Examples of multiple emerging evolutionary scenarios obtained by varying the sliders in Segregation and Flocking simulations.
Image: NetLogo software

To deepen the concept of emergence, students were introduced to the physical phenomenon of Bénard cells. A fluid heated from below can spontaneously organize into convection patterns: from above, the collective motion of molecules appears as a tessellated arrangement of polygonal cells. This activity made visible the circular relation between parts and whole: the cells are produced by molecular motions, yet those very motions follow the structure of the cells they collectively generate. Self-organization, therefore, becomes recognizable only at a level much larger than that of individual molecules and their interactions.

This example also introduced further key concepts of complexity, such as instability in far-from-equilibrium conditions and sensitivity to contingent events. When the temperature gradient exceeds a critical threshold, small fluctuations are amplified, producing ordered macroscopic motion (Fig. 2). There is, therefore, a deterministic relation between the threshold and the onset of convection. At the same time, the specific direction of the first convective flow depends on local perturbations and cannot be predicted in advance: molecules can rotate either clockwise or anticlockwise. Students were thus guided to observe that complex systems evolve through an interplay of determinism and contingency: critical thresholds make new order possible, while fluctuations shape the particular pathway the system follows.

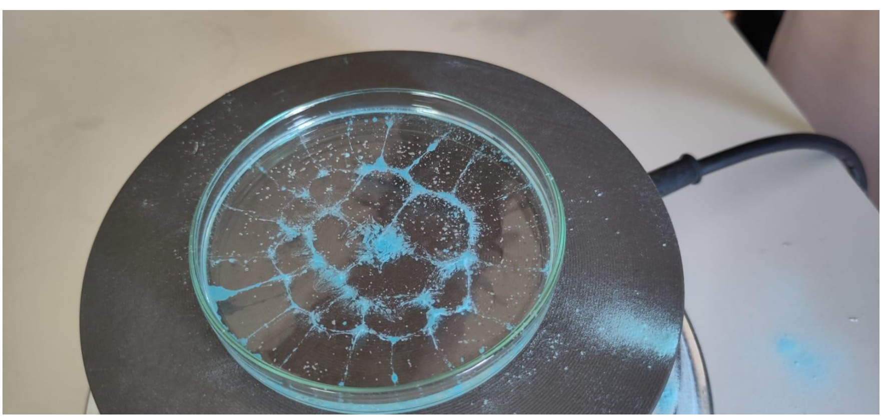


Figure 2. Bénard cells obtained by heating silicone oil in a Petri dish using a metal plate. To make the tessellation of the fluid surface visible, a blue powder of aluminum salts was added as a tracer. (CLIMADEMY project[3])

Image courtesy of the authors

[3] https://climademy.eu/

The study of Bénard cells also highlighted the importance of contingency and bifurcation points, moments at which the system undergoes sudden qualitative changes. At these points, instability becomes a source of novelty, allowing multiple possible evolutionary paths to emerge (Fig. 3). Complex systems are therefore not only capable of generating new forms of order, but also of adapting to local contingencies while maintaining robust macrostructures over time. The model of time evolution of a complex system implies more than one possible future, whose actualization is a matter of tension between inner dynamics, interaction with the environment, and the role of contingency.

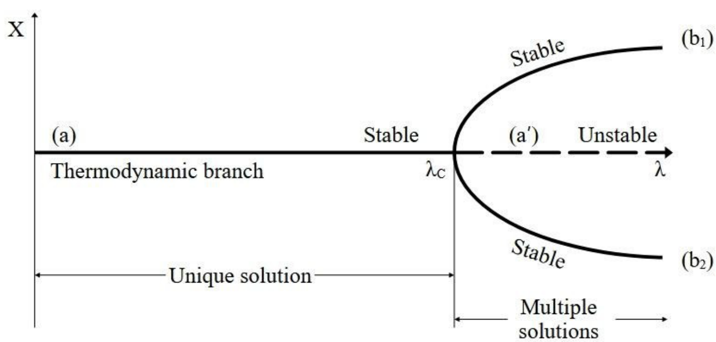


Figure 3. Bifurcation diagram describing the temporal evolution of a complex system, as in the case of Bénard cells. In the continuous interaction between the system and its environment, once a critical threshold of non-equilibrium (λ_c), known a priori, is reached, instability becomes a source of new order (e.g., spatial). At the bifurcation point, the system's sensitivity to contingent events makes it possible for a plurality of evolutionary pathways to emerge. (Ilari, 2024)
Image adapted from Nicolis and Prigogine (1991, p. 85)

In the final part of the activity, attention focused on feedback mechanisms and circular causality. Students observed that, in systems composed of many interconnected variables, causality cannot be described through the simple linear model typical of classical physics. Instead, causes and effects become mutually entangled through feedback processes that may amplify or dampen change. This perspective was synthesized in a shared definition of a complex system as a system composed of many dynamically interacting elements, open to exchanges with its environment, and capable of exhibiting self-organized collective behaviors that emerge from microscopic dynamics and, in turn, feed back on them.

Following these activities on the physics of complex systems, students participated in a creative writing workshop led by literature, history, and physics teachers. Working in small groups, they produced six stories based on selected complex systems, such as a nest, an anthill, or a cloud, while following specific narratological constraints provided by the Italian literature teacher (De Zuani Cassina *et al.*, 2023). As anticipated at the beginning of the paragraph, these stories were collected in the dataset *The physics of clouds*, which was subsequently analyzed.

The study

In this section, we present a comparative qualitative analysis of two datasets of writings produced by secondary school students, collected in different contexts within the Horizon EU-funded project FEDORA (2020–2023).

The first dataset consists of the collection of the six stories of *The physics of clouds*, written in the context just presented, after the activities on the science of complex systems.

The second dataset consists of a selection of 27 essays written between 2018 and 2021 by students aged 17 to 19, prior to their participation in extracurricular activities organized by the Physics Education Research Group at the University of Bologna. The essays concern students' descriptions of their future lives, imagined as an ideal day in 2040, in terms of *(i)* the place where they imagine to live; *(ii)* the kind of life they are leading; *(iii)* the types of problems that they, in their daily life, in their community of people and, in general, in their society are discussing and/or facing; *(iv)* the possibilities and new opportunities they can seize; *(v)* the technology, objects, the house, the city and the environment that surround them; *(vi)* the type of social life they lead. This dataset, entitled *A day in 2040*, has already been analyzed in a previous study (Barelli *et al.*, 2023), which allowed us to select a set of emblematic essays representing the differences among students.

Methods of data analysis

The reading of the two datasets revealed that, in their writings, students express different ways of conceiving and relating to time – an aspect that prompted a strong interest in conducting a qualitative analysis through a temporal lens.

A triangulated bottom-up thematic analysis (Braun & Clarke, 2006) was carried out with the aim of describing the images of time represented in students' writings. The analysis led to the identification of two main temporal images – the *time of the clock* and the *time of experience* – each characterized by specific markers (Table 1).

The time of the clock		*The time of experience*	
Temporal marker	**Description**	**Temporal marker**	**Description**
Linearity – Standardization *of time*	Identifies time as an ordered, repetitive (and predictable) sequence, marked by regular cycles (day/night, weekends) and by personal or social rituals.	*Non–linearity, flexibility*	Indicates a fluid and non-uniform time, in which events do not follow a repetitive sequence and where sudden changes, accelerations, slowdowns, expansions, and suspensions are expected.
Quantifiability, objective measurability of time	Indicates time as an objective entity, countable and divisible, which can be measured with precision.	*Quality of time assessed in terms of the scope or nature of events*	Indicates time that acquires meaning insofar as it is marked by events or changes that are significant due to their social, geopolitical, or environmental impact.
Time as a structure of social organization	Indicates time regulated by external constraints, social norms, and rituals that synchronize the members of a community.	*Relational time*	Indicates time generated through interactions, whose rhythm is shaped by the needs and desires of a collective and/or accelerated by the emotional and affective intensity of relationships among individuals.

Functionality – Time as a resource	Indicates time as a means to achieve a goal and as a resource to be saved or exploited in the best possible way.	*Time open to contingency and surprise*	Indicates time interrupted by unexpected events that create new possibilities. These are contingencies emerging from the context–opportunities to be seized or surprises–not linked to functionality, but capable of opening bifurcations and transforming experience.

Table 1. Markers characterizing the images of time represented in students' writings.

Subsequently, the markers emerging from the data analysis were used to code the writings in the *A day in 2040* and *The physics of clouds* datasets.

Findings

The results of the application of markers to the two datasets are presented in Figure 4. In particular, Fig. 4a shows the temporal profiles of the twenty-seven future essays (dataset *A day in 2040*), while Figure 4b represents the temporal profiles of the six complexity stories (dataset *The physics of clouds*).

Figure 4a. Time profiles of the twenty-seven future essays (dataset *A day in 2040*).

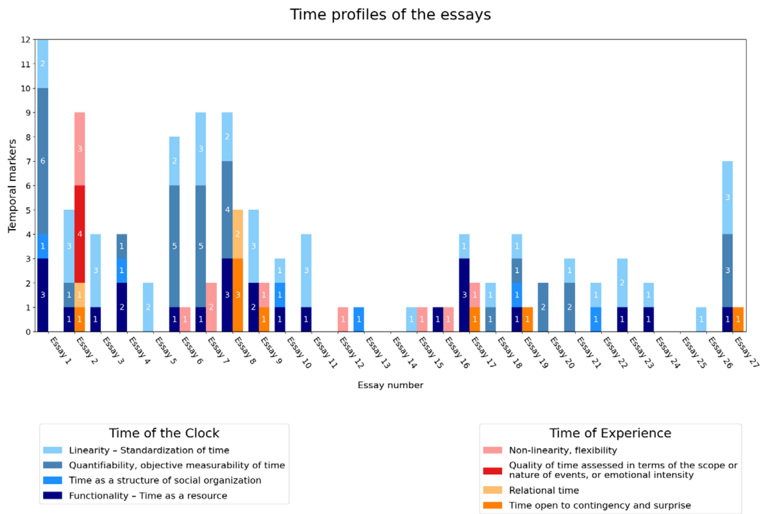
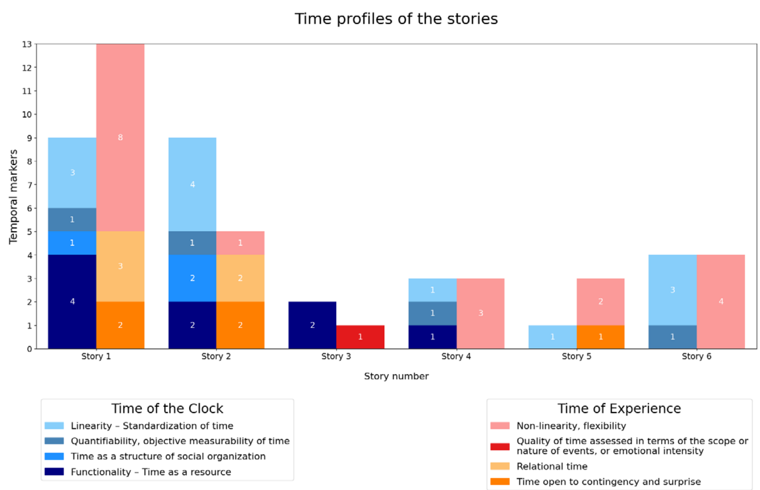


Figure 4b. Time profiles of the six complexity stories (dataset *The physics of*



clouds).

Two future essays (essays 14 and 25 in Fig. 4a) do not display temporal markers. However, it is important to note that, of the 27 essays – originally selected not on the basis of temporal criteria but because they were considered representative of the diversity among students – 25 can be effectively coded using the identified markers and sub-markers. This broad coverage of the sample is an indicator of the generality and robustness of the temporal framework developed.

The figures highlight a clear distinction between the two analyzed datasets. The future essays are strongly characterized by the presence of markers of the *time of the clock*, whereas the stories exhibit a combination of markers from both temporal images. Two essays in the dataset, *A day in 2040* (essays 2 and 8 in Figure 4a), represent exceptions, as they display a significant presence of the *time of experience* alongside the *time of the clock*. In essay 2, an image of the future emerges that is characterized by a move beyond the notion of efficiency and by a relationship – defined by the student as symbiotic – between humans, technology, and nature. This results in a renewed space for the *time of experience*. However, these aspects are ultimately framed within an optimistic view of technological progress, aligning the writing with the hegemonic technocratic narrative.

In essay 8, time emerges as something constructed through the experience of authentic and meaningful relationships with others; however, this is embedded within an organized framework of activities structured by predefined schedules and durations.

Overall, the temporal framework presented in Table 1, developed from the data, enabled us to compare and contrast the images of time emerging from the two datasets (*A day in 2040* and *The physics of clouds*). It allows us to notice how the dominant conception of time among students in the former is that of the *time of the clock*, while also showing, in the *The physics of clouds* stories, the potential contribution of complexity science to expanding and diversifying students' conceptions of time.

Discussion and conclusions

The results obtained from the analysis of the two datasets collected within the FEDORA project are highly promising: introducing the perspective of complex systems science and its model of temporal evolution into the science curriculum can contribute to expanding students' conceptions of time and, consequently, their imagination of the future.

This result is not surprising. The temporal structures of complexity science epistemologically challenge those of Newtonian-Laplacian physics and, with them, the linear, homogeneous, and uniform conception of clock time. Nobel laureate Ilya Prigogine, known for his work on dissipative structures and irreversibility (Nicolis & Prigogine, 1977), distinguishes between the external time of classical physics and the internal time of complexity science (Prigogine, 1980). Newtonian-Laplacian time can be described as:

an external framework independent of events, identical for all systems, which can be conceived as a container or as a coordinated and standardized structure for organizing events;

characterized by a linear and chronological progression;

weakly sensitive to external noise and to the contingency of reality;

the guardian of the order and regularities it imposes;

based on a succession of equally important instants, in which no moment is more significant than another and, consequently, no genuine historicity emerges.

On the other hand, the time of complex systems:

is rooted in the internal dynamics of processes, in open systems interacting with the environment;

is characterized by discontinuities, in which chance plays a crucial role;

exhibits a high sensitivity to both internal and external noise;

acts as a source of new order;

describes becoming, rendering complex systems historical entities, in which critical (or "kairological") moments mark a "before and after" and in which multiple plausible ordered structures may emerge thanks to intrinsic forms of uncertainties.

The perspective of complexity problematizes determinism, predictability, linear causality, and the temporal model of classical Newtonian physics, which has historically underpinned both classical futurology and modernity, with its strong faith in progress. The "words" of complexity – such as uncertainty, probability, contingency, and bifurcation – constitute the basis of the temporal structure represented by the Futures Cone (Fig. 5): analogously to what occurs in systems such as Bénard cells, from certain "critical points" multiple evolutionary trajectories may emerge, making visible the open time of complex systems and the unpredictability of future scenarios (Fig. 3).

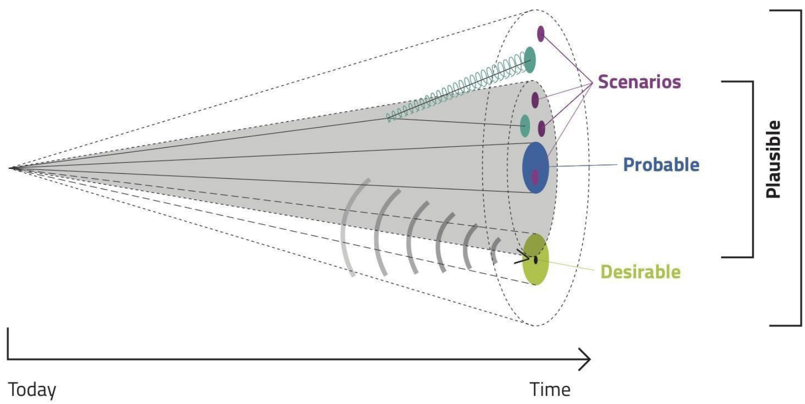


Figure 5. The Futures Cone re-elaborated from (Voros, 2003).
Image developed in the I SEE project[4].

In light of these empirical findings, in subsequent implementations, Prigogine's distinction between external and internal time has become a key reference framework for the design of interdisciplinary curricular activities at the "A. Einstein" Scientific High School in Rimini, in collaboration with the Physics Education Research Group at the University of Bologna.

Between 2022 and 2028, the complexity science activities were progressively expanded across the FEDORA, CLIMADEMY, and FEDORAS[5] projects, integrating interdisciplinary perspectives on time, self-organization, sustainability, and *GreenComp* competences (Bianchi *et al.*, 2022). The latest version of the materials is available at the links in the footnote[6].

The data we are collecting are highly promising, revealing the strong potential of complexity science to futurize science education and, through this, to regenerate school knowledge so that it can equip students with the competences needed to navigate contemporary society and to imagine

[4] https://iseeproject.eu/contact/
[5] https://www.fedoras-academy.eu/
[6] The words of complexity: https://bit.ly/4gNaYqL.
Bénard cells: https://bit.ly/4vI6Hse.
Oscillating chemical systems (e.g. BZ reaction): https://bit.ly/4vJU7cg.

and enact alternative futures.

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Between June and September 2025, Veronica Ilari revisited the thematic bottom-up analysis of the two datasets. The final refinement and consolidation of the temporal markers were carried out under the supervision of Olivia Levrini, with Paola Fantini contributing to the triangulation process.

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