

A VERTICAL SPIRAL CURRICULUM TO PROMOTE SCIENCE EDUCATION IN THE AGE OF THE ANTHROPOCENE: NEW CHALLENGES FOR TEACHER TRAINING

M. Tombolato

University of Urbino Carlo Bo (ITALY)

Abstract

In this era of ecological transition, responding to the challenges posed by the Anthropocene requires collective and coordinated efforts from researchers and experts across academic and professional communities. However, it also requires ordinary citizens to think and act responsibly when making decisions on complex and controversial socio-scientific issues, such as climate change and biodiversity loss. Against this backdrop, the task of schools is to cultivate in individuals the ability to engage with any form of scientific communication that aims to raise environmental awareness and expose misinformation, equipping them to make rational decisions in situations of uncertainty. In this article, we aim to address this highly topical matter by examining two related issues. The first concerns the need to reconsider the relationship between the curriculum and knowledge in light of curriculum overload due to constant societal demands, including those relating to environmental literacy. The second issue concerns which curriculum model is best suited to promoting the relevant types of learning and the training needs of teachers in this regard.

The work is divided into three sections. The first section provides a reflection on the nature of scientific knowledge to address a crucial question for teachers today: “How to avoid creating a ‘mile wide – inch deep’ curriculum?” [4]. The second section, based on valuable insights from the PISA conception of science education, seeks to clarify how teaching science as a practice could be an appropriate solution in both epistemological and pedagogical terms. The third section draws on Stenhouse [5] and Bruner [6] to propose a vertical spiral curriculum based on principles of procedures to help teachers at various school levels to design learning activities consistent with a conception of science as a practice.

Keywords: Curriculum design, science education, education for sustainability, teacher education, principles of procedure.

1 INTRODUCTION

In this era of ecological transition, responding to the challenges posed by the Anthropocene requires collective and coordinated efforts from researchers and experts across academic and professional communities. However, it also requires ordinary citizens to think and act responsibly when making decisions on complex and controversial socio-scientific issues, such as climate change and biodiversity loss. Against this backdrop, there is growing interest in environmental education worldwide, with many nations investing resources to raise awareness and educate new generations about more sustainable lifestyles [1]. Consequently, schools, as the primary place for educating citizens, are called upon to integrate and update their curricula to meet the educational needs of 21st-century students. While the first curriculum reform prompted by the launch of Sputnik (1957–1970) primarily aimed to place students in a 'pipeline' for science careers, recent international education trends have focused on promoting science education to foster engaged and responsible citizenship [2]. The pandemic has clearly shown that easy access to information, enabled by advanced technology, can be a double-edged sword. Lacking the epistemological and critical tools necessary to navigate virtual environments and social networks effectively exposes individuals to the risk of developing false beliefs that could lead to dangerous behavior. The same applies when judging the impact of human activities on ecological systems and the resulting damage.

International literature [3] highlights numerous fallacies in sustainability discourse, such as the omission of relevant data, selective information, and logically invalid arguments, which can be exploited by companies or governments to create a positive image or avoid social and environmental responsibilities. Whether intentional, aimed at manipulating the public, or unintentional, stemming from flawed reasoning, fallacies contribute to information disorder.

Therefore, to prevent individuals from being exposed to the risk of epistemic deprivation when consuming information, it is more important than ever to enhance public understanding of how scientific research works and how the quality of research is evaluated. In this context, the task of schools is to cultivate in individuals the ability to engage with any form of scientific communication that aims to raise environmental awareness and expose misinformation, equipping them to make rational decisions in situations of uncertainty.

In this article, we aim to address this highly topical matter by examining two related issues. The first concerns the need to reconsider the relationship between the curriculum and knowledge in light of curriculum overload [4] due to constant societal demands, including those relating to environmental literacy. The first research question (RQ1) we intend to answer is therefore: "What knowledge is of most worth to avoid a 'mile wide – inch deep' approach to environmental and sustainability education?"

The second issue concerns which curriculum model is best suited to promoting the relevant types of learning and the training needs of teachers in this regard. Hence, the second research question (RQ2) is: "How can in-service and pre-service teacher training be updated to cultivate students who are committed to environmental stewardship and sustainable living?"

The work is divided into three sections. The first section provides a reflection on the nature of scientific knowledge to address a crucial question for teachers today: "How to avoid creating a 'mile wide – inch deep' curriculum?" [4]. The second section, based on valuable insights from the PISA conception of science education, seeks to clarify how teaching science as a practice could be an appropriate solution in both epistemological and pedagogical terms. The third section draws on Stenhouse [5] and Bruner [6] to propose a vertical spiral curriculum based on principles of procedures to help teachers at various school levels to design learning activities consistent with a conception of science as a practice.

2 THE NATURE OF KNOWLEDGE AND THE CURRICULUM

In his book *Introduction to Curriculum Development* (1975), Lawrence Stenhouse [5, p. 30] argues that "thought about curriculum is, in one of its dimensions, thought about the nature of knowledge". Several decades later, educational sociologist Michael Young [8] highlights the significance of a theory of knowledge in shaping curriculum studies. He attributed the current crisis in the field to his colleagues' reluctance to question the epistemological issues concerning the truth and reliability of different forms of knowledge, as well as the fact that these issues have both philosophical and sociological dimensions [8, p. 103]. The result of this crisis is that the curriculum has become overloaded, as stated in the title of the OECD report published in 2020 [4].

Today, schools face increasing social and cultural pressures that lead to fragmentation of the curriculum into a variety of educational domains (e.g., civic, environmental, emotional, digital, information literacy), in addition to traditional teaching disciplines. This trend towards expanding the curriculum instead of seeking to address, in an up-to-date manner, the key questions that guide its design (what to teach; how to teach; why; when; in what types of environments or contexts), risks preventing students from gaining a deep understanding of the "structural constraints" to which the process of disciplinary "knowledge in the making" is subject.

To clarify what we mean by these constraints, we refer to the concept of "consensus practice", formulated by philosopher of science Philip Kitcher [9], to identify the shared framework that enables scientists to collaborate, communicate, and build upon each other's work effectively.

Seeking to detail and disambiguate Kuhn's notion of "paradigm", Kitcher describes the consensus practice of a scientific community as including the following components:

- a) Disciplinary Language: The shared terminology and concepts used by the community.
- b) Significant Questions: The impersonal ordering of questions deemed important by the community.
- c) Accepted Goals and Values: The objectives or aims collectively pursued by the community and the commitment to shared epistemic and ethical values.
- d) Accepted Statements (pictures, diagrams): The body of knowledge, including theories and facts, agreed upon by the community, with a partial justificatory structure.
- e) Explanatory Schemata: a set of explanatory patterns that scientists are committed to when trying to make sense of phenomena.

- f) Authority Paradigms and Criteria: Standards for identifying authoritative sources and assigning credibility within the community.
- g) Experimental Lore: A set of exemplary experiments, observations, and instruments, and justificatory criteria;
- h) Methodological Exemplars and Principles: Examples of good and faulty reasoning, and principles for assessing scientific claims.
- i) Division of Epistemic Labor: An organization of the community into sub-communities recognized as authoritative on specific issues.
- j) A virtual consensus stemming from the mutual epistemic dependence among scientists: in order to contribute to advancing the state of research in their field, every scientist needs to draw on the knowledge of other scholars who are considered experts in specific disciplinary domains (sub-communities).

These components belong to the “common ground” shared by members of a scientific community [10;11] that ensures the possibility of open dialogue and constructive criticism on which scientific endeavor is based. In this sense, these components represent the constraints to which scientists must submit in order to collaboratively advance knowledge within a disciplinary field.

In an era of “knowledge explosion”, characterized by an increasingly specialized culture and the spread of user-friendly technologies for accessing information and generating content (such as generative AI), awareness of such constraints is crucial for identifying the range of epistemically correct behaviors that can be enacted when socio-scientific and socio-environmental issues are at stake.

Indeed, gaining insight into the consensus practice of a scientific community can help students better understand what counts as knowledge in a given field, as well as the reliable methods and practices for advancing it, thereby preventing them from falling victim to information disorder [12].

Concerning RQ1, we can therefore propose the following broad hypothesis: the knowledge most worth avoiding a “mile wide – inch deep” approach to environmental and sustainability education is that relating to the components of the consensus practice. This is because it allows access, in the words of Duschl [13], not only to *what* we know, but also to *how* we know what we know and *why* we believe it.

But how can consensus practice be taught and learned at primary and secondary schools to educate scientifically responsible citizens? To formulate an initial hypothesis, we will quickly look at how apprentices learn consensus practice from veterans to join the scientific community.

Drawing on Wittgenstein's philosophy [14], we could argue that becoming acquainted with the consensus practice of a disciplinary community is like learning a new 'language game', comprising explicit rules and tacit knowledge embedded in practice that together define acceptable behavior and thought within the community.

As Schwab explains [15], disciplines are distinguished by their conceptual and syntactical structures. The conceptual structure of a discipline refers to the body of imposed concepts that serve as guiding principles of inquiry, shaping the scope and meaning of the knowledge produced. These concepts act as heuristic and hermeneutic tools, helping researchers decide what “facts” are sought, and how those facts are interpreted. The conceptual structure also influences the validity and limitations of the conclusions drawn within the discipline, emphasizing that knowledge is not absolute but contextually bound to the principles of inquiry. Simplifying for the sake of clarity, we can relate components a), b), and d) of consensual practice to this conceptual structure.

The syntactical structure (syntax) of a discipline refers to the methods, procedures, and processes it employs to achieve its goals, discover knowledge, and verify truths. It encompasses how a discipline uses its conceptual structures to guide inquiry and determine what is considered verified and warranted knowledge. In this context, the remaining components of consensus practice can be related to this second kind of structure.

By directly engaging with problems considered paradigmatic by the scientific community [16], novices develop a disposition for interpreting reality from the perspective of the discipline, using its network of concepts, as well as for interacting with it in disciplinary ways. For example, they develop a disposition for using core concepts to select only the aspects of reality important to their discipline, as well as for representing these aspects using “tools” such as mathematical formulas, tables, graphs, figures, and diagrams [17]. They also develop a disposition to set up certain experimental or observational situations

and to avoid others. Further, they tend to act in specific ways, rather than in others, when those situations arise and to respond in particular ways to the stimuli those situations produce [9, p. 85].

This process of enculturation into the scientific community requires novices to undergo extensive and repeated training under the mentorship of experts to understand and internalize the 'rules of the game' of scientific practice and thus to develop habits of thought and action [18] consistent with the consensus practice of the community – the *habitus* of the scientist.

According to Bateson's theory of learning [19], the development of these types of dispositions can be classified as deuterio-learning. This second-level learning is collateral to first-level learning (declarative and procedural knowledge) and is therefore predominantly implicit, giving results in the medium to long term. This is why, according to Dewey [18], teachers often pay more attention to pupils' acquisition of declarative and procedural knowledge, which is more evident and easier to assess, while overlooking the formation of enduring habits of thought and action.

In light of this final consideration, the question can be refined as follows: What choices should teachers make regarding what and how to teach, to provide students with the opportunity to develop habits of thought and action that align in "kind", though not in "degree", with those of experts [6]?

The next section will advance a hypothesis based on the conception of science education from the PISA 2025 science framework.

3 FROM KNOWLEDGE "IN USE" TO KNOWLEDGE TO BE TAUGHT AND LEARNED: TEACHING SCIENCE AS A PRACTICE

The Programme for International Student Assessment (PISA) by the Organization for Economic Co-operation and Development (OECD) measures the ability of 15-year-olds in participating countries to apply their knowledge and skills in reading, mathematics, and science to real-life challenges. It was first performed in 2000 and then repeated every three years. A new feature of the 2025 edition is the concept of 'agency in the Anthropocene', which measures students' knowledge of, engagement with, and capacity to act on environmental and sustainability issues as they complete their compulsory education. Specifically, a 15-year-old school leaver prepared to address socio-ecological challenges in modern society should be able to 1) explain the impact of human interactions with Earth's systems, 2) make informed decisions to act based on evaluation of diverse sources of evidence and application of creative and systems thinking to regenerate and sustain the environment, 3) demonstrate respect for diverse perspectives, and hope, in seeking solutions to socio-ecological crises. As the PISA document clarifies, these competencies represent a domain-specific example of the three broad competencies characterizing scientifically literate citizens who can "engage in reasoned discourse about science, sustainability, and technology to inform action" [5, p. 9].

Adopting the PISA perspective on science education requires a dual commitment to promoting a dynamic concept of science as an activity governed by rules established and shared by a scholarly community and to developing a scientifically literate population capable of participating in the economic and democratic agendas of current techno-scientific societies.

Teaching science as a practice is a didactic approach likely to fulfil both these commitments. The concept of science as a set of practices has evolved over the past 60 years, drawing on the research of historians, philosophers, psychologists, and sociologists, and has gradually gained endorsement from many scholars, including the authors of the PISA framework. This approach aims to shed light on how science is actually practised, focusing on the wide range of activities scientists undertake, such as asking questions, developing and using models, planning and carrying out investigations, analysing and interpreting data, applying mathematical and computational thinking, constructing explanations and designing solutions, engaging in argument from evidence, and obtaining, evaluating, and communicating information [20; 21].

The rationale behind designing curricula based on this conceptual framework is that, by engaging with the practices deployed by scientists to produce, validate, evaluate, justify, and communicate knowledge within a particular domain, students are expected to grasp the epistemic criteria necessary to make informed decisions about science-related issues, such as health and the environment. Although fostering students' participation in such activities aligns with how experts share the consensus practices of their community with science novices, significant differences concerning prior knowledge, training quality, intensity, and duration, as well as the educational purposes attributed to science teaching, are to be considered from a didactic perspective.

Recognizing these differences raises the challenge of identifying the conditions under which school science — which does not coincide with scholarly and expert knowledge and practices (“knowledge in use”) — represents a worthwhile activity for students.

This complex problem lies at the heart of the theory of didactic transposition, a concept developed in mathematics education by Yves Chevallard [22, p. 58] to describe “the transition from knowledge regarded as a tool to be put to use, to knowledge as something to be taught and learned”. To prevent the outcome of this transformation from being a mere simplification of “knowledge in use” (i.e., academic and expert knowledge and practices), the theory and its updated versions [e.g., 23; 24; 25] impose epistemological and pedagogical constraints [23]. Epistemological constraints ensure that scholastic knowledge differs in degree, but not in kind, from that assumed as the point of reference. Conversely, pedagogical constraints help to ensure that the knowledge taught at school is accessible to students and meaningful to their personal, cultural, and professional growth.

In short, the transposition process must be understood as an *epistemological process* of reconstructing explicit and tacit “knowledge in use” to enable students to appropriate it, to profoundly change “the ways in which individuals think, speak, and act” [25, p. 171].

Regarding epistemological constraints (what to teach), the PISA framework emphasizes that, to behave epistemically responsibly when researching, selecting, evaluating, and using information to support decision-making in the Anthropocene, citizens must be equipped with content, procedural, and epistemic knowledge. All three of these types of knowledge are key components of science education, as they collectively address the “what”, “how”, and “why” of science.

Content knowledge represents the “what” of science, referring to the facts, concepts, ideas, and theories about the natural world that science has established. It provides students with the core concepts to be used as principles of inquiry, allowing them to “see” reality through the lens of the discipline [15].

Procedural knowledge represents the “how” of science, referring to the standard procedures and practices employed by scientists to formulate reliable statements about the natural and human-made worlds, and to evaluate evidence that can substantiate claims within a specific field of study. It provides students with the procedural components of the syntax of the discipline, such as experimental procedures, modeling techniques, control of variables strategies, techniques for minimizing uncertainty, as well as for abstracting data using tables, graphs, and charts.

Finally, epistemic knowledge is the “why” of science, referring to the philosophy and rationale behind scientific practices. It provides students with the justificatory standards of the syntax of the discipline, enabling them to understand why the practices employed by scientists to pursue specific epistemic goals are reliable and how scientific claims are validated. Topics typically covered by the history and philosophy of science, social epistemology, and the sociological study of science fall within this category, including the nature of scientific observations, hypotheses, models, and theories, the purpose and goals of science, the types of scientific reasoning, and the role of collaboration, critique, and peer review in establishing confidence in scientific claims.

Referring to the closing question of the previous section, these three types of knowledge, which together cover all components of consensus practice, assume different but complementary roles.

Specifically, mastery of content knowledge is necessary to interpret reality from a scientific perspective, using scientific concepts to formulate research questions and interpret research findings.

Mastery of procedural knowledge is necessary to implement scientific behaviors consistent with this interpretation in order to answer these questions.

Mastery of epistemic knowledge is necessary to transform these potential capabilities into stable and enduring dispositions, that is, into scientific habits of thought and action. Indeed, for the connection between a domain-specific view of reality and a domain-specific way of interacting with it to result in a stable and lasting disposition as opposed to a mere mechanical routine easily forgotten after leaving school, it is necessary to understand why disciplinary knowledge is intrinsically perspectival and why certain behaviors are accepted within this perspective rather than others.

However, for epistemic knowledge to effectively connect and make sense of content and procedural knowledge, it must not be taught in isolation, but rather brought to students' attention while they engage in proper scientific practices. This concern relates to the pedagogical constraints of didactic transposition (how to teach) and is connected to our second research question (RQ2).

4 TOWARDS A VERTICAL SPIRAL CURRICULUM BASED ON PRINCIPLES OF PROCEDURE

In the preceding paragraphs, we proposed an answer to the first research question by identifying the most valuable knowledge in the consensus practice of the scientific community of reference, to avoid a 'mile wide – inch deep' approach to environmental and sustainability education.

Taking as a reference how expert scientists share this practice with novices, we interpreted its acquisition in terms of the development of scientific habits of thought and action.

We then considered the epistemological constraints that must be met in the process of transposing this “knowledge in use” (knowledge relating to the components of the consensus practice) into knowledge to be taught and learned, so that students can become epistemically responsible citizens.

Drawing on the PISA 2025 Science Framework, we identified these epistemological constraints (i.e., what should be taught) in the three forms of knowledge (content, procedural, and epistemic), clarifying their distinct yet complementary functions in fostering scientific habits of thought and action.

Turning to pedagogical constraints, which depend on the specific type of learning involved, we must clarify how this knowledge should be taught to attempt to answer the second research question (RQ2). To this end, this final section draws on Stenhouse's process model and Bruner's spiral model to propose a vertical spiral curriculum based on principles of procedure. First, we will provide a theoretical justification for our proposal, and then we will highlight its implications for teacher training.

A vertical spiral curriculum [e.g., 26] is an educational approach where topics, subjects, or themes are introduced at a basic level in earlier grades and revisited with increasing complexity and depth in subsequent grades. This model builds on students' prior knowledge, gradually deepening their understanding of a subject over time. When introducing the concept of the spiral curriculum in 1960, Bruner wrote, “I was struck by the fact that successful efforts to teach highly structured bodies of knowledge like mathematics, physical sciences, and even the field of history often took the form of a metamorphic spiral in which at some simple level a set of ideas or operations were introduced in a rather intuitive way and, once mastered in that spirit, were then revisited and reconstrued in a more formal or operational way, then being connected with other knowledge, the mastery at this stage then being carried one step higher to a new level of formal or operational rigour and to a broader level of abstraction and comprehensiveness. The end state of this process was eventual mastery of the connexity and structure of a large body of knowledge” [6, p. 141].

This curriculum model, therefore, appears to be particularly effective in promoting higher-level learning, which requires extended time and a variety of teaching and learning experiences for development and consolidation. In this sense, it meets our objective of cultivating stable and enduring scientific dispositions in students. As a vertical spiral curriculum can be based on either predefined objectives or procedural principles, we will now explain why we opted for the latter.

The objectives model and the process model differ fundamentally in their approach to curriculum design and development. The former emphasizes pre-specified goals and conceives learning as a linear, measurable process based on a behaviorist approach, whereby 'intended learning outcomes' are achieved through carefully planned interventions [5; 27]. In contrast, the latter focuses on guiding principles that shape how teachers and students engage with disciplinary knowledge, fostering critical inquiry and deeper understanding. Insofar as the process model values knowledge structured by theory and open to critical scrutiny, rather than fixed facts, learning is viewed as the growth of understanding, which is unpredictable and cannot be fully predetermined.

In short, the objectives model is outcome-driven and prescriptive, whereas the model based on principles of procedure provides teachers with criteria for designing activities centered on processes that have intrinsic epistemic, cultural, and educational value. Adopting the model process would therefore help teachers shift from an interest in the products of science (static view of science) to an interest in the processes and practices of science (dynamic view of science, i.e., science “in the making”), as the PISA framework suggests.

However, teachers in Italy are generally unfamiliar with curriculum design based on principles of procedure. This is partly because the objectives model has become widespread in schools, and partly because treating disciplinary knowledge as a process (i.e., “in the making”) requires a deep epistemological awareness, which teachers generally lack. So, to answer RQ2, we propose training teachers in the use of principles of procedure designed to highlight the different but complementary roles that content, procedural, and epistemic knowledge play in the core scientific practices undertaken by

scientists (see the section above). Specifically, these principles aim to support teachers at different school levels in designing educational activities that promote a deeper understanding and awareness of the structural constraints to which “science in the making” is subject.

In summary, our proposal for a vertical spiral curriculum based on principles of procedure must meet two requirements.

First, its procedural principles must capture the most valuable knowledge (in the sense we explained in the text) to avoid a “mile wide – inch deep” approach to environmental and sustainability education.

Secondly, these principles should suggest a variety of activities tailored to different grade levels, to encourage the development of scientific habits of thought and action, consistent with this worthy knowledge, from primary school onwards.

The first requirement is met through a selection process involving an analysis of the PISA 2025 scientific framework, as well as a review of academic scientific textbooks [e.g., 28], and epistemological and educational literature [e.g., 9; 29; 30; 31]. The second requirement involves an empirical study of the training needs of primary and secondary school teachers. To this end, a semi-structured questionnaire is being developed to evaluate the alignment between teachers' instructional choices and the science education approach recommended by the PISA 2025 framework. Teachers' epistemic and didactic beliefs will be investigated, particularly in relation to the set of key practices that a scientifically literate citizen should be able to perform and be disposed to do [21].

5 CONCLUSIONS

Thinking and acting as an informed and responsible citizen in a knowledge-based society is the goal of lifelong and lifewide learning. In this context, formal education and scientific dissemination play different but complementary roles. Public science communication addresses the need for citizens to continuously update their knowledge to make rational choices in uncertain situations.

According to the PISA 2025 science framework, schools have the responsibility to train students to become critical consumers of scientific information, cultivating in them the ability to make the most of any form of science dissemination aimed at improving their understanding and countering misinformation. The task of teachers is therefore to enable future citizens to acquire stable and lasting dispositions to correctly use the three types of knowledge specified in PISA 2025 (content, procedural, and epistemic) when they encounter communications on scientific topics in media and information contexts, during popular events, in colloquial situations, and while browsing institutional websites.

In this paper, it is argued that a step forward in this direction can be taken by a vertical spiral curriculum based on principles of procedure, formulated according to a conception of science as a practice. However, much work still needs to be done in terms of teacher training to ensure practitioners can benefit from this model. Identifying a set of principles that meet the above two requirements is the next goal of this ongoing research.

REFERENCES

- [1] M. Rieckmann, Education for sustainable development goals: Learning objectives. Paris: UNESCO, 2017.
- [2] European Commission: Directorate-General for Research and Innovation, *Science education for responsible citizenship – Report to the European Commission of the expert group on science education*. Publications Office, 2015, <https://data.europa.eu/doi/10.2777/12626>
- [3] L. R. de Lima, F. de Souza Freire, & N. O da Silva. “Fallacies in Sustainability: a Systematic Review”. *Revista de Gestão Social e Ambiental*, vol. 17. no. 10, pp.1–21, 2023.
- [4] OECD, Curriculum Overload: A Way Forward. Paris: OECD Publishing, 2020.
- [5] OECD, *PISA 2025 Science Framework (DRAFT)*, May 2023, <https://pisa-framework.oecd.org/science-2025/>
- [6] J.S. Bruner, *The Process of Education*. Cambridge, MA: Harvard University Press, 1977.
- [7] L. Stenhouse, An introduction to curriculum research and development. London: Heinemann, 1975.

- [8] M. Young, "Overcoming the crisis in curriculum theory: A knowledge-based approach", *Journal of curriculum studies*, vol. 45, no 2, pp. 101-118, 2013.
- [9] P. Kitcher, *The advancement of science: Science without legend, objectivity without illusions*. New York: Oxford University Press, 1993.
- [10] R. N. Giere, "An agent-based conception of models and scientific representation", *Synthese*, vol. 172, no 2, pp.269-281, 2010.
- [11] M. Tombolato, *La conoscenza della conoscenza scientifica. Problemi didattici*. Milano: FrancoAngeli, 2020.
- [12] C. Wardle, *Information disorder: The essential glossary*, 2018, https://firstdraftnews.org/wp-content/uploads/2018/07/infoDisorder_glossary.pdf
- [13] R. Duschl, "Science education in three-part harmony: Balancing conceptual, epistemic, and social learning goals", *Review of research in education*, vol. 32, no 1, pp. 268-291, 2008.
- [14] L. Wittgenstein, *Philosophical Investigations*. Oxford: Blackwell, 1953.
- [15] J. J. Schwab, "The concept of the structure of a discipline", *Educational record*, vol. 43, no 3, pp. 197-205, 1962.
- [16] T. S. Kuhn, *The structure of scientific revolutions*. Chicago: University of Chicago Press, 1962.
- [17] W. M. Roth, K. Tobin, "Cascades of inscriptions and the re-presentation of nature: how numbers, tables, graphs, and money come to re-present a rolling ball", *International Journal of Science Education*, vol 19, no 9, pp. 1075-1091, 1997.
- [18] J. Dewey, *Experience and Education*. New York: Macmillan, 1953.
- [19] G. Bateson, *Steps to an ecology of mind*. Chicago: University of Chicago Press, 2000.
- [20] J. Osborne, "Teaching scientific practices: Meeting the challenge of change". *Journal of Science Teacher Education*, vol. 25, no 2, pp. 177-196, 2014.
- [21] National Research Council, *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. Washington, DC.: Committee on a Conceptual Framework for New K-12 Science Education Standards. Board on Science Education, Division of Behavioral and Social Sciences and Education, 2012.
- [22] Y. Chevallard, "On didactic transposition theory: Some introductory notes" in *Proceedings of the international symposium on selected domains of research and development in mathematics education* (Bratislava, 3–7 August 1988), pp. 51–62, Bratislava, 1989, http://yves.chevallard.free.fr/spip/spip/IMG/pdf/On_Didactic_Transposition_Theory.pdf
- [23] B. Martini, *Pedagogia dei saperi: problemi, luoghi e pratiche per l'educazione*. Milano: Franco Angeli, 2011.
- [24] M. L. Schubauer Leoni, "Didactique", in *Dictionnaire de l'éducation* (A. van Zanten eds.), pp. 129-133, Paris: PUF, 2008.
- [25] B. Schneuwly, "'Didactiques' is not (entirely) 'Didaktik' The origin and atmosphere of a recent academic field", in *Didactic and Curriculum in an Ongoing Dialogue* (E. Krogh, A. Qvortrup, S.T. Graf eds.), pp.164-184, New York: Routledge, 2021.
- [26] S. Wulandari, "What Should be Mastered by Elementary, Junior and Senior High School Teachers Related to the Concept of Evolution?", *European Online Journal of Natural and Social Sciences*, vol.10, no 1, pp. 9-18, 2021.
- [27] M. James, "An alternative to the objectives model: the process model for the design and development of curriculum", in *Curriculum, Pedagogy and Educational Research. The work of Lawrence Stenhouse* (N. Norris, J. Elliott eds.), pp. 61-83, Abingdon: Routledge, 2012.
- [28] T. M. Smith, R. L. Smith, *Elements of Ecology* (8th Edition). San Francisco: Pearson Benjamin Cummings, 2012.
- [29] R. N. Giere, *Explaining science: A cognitive approach*. University of Chicago Press, 1988.

- [30] W.C Newstetter, E. Behraves, N.J. Nersessian, *et al.*, "Design Principles for Problem-Driven Learning Laboratories in Biomedical Engineering Education", *Ann Biomed Eng*, vol. 38, pp. 3257–3267, 2010. <https://doi.org/10.1007/s10439-010-0063-x>.
- [31] M. R. Matthews, "Learning about Scientific Methodology and the 'Big Picture' of Science: The Contribution of Pendulum Motion Studies", in *Philosophy of Education Yearbook*, pp. 204-213, 2001.