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To cite this article: Mina Mani, Måns Gezelius, Jonas Löwgren, Gunnar Höst, Marta M. Koć-Januchta, Lena A. E. Tibell & Konrad J. Schönborn (30 Apr 2025): Designing with multiple perspectives: an interactive learning environment for developing systems thinking in a carbon cycle context, Interactive Learning Environments, DOI: [10.1080/10494820.2025.2494161](https://doi.org/10.1080/10494820.2025.2494161)

To link to this article: <https://doi.org/10.1080/10494820.2025.2494161>



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Published online: 30 Apr 2025.



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Designing with multiple perspectives: an interactive learning environment for developing systems thinking in a carbon cycle context

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ABSTRACT

Although there is an increasing body of knowledge on interactive learning environments in science education, there is little reported on the empirical process of designing such environments with multiple perspectives. This study describes the design of *Tracing Carbon*, a learning environment for developing grade 7–9 pupils' systems thinking skills in the context of the carbon cycle. Following an educational design research approach, we describe an explorative iterative design process that integrates multiple perspectives, including conceptual drivers, the design team, science teachers, and pupils. The design process resulted in an adaptive interactive visual learning environment with multiple learning tasks and quizzes organised in three modules addressing ecological, global and human intervention-related aspects of the carbon cycle. Each module is designed with coherent learning objectives aligned with a systems thinking skills hierarchy and the Swedish school curriculum. Our main insights concern the applicability of the systems thinking hierarchical model, the didactic value of adaptive and interactive visual learning tasks, and the contributions of professional teachers to going beyond established interaction design conventions. These findings might guide the development of interactive learning environments for other science learning situations. Future work will investigate the integration of *Tracing Carbon* in science teaching in schools.

ARTICLE HISTORY

Received 24 February 2024
Accepted 10 April 2025


KEYWORDS

Multiple-perspective design process; adaptive interactive learning environment; systems thinking; carbon cycle; science education; educational design research

1. Introduction

Interactive digital learning environments are used to support education at all levels. The details of how interactive learning environments are designed and integrated into educational contexts are highly significant for their outcomes. Here, a complex set of interrelated factors come into play, including domain-specific instructional theories, learning theories, national curricula, professional teaching practice, interaction design skills, and pupils' preconditions and learning needs (cf. Mor & Winters, 2007; Mork, 2011). Hence, interactive learning environments are typically developed for situations where the interests of multiple stakeholders intersect. To ensure that the interests of multiple stakeholders are effectively addressed, they need to be represented in the design process. Therefore, considering a multiple-perspective approach for setting up the process of designing interactive learning environments is of high importance.

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 Supplemental data for this article can be accessed online at <https://doi.org/10.1080/10494820.2025.2494161>.

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While the body of knowledge in educational design research on interactive learning environments is vital and growing (e.g. Alevén et al., 2003; Lancaster et al., 2013; Mayer, 2021; Moreno & Mayer, 2007), we find that the issue of working with multiple perspectives is not studied to its full extent (cf. Hall, 2020; Mor & Winters, 2007; Nelson et al., 2005; Reeves, 2006; Squire, 2005). This paper contributes by describing the creation and execution of an authentic design process that affords explorative design of an interactive learning environment with multiple perspectives in play, while still adapting to the constraints of a realistic development situation. The study is thus a methodological contribution in the sense of guiding action; our aim is to empower educational designers and researchers in developing effective learning environments for similar learning situations (cf. Bopadikar et al., 2023; Reeves, 2000).

By employing an educational design research approach (Van den Akker et al., 2006), we provide a detailed design case study account (cf. Howard et al., 2012; Scaife et al., 1997) of our process and the key insights that were gained. Specifically, we present the design process and prototype of an interactive learning environment called *Tracing Carbon*. The environment is intended to support the development of systems thinking in the context of the carbon cycle among grade 7–9 pupils (ages 13–15), based on individual learning progressions through adaptive difficulty.

In this vein, example contributions include Mor and Winters' (2007) emphasis on the critical importance of a design process for technology-enhanced learning environments that involve inputs from multiple perspectives. In addition, Mork (2011) reported the design of an interactive learning environment intended for supporting pupils' learning of radioactivity based on the integration of quality digital learning principles. Furthermore, Mavroudi et al. (2016) stressed the involvement of in-service teachers in the design of adaptive learning environments intended to meet envisaged learning outcomes. Taking a similar approach, the presented work focuses on bringing multiple perspectives to the iterative design process of *Tracing Carbon*, an adaptive learning environment to support the development of systems thinking skills for lower secondary pupils. We wish to point out that alongside conventional design perspectives representing groups of human stakeholders, we also incorporate conceptual drivers as an informing theoretical perspective also driving the design process. Conceptual drivers include the relevant theoretical frameworks and technological considerations that inform key decisions in various stages of the design process.

This paper continues by focusing on the theoretical perspectives and describing core conceptual drivers, followed by the research aim and research questions. In section 4, we describe the methodological framework, participants, and informing perspectives of the design process in addition to data collection and analysis. Then, section 5 provides an in-depth account of the design process as the “data” for our study that was analysed interpretively with respect to the research questions. To provide a broader context for assessing our methodological findings, the design process is then followed by a brief overview of the outcome, i.e. the *Tracing Carbon* learning environment. In section 7, we present our findings by structuring them in alignment with the research questions and conclude by reflecting upon contributions, limitations, and future work.

2. Theoretical background and intended learning context

This section overviews previous research relevant to the study by focusing on systems thinking skills in connection to the carbon cycle and interactive adaptive visualizations for supporting the development of these skills. The background aims to highlight the relevance of the intended learning context and emphasise the significance of our work within science learning at large. We refer to the core perspectives discussed in the background as conceptual drivers, one of the four perspectives informing the design process.

2.1. Systems thinking skills and the carbon cycle in science education

In recent years, systems thinking has gained significant attention as a crucial aspect of teaching and learning in science education (Hmelo-Silver et al., 2007; Hmelo-Silver & Azevedo, 2006; Mambrey

et al., 2022; Seher Budak & Defne Ceyhan, 2024). Systems thinking involves the ability to understand, explain, and interpret complex and dynamic systems (Verhoeff et al., 2018). As a case in point, climate change is one of the most pressing challenges of our time, and learning about relevant earth systems, such as the carbon cycle, has become an essential part of educational curricula worldwide. For instance, the Swedish compulsory school curriculum emphasises the need to understand the carbon cycle and its connection to various environmental and biological issues (Skolverket, 2018). Doing so requires learners to recognise carbon reservoirs and the processes that circulate carbon atoms between these reservoirs, as well as understanding how human activities affect the natural balance of the dynamic relationships within this cycle.

In the context of earth systems, Assaraf and Orion (2005) have proposed the Systems Thinking Hierarchical (STH) model, where the skills required for systems thinking are summarised through eight characteristics (Table 1). The STH model suggests that the development of systems thinking skills occurs in three sequential levels, namely *Analysis*, *Synthesis*, and *Implementation* (Assaraf & Orion, 2010).

Applying this model to the carbon cycle suggests that the basic level of systems thinking skills, Analysis, is about the ability to identify the components of the carbon cycle, including carbon reservoirs and processes that transfer and transform carbon atoms between reservoirs. The second hierarchical level is about synthesising the components of the carbon cycle and focuses on the ability to identify the simple and dynamic relationships within the carbon cycle and the ability to understand its cyclic nature in terms of matter and energy. The highest level, Implementation, focuses on understanding the hidden dimensions of the system, the ability to generalise, and the ability to think temporally (Table 1).

Learning about the carbon cycle is known to be challenging in practice. Several studies point to difficulties in identifying the components of this complex system, as well as how they are connected through processes of transformation at different levels (Asshoff et al., 2010; Düsing et al., 2019; Hmelo-Silver et al., 2007; Hmelo-Silver & Azevedo, 2006; Pazicni & Flynn, 2019). It is also difficult to learn how the carbon cycle relates to other environmental and biological issues (Asshoff et al., 2010; Mohan et al., 2009; Zangori et al., 2017) and to understand its hidden dimensions and dynamic behaviours (Asshoff et al., 2020; Düsing et al., 2019; Mohan et al., 2009). To address these learning challenges, we propose that the STH model can be used to structure subject content about the carbon cycle in a progression that facilitates learning.

Additionally, in a Swedish school context, the content of the carbon cycle in the grade 7–9 curriculum is scattered across different components of chemistry, biology, and physics subject content (Skolverket, 2018). Having the content dispersed among multiple subjects may pose extra barriers to perceiving the interconnected aspects of this cycle.

After reviewing the role of systems thinking in science education, we now introduce relevant aspects of interactive visual learning environments.

Table 1. Eight characteristics of systems thinking skills in the STH model structured in three sequential levels based on Assaraf and Orion (2005, p. 523, 2010, p.541).

Level	Systems thinking abilities
Analysis	"The ability to identify the components of a system and processes within the system."
Synthesis	"The ability to identify simple relationships between or among the system's components."
	"The ability to identify dynamic relationships within the system."
Implementation	"The ability to organize the systems' components, processes, and their interactions, within a framework of relationships."
	"The ability to identify cycles of matter and energy within the system – the cyclic nature of systems."
	"The ability to recognize hidden dimensions of the system – to understand natural phenomena through patterns and interrelationships not seen on the surface."
	"The ability to make generalizations – to solve problems based on understanding systems' mechanisms."
	"The ability to think temporally: retrospection and prediction. Understanding that some of the presented interaction within the system took place in the past, while future events may result from present interactions."

2.2. Adaptive interactive visual learning environments to support the development of systems thinking

Digital learning environments offer learners various possibilities to engage with and explore scientific concepts. This study draws upon four main possibilities that can contribute to learning about complex systems, including visual representation, interactive visualization, multiple representations, and adaptive characteristics. Utilising these in a meaningful way can potentially facilitate guiding learners through carbon cycle content and scaffold their systems thinking skills.

2.2.1. Visual representations for learning science

Visual representations are essential for learning and communicating science (Gilbert, 2008; LaDue et al., 2015; Mathewson, 1999; Mayer, 2021) as they can promote a shared understanding of scientific phenomena by displaying data and organising complex information in an accessible manner (Cook, 2006). Visual representations can significantly enhance the understanding of complex scientific concepts by going beyond textual explanations and visualising intangible and abstract aspects not directly observable to the naked eye (Buckley, 2000; Ryoo & Linn, 2012).

Diagrams are one form of visual representation that are commonly used for scientific communication in the earth and environmental sciences (Fandel et al., 2018) as they can provide a broad view of a whole system and simultaneously reduce learners' cognitive effort by making relevant aspects of the processes more salient (Cheng et al., 2001). The carbon cycle is an abstract and complex system that requires understanding various otherwise unobservable components and processes (e.g. Asshoff et al., 2020; Düsing et al., 2019). Visualising carbon reservoirs and processes helps learners to recognise the components of the carbon cycle and can potentially facilitate acquiring the *analysis* level of systems thinking skills in the STH model. A diagrammatic representation of the carbon cycle facilitates an understanding of the relationships and the cyclic nature of this system and contributes to developing *synthesis* and *implementation* systems thinking skills in the STH model.

Learners' cognitive effort and prior knowledge are recognised factors for designing effective visualizations (Cook, 2006). Cognitive load theory implies that the design of instructional materials needs to account for the capacity of learners' working memory (Sweller et al., 2011). In this regard, effectively utilising cognitive resources for actual learning requires avoiding elements that unnecessarily consume these resources (Sweller et al., 2019). Another strategy for moderating the required cognitive effort while engaging with visual material is to opt for multiple representations instead of representing all the information in a single visualization.

2.2.2. Multiple representations in the learning of complex science concepts

A large volume of research has shown the potential benefits of multiple representations for learning complex scientific concepts (e.g. Ainsworth, 2008; Schönborn & Anderson, 2006). The literature contains several seminal contributions indicating the crucial role that multiple representations play in learning and teaching science. For example, multiple representations can help enhance understanding by providing different perspectives and ways to interpret information (e.g. Kozma, 2003). Multiple representations can also support engagement and motivation by making learning more interactive, which can promote the transfer and application of knowledge across other representations and contexts (e.g. Ainsworth, 2006). Digital learning environments and multimedia applications enable learners to engage with various types of visual representations, and they have the potential to enhance the learning experience through additional features, such as segmentation (Mayer, 2021). Multimedia learning environments that present information in learner-paced segments facilitate the learning process by providing learners with enough time to process the information (Rey et al., 2019). Additionally, the assistance provided in chunking visual information could potentially help learners perceive the underlying structure of the process or procedure (Spanners et al., 2010).

Segmenting the carbon cycle content informed by the STH model might help guide students through the three systems thinking skill levels. It additionally provides the opportunity to address known domain learning challenges including understanding carbon transformation at different organisational levels, realising the connection between the carbon cycle and environmental threats, and recognising hidden aspects of the carbon cycle.

2.2.3. Interactive visualization environments for learning abstract science concepts

Aside from visual design, how learners interact with visualizations is also highly important. Given the widespread utilisation of technology, integrating interactivity has become a dynamic and engaging approach to enrich visualizations across various educational domains (Moreno & Mayer, 2007; Ryoo & Bedell, 2019; Schönborn et al., 2016). Interactive features can potentially enhance the effectiveness of visualizations in various ways, such as allowing learners to control the rate of information or test their ideas (Koć-Januchta et al., 2020; McElhaney et al., 2014; Stenlund & Tibell, 2019). They additionally provide the opportunity for an active learning process by engaging the learner rather than passively presenting information (Koć-Januchta et al., 2020; Stenlund & Tibell, 2019).

Previous research supports the positive effect of interactive visualization on learning complex and abstract science topics. For instance, Ryoo and Linn (2012) investigated the influence of dynamic visualizations, compared to static illustrations, and found that dynamic visualizations can facilitate understanding abstract subjects such as molecular processes. Evagorou et al. (2009) explored the influence of a simulation-based interactive learning environment on developing systems thinking skills in elementary pupils. They advocated for incorporating well-designed interactive educational tools to foster the development of systems thinking skills.

2.2.4. Adaptive characteristics of interactive science learning environments

Adaptive interactive learning environments that can provide automated feedback and adapt to the learner's pace and level of understanding have started to receive attention in science education (Gerard et al., 2015). Previous and emerging research in this area includes work on interactive learning environments in STEM contexts and adaptive feedback for supporting the learning of complex natural systems, and more recently on the role of natural language processing (NLP) models for helping students integrate knowledge when interacting with adaptive systems (Gerard et al., 2024; Linn et al., 2014; Vitale et al., 2016).

Our analysis of the literature has yielded several key adaptive characteristics of interactive learning environments that are associated with enhancing understanding and engagement for science and STEM-related learning. Five key adaptive characteristics are as follows. Firstly, interactive models such as the inclusion of interactive simulations help visualize complex scientific concepts. Secondly user interaction that promotes active engagement through interactive interfaces are strongly related to maintaining student interest and motivation. Thirdly, environments that offer automated assessment providing feedback and adjusting task difficulty based on students' progress can enhance learning (e.g. Paiva et al., 2022). Fourthly, self-regulation features such as instructional prompts and opportunities to monitor self-assessment can facilitate learning processes. Fifthly, personalisation features that provide tailored guidance based on learners' performance can yield effective learning processes (e.g. Scheiter et al., 2017). In this regard, automated feedback can be provided instantly or with a delay to support learners' needs in different contexts. Immediate feedback allows learners to rapidly adjust their actions by helping them to recognise the accuracy of their responses. Delayed feedback, on the other hand, aims to encourage learners to reflect on their responses before seeking guidance and is usually suggested to promote a deeper understanding of the material.

Multiple studies have shown that guidance with adaptive features can support individual learning and progress. Nevertheless, although learners' access to adaptive interactive platforms for science education is on the rise, there is a dearth in efforts focusing on the empirical process of the design of such tools for meaningful integration in teaching about systems thinking.

3. Aim of the study and research questions

In the spirit of the approaches motivated above, the overall aim of this study is to adopt a multi-perspective and iterative process for designing an adaptive learning environment to support the development of systems thinking skills for lower secondary pupils. In applying an educational design research approach that connects research and practice, we identify four prominent perspectives in the intended learning situation, including teachers, pupils and the design team, and finally what we term conceptual drivers. In aiming to structure and communicate a set of process-related insights from a design case study, we pose the following research questions:

- (1) How can a systems thinking theoretical model inform the design of an adaptive interactive learning environment intended to guide pupils through different levels of systems thinking skills in the context of the carbon cycle?
- (2) How can multiple interactive visual representations and elements of adaptivity be utilised in the design of the intended learning environment?
- (3) How can experienced and practicing secondary science teachers be involved in the iterative design process?
- (4) How can grade 7–9 pupils be involved in the iterative design process?

4. Methods

In the method section, we first introduce the methodological framework and then provide a detailed account of our research method, including participants and informing perspectives, as well as data collection and analysis methods.

4.1. Methodological framework

The methodological approach in this study aligns with Educational Design Research (EDR) while drawing inspiration from how knowledge is produced in Constructive Design Research (CDR).

EDR is the systematic study of the design, development, and evaluation of educational programs, processes, and products (Van den Akker et al., 2006). It is an umbrella term for various labels, including design-based research (Barab & Squire, 2004; Kelly, 2003), design experiments (Brown, 1992), engineering research (Burkhardt, 2006), development research (Reeves, 2000), and design studies (Shavelson et al., 2003). EDR is generally considered suitable for combining theoretical knowledge with practical interventions in real educational contexts (McKenney & Reeves, 2018), hence bridging the bidirectional gap between research and application (Anderson & Shattuck, 2012; Barab & Squire, 2004; Biesta, 2007; Plomp, 2013).

CDR refers to processes of knowledge production with design practice at their core (Frayling, 1993). The kind of knowledge they produce is based on specific cases and abstracted only to a limited extent, yielding what is known as intermediate-level knowledge (Löwgren, 2013). For other researchers to benefit from such knowledge contributions, it is essential that they are presented in enough detail to support critical assessment and potential transfer to other contexts. This is very similar to how case studies are performed and communicated in general qualitative research (cf. Howard et al., 2012).

Although EDR and CDR are typically used for different purposes, they both intend to enhance real-world situations by exploring innovative solutions while aiming to generate theoretical knowledge as key research contributions. Both approaches advocate collaboration between stakeholders throughout multiple iterative intervention cycles to achieve enhanced outcomes. However, the nature of the intervention differs slightly in the two traditions. EDR broadly utilises the term intervention to denote different kinds of designed solutions, including educational products, processes,

programs, or policies (McKenney & Reeves, 2018). CDR, on the other hand, usually uses the term *design artifact* as the outcome of the design process that could take various forms ranging from designed objects to services to processes (Stappers & Giaccardi, 2017). In both approaches, however, interventions can be seen as entities designed to study a phenomenon or create change in specific settings. This article recognises the design process of an educational resource as a form of intervention that addresses a learning challenge in the science education domain. In response to the posed research questions, the study described here is a design case representing the involvement and iterative input of four different perspectives, including conceptual drivers, the design team, teachers, and pupils during the design process of the developed learning environment. Since there were no obvious precedents to the objectives of this study, we took an explorative approach to investigate different design possibilities and their merits.

4.2. Participants and informing perspectives

Traditionally, the term “participants” refers to the human actors involved in the research process. However, a key aspect of our work is the inclusion of conceptual drivers in the design process as theoretical perspectives and technological considerations that inform the design decisions. Therefore, in this section (see Table 2), we introduce participants and informing perspectives to emphasise human actors and theoretical perspectives that informed various stages of the design process, respectively.

The research described here has strictly adhered to established ethical guidelines (Vetenskapsrådet, 2024) to protect the integrity and confidentiality of all participants. Specifically, all participants were informed about the purpose of the research, and informed consent was collected from participants and their legal guardians when required.

4.3. Data collection and analysis

As stated earlier, this article considers the design process of an educational resource as an intervention intended to support systems thinking in the science education domain. Therefore, the design process itself is the empirical data that is recorded, communicated and analysed reflexively (Alvesson & Skoldberg, 2017). Various methods have been used to record the involvement of different participants throughout the design process.

Relevant theoretical frameworks and technological considerations were identified through desk research and review of the literature and then structured and synthesised to form the conceptual drivers.

Teachers were involved in all design phases through one round of individual reflections, three online focus group meetings, and two rounds of semi-structured individual online interviews. The focus group meetings and individual interviews were screen-recorded and analysed interpretively by the first author to provide insights for iterating the outcomes of various design phases.

Pupils from the teachers’ classes were involved in the design process on two occasions in the final design phases. Firstly, six grade 8 pupils aged 14–15 provided eye tracking data that informed the

Table 2. Participants and informing perspectives and their accompanying descriptions.

Participants and informing perspectives	Description
Conceptual drivers	Theoretical frameworks and technological considerations that informed decisions in various stages of the design process.
Design team	Science education researchers, interaction designers, and interactive learning technology developers who planned and led the design process.
Teachers	Ten practising grade 7–9 science teachers from around Sweden.
Pupils	Participating grade 8–9 pupils from the teachers’ classes.

fourth design phase (see section 5.4). Secondly, 97 grade 8–9 pupils engaged with the non-adaptive prototype version of the learning environment as part of a classroom activity. The data from pupils' interactions, including the time and content of each interaction event as well as the number of mistakes made, was recorded and led to significant iterations on the overall design.

The design team planned and led the iterative design process based on the collected input from other perspectives. The events during the design process were documented through researchers' notes and the research diary, which were later organised to provide a structured account of the complex design process (section 5).

In the remainder of this article, we first provide an account of the design process as the recorded empirical data. Then, in section 6, we describe the produced outcome termed Tracing Carbon. Subsequently, in section 7, we present our interpretive qualitative analysis of the data structured by the research questions that drive our inquiry in this paper.

5. Design process

This section aims to provide a detailed account of the design process as a basis for our interpretive analysis. The design process of this study comprises four contributing perspectives and five main phases with an overall sequential progression (Figure 1). However, as indicated by the arrows in Figure 1, the project was iterative rather than linear, wherein the subsequent four phases often occurred in parallel. This section presents the design phases in turn.

5.1. Framing the design space

The initial phase of our design process provided a first overview of the design situation and specifically the constraints and opportunities that would direct our work. We focused on the carbon cycle

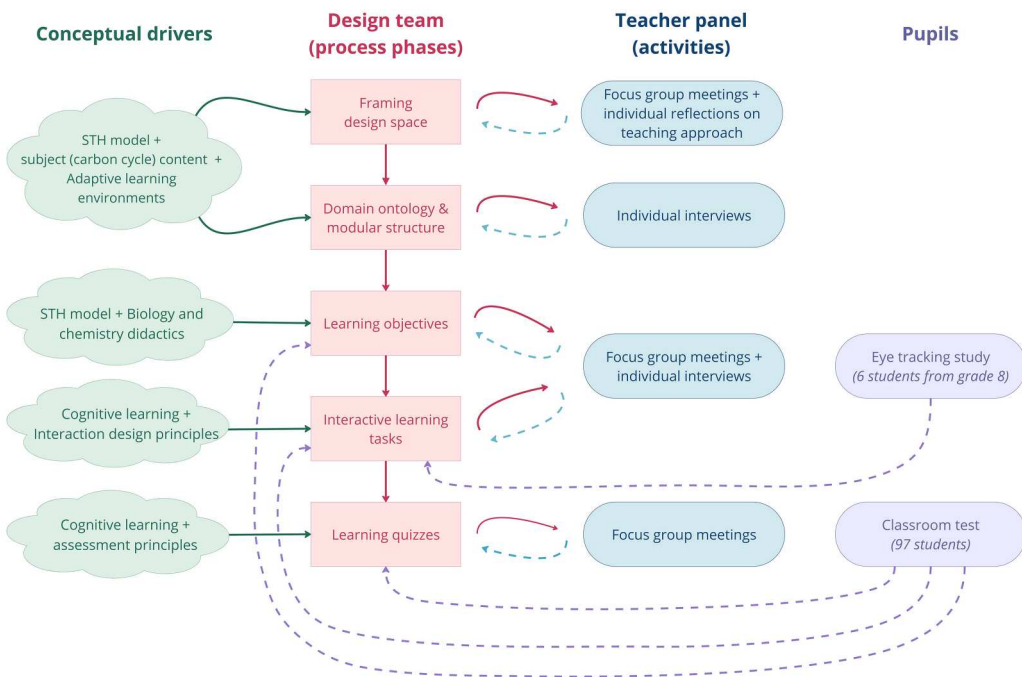


Figure 1. The design process of this study comprising four contributing perspectives and five main phases with an overall sequential progression. The arrows indicate insight and feedback between various perspectives and the design phases, with the dashed arrows highlighting validation and iteration.

subject knowledge relevant to grades 7–9. In the Swedish educational system, there are no unified learning materials for compulsory school. The carbon cycle is mentioned in different subjects for the target group, and the national curriculum does not provide clear instructions on the detailed specifications of this topic. To map out the relevant subject content, we consulted the grade 7–9 curriculum for the Swedish compulsory school (Skolverket, 2018) and analysed other available digital learning resources, including two digital teaching supplements and coursebooks (e.g. Andréasson et al., 2011b; Mårtensson, 2010; Nationalencyklopedin, n.d.; Gleerups, n.d.; Andréasson et al., 2011a; Nettelblad & Nettelblad, 2013). We then identified the components of the carbon cycle content across different science subjects – including biology, chemistry, and physics – and organised them into four categories (Figure 2). In parallel, by reviewing the previous work on systems thinking skills in the science education literature, we selected the STH model (Assaraf & Orion, 2005) as the main theoretical driver to scaffold the development of systems thinking skills within the design.

A focus group meeting with the teachers was arranged to involve them in the first phase of the design process. The meeting addressed teachers' current approaches to teaching the carbon cycle and the strengths and weaknesses of existing learning resources. One of the main takeaways from this meeting was that there is not one standardised way of teaching the carbon cycle. This insight was echoed in multiple instances across teachers' individual reflections – translated from Swedish by the authors – presented in the following quotes:

“My big focus when I teach natural science is language development and building knowledge around images. I usually go through the carbon cycle in different rounds. It starts in grade 7 when we go through the impact on soil and water. Then when I teach about the chemistry of the carbon atom in year 8, and also when I teach about different parts of the environmental impact in year 9. It is important that the pupils see the big picture, both how the natural cycle works and how our way of life affects it.” (Teacher A, Individual reflection on teaching approach)

“What I usually do is to use closed ecosystems in glass containers. With the pupils, we then discuss what will happen to the animals and plants in the container. Pupils can write a story about why it does not need to be opened to let in air or filled with water. Then, make comparisons between the glass container and the whole Earth as an ecosystem.” (Teacher B, Individual reflection on teaching approach)

Other insights from the meeting were that conventional visual diagram representations of the carbon cycle often contain too much information and are difficult for grade 7–9 pupils to understand, and that existing digital learning resources do not take full advantage of interactive features.

Carbon reservoirs in the earth's subsystems	Trophic levels of organisms	Processes that transform and transfer carbon compounds	Dynamic systems properties of the carbon cycle
Atmosphere	Primary producer	Photosynthesis	Reservoir sizes, flux magnitudes & residence times
Hydrosphere	Consumer	Biosynthesis	
Lithosphere	Decomposer	Digestion	System behavior : feedback loops, accumulation & time delays
Biosphere		Cellular respiration	
		Combustion	Slow/Fast carbon cycle
		Geological processes	Human intervention
		Ocean-Atmosphere exchange	Climate change

Figure 2. Components of the carbon cycle identified and organised into four categories by the authors.

Furthermore, teachers confirmed that the identified components of the carbon cycle content (Figure 2) were compatible with the curricular requirements for grade 7-9. An important remark was that not every pupil is expected to develop a deep understanding of every component.

5.2. Domain ontology with a modular structure

In the second phase of the design process, we continued working on the subject content to discern a representation that would accommodate diverse teaching approaches and at the same time align with the hierarchical progression of systems thinking skills. The work entailed iterative development of a domain ontology for grade 7–9 with a modular structure that would serve as the backbone of our adaptive learning environment. We structured the components of the carbon cycle content according to the STH model, starting the progression of learning content from the Analysis level, followed by Synthesis and Implementation. Then, we organised the components into different content blocks (Figure 3), each addressing specific aspects of the carbon cycle with its own learning goals. These blocks were designed to be independent, allowing for flexible combinations. They were later rearranged by the authors and formed six preliminary learning modules across four thematic contexts, each entailing various levels of systems thinking (Figure 4).

To validate our view, we conducted six semi-structured interviews with individual teachers from the panel and presented them with the domain ontology and prototyped learning tasks (prototyped tasks marked with star icons in Figure 3). As expressed in the following quotes, the consulted teachers verified our thinking and overall direction concerning the domain ontology:

“I think each box [content blocks in Figure 3] is very important for students. In year 7–9 we do not go very deep into each box because it can get to be too much information for the students. But at the same time these are important issues. In my school we start with climate change discussions and the global carbon cycle.” (Teacher C, individual interview)

“I like the way that you have grouped different parts of it [the carbon cycle knowledge]. It is very good to start with natural processes and then human intervention and fossil fuel ... It is interesting that you have cement

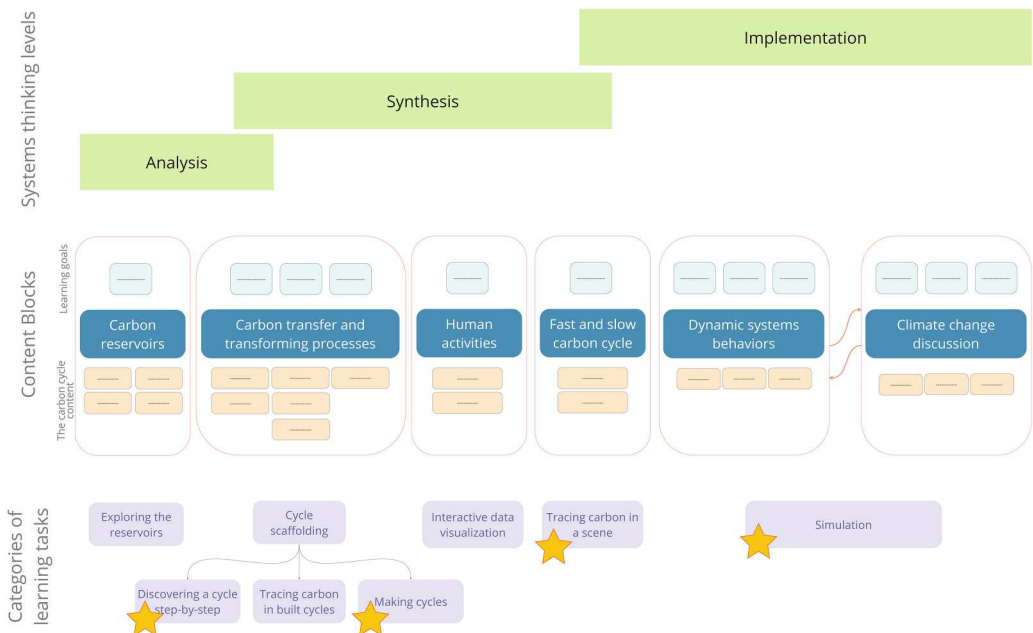


Figure 3. Simplified representation of the domain ontology with stars marking the developed static prototypes. Learning goals and carbon cycle content are symbolically presented with light blue and orange boxes, respectively.

Thematic contexts	Global level	Forest	Ocean	Farm
Carbon reservoirs, Processes & cycles	1. Global carbon cycle	3. Forest carbon cycle	4. Oceanic carbon cycle	6. Farm carbon cycle
Dynamic system behaviors	2. Human intervention		5. Ocean acidification	

Figure 4. Content blocks in Figure 3 structured into six preliminary learning modules across four thematic contexts by the authors.

production ... because in the media the focus is usually on the fossil fuel. So that is a good point to show to the students. ... I really like that students can make the cycles themselves” (Teacher D, individual interview)

All teachers confirmed that the carbon cycle content is spread out across different subjects and hence cannot be expected to be taught all at once. Therefore, a modular approach could potentially facilitate using this learning resource in connection with multiple subjects. Overall, teachers’ feedback validated our direction and enhanced our understanding of how such learning tasks could be brought into real-world classroom settings. Their input on the presented prototypes informed our design choices for further iterations of the learning tasks described in section 5.4.

5.3. Learning objectives in relation to the carbon cycle and systems thinking

The third phase of the design process focused on learning objectives, providing the connection between the carbon cycle content and learning tasks. We identified learning objectives based on existing learning resources and national curricula together with the science education literature on carbon cycle learning challenges. We then aligned them with the learning modules and the hierarchical progression captured by the STH model.

Learning about the carbon cycle is facilitated by relating it to various environmental and biological perspectives, such as the global cycle, familiar ecosystems, and the impact of human activities (Asshoff et al., 2010; Mohan et al., 2009; Zangori et al., 2017). We were of the view that ocean and farm contexts might be less familiar to the pupils and the modules on the forest carbon cycle, the global carbon cycle, and human intervention would provide more familiar contexts. Further on, we reorganised the learning objectives for each of the selected modules (Figure 5).

The module structure, content, and learning objectives were validated by teachers in a second focus group meeting. They were found to be in line with pedagogical expectations and perceived effective use in practical education. Our initial idea was to start the sequence of modules with the global carbon cycle module. However, the classroom test with pupils indicated that the forest carbon cycle seemed easier to grasp, and we revised the order to make the overall progression more accessible.

5.4. Interactive learning tasks

The fourth phase of our design process focused on designing multiple interactive tasks for the learning environment. The carbon cycle content, the systems thinking hierarchy and learning objectives materialised in concrete, visual, and interactive learning tasks. Our work started as pencil sketches and went through numerous iterative cycles of detailing and refinement, leading to the decision to rely on four specific interaction mechanisms for all learning tasks. They are introduced in subsequent parts of sections 5.4.1-5.4.4, respectively.

In the initial stages of this phase, an eye-tracking study with 6 pupils from grade 8 was conducted. In this study, we presented static images of four of the designed tasks to the pupils and recorded their eye movements while they were being asked to think about the solution. This study validated

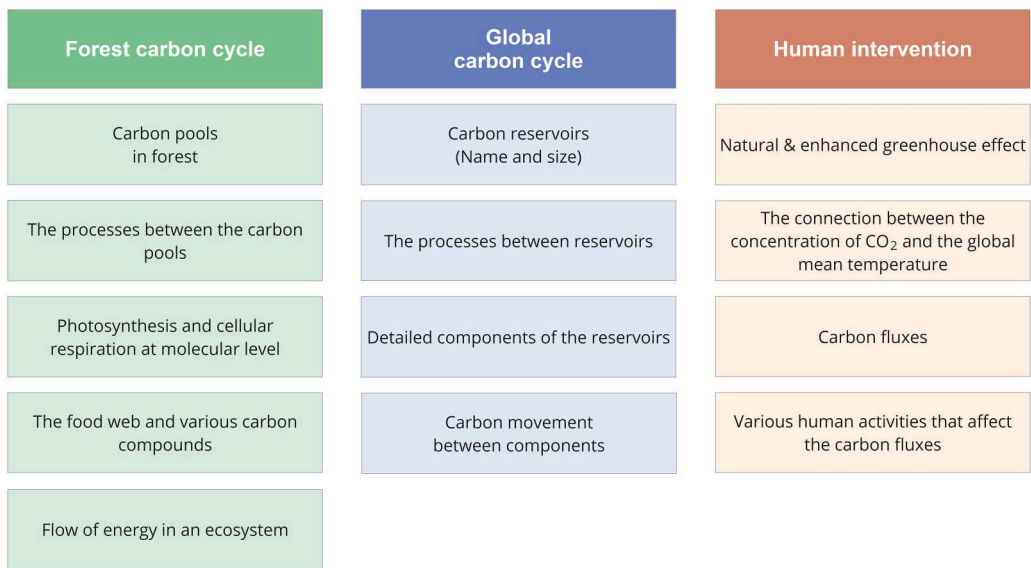


Figure 5. Summary of the learning objectives for the three modules.

the layout design of the tasks by observing the attention distribution between instruction and the visual elements in the presented samples. The outcomes favoured short-length textual descriptions and verified the spatial arrangement of the graphical elements.

Detailing and implementing the adaptive characteristics of our learning environment (to support individualised learning progressions) was also initiated during this phase. Each learning task was designed for three different difficulty levels. The system was designed to track individuals' performance and suggest a suitable difficulty level for each task.

The scoring algorithm that supports this adaptive behaviour was developed through an iterative process and was refined at the final stage. The data that we collected in the classroom test on pupils' performance enabled us to refine the adaptive behaviour of the learning environment. We used the data to identify performance thresholds for the three difficulty levels. In the current version, all pupils will start the learning experience at the medium difficulty level. When they interact with the tasks and quizzes, the system tracks their performance – including the number of errors and the time spent on each task. It then calculates a (standard) score for each pupil, reflecting their performance over the last four tasks. If the pupil exceeds the higher threshold of the medium-difficulty level, the system increases the difficulty of the next task. On the other hand, if pupils fall below the lower threshold of the medium-difficulty level, the difficulty of the next task is decreased to facilitate the learning process. If pupils stay within the thresholds, the level of difficulty remains unchanged. This adaptive behaviour is technically implemented by calculating a Z-score (Abdi, 2007) for each pupil and each task. The Z-score represents the performance of each individual in relation to the identified means.

5.4.1. Dragging and dropping cards to complete a diagram

It is common in science education to present the components of complex systems, such as the carbon cycle, in the form of diagrams with textual labels (Fandel et al., 2018). We chose the well-known technology-enhanced interaction response of drag-and-drop (e.g. De Jong et al., 2014; Ponce et al., 2021; Tidwell, 2010) to leverage existing diagram conventions but avoid the problem identified by the teachers of too much information being presented in existing learning resources. This interaction mechanism is used in several tasks to convey systems thinking skills at the Analysis

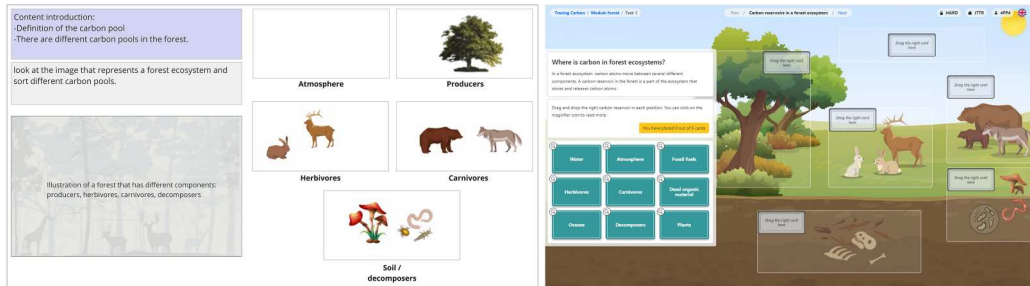


Figure 6. Initial design sketch (left) and final version (right) of a task with card drag and drop.

level by pairing labels to carbon cycle components, including carbon reservoirs, carbon pools in the forest ecosystem (Figure 6), carbon compounds, and carbon transformation processes.

Our initial version of card drag-and-drop provided immediate automated feedback, where incorrect placements of labels were promptly rejected. As pointed out by one of the teachers, this approach would run the risk of encouraging trial-and-error behaviours and obviating reasoning and deep learning:

“These [dragging and dropping cards] tasks look very nice and clean. It would be easy to know what to do. I think some students would just test until they get the right answer ... I think it would be nice to have an exit ticket to know that students have read the information and learned something. Maybe they need to answer some questions.” (Teacher E, individual interview)

In response to these directions of feedback, we integrated a delayed form of automated feedback that allows pupils to complete the task before submitting the answer and receiving feedback. Moreover, after completing several connected tasks, we integrated a quiz (see section 5.5).

5.4.2. Drawing arrows to complete cycles and sub-cycles

The movement of carbon atoms between reservoirs in the carbon cycle is directly related to the second level of systems thinking skills (synthesis) and is known to be a learning challenge (Asshoff et al., 2020; Düsing et al., 2019). These movements are conventionally visualised as arrows in diagrams (e.g. see Menendez et al., 2020; and Nelson & Olander, 2024, for structurally similar examples). The mechanism of drawing arrows (Figure 7) provides a means to trace carbon atoms between different pools, which is a recognised fruitful pedagogical strategy (Asshoff et al., 2010; Düsing et al., 2019). Inviting pupils to participate in creating the visual representations can be engaging and stimulate a deeper understanding of the subject (cf. Cheng et al., 2001). Similar to the drag-and-drop mechanism, the arrow-drawing mechanism adds interaction to conventional visual formats.

For this task, the possibility of incorporating automated feedback that is either immediate or delayed was considered. Immediate feedback has the potential to reinforce correcting mistakes promptly. However, feedback can also have a negative impact on learning (Hattie & Timperley, 2007). The potential drawback here is to make tasks too easy or encourage a passive learning approach. Delayed feedback, on the other hand, makes the task more difficult and allows learners to keep their initial, potentially incorrect arrows until they submit their answers. Since the main learning objective of this category of learning tasks was to recognise and visualise multiple carbon-transforming processes simultaneously, the delay in receiving corrective feedback could hinder the learning process by allowing misunderstandings to persist. Therefore, providing immediate feedback seemed more suitable.

The insights from the classroom test indicated that the arrow-drawing tasks might have been too demanding for pupils. The increase in the average time required to complete the task and an increased number of errors in the results suggested that the tasks required modification. The

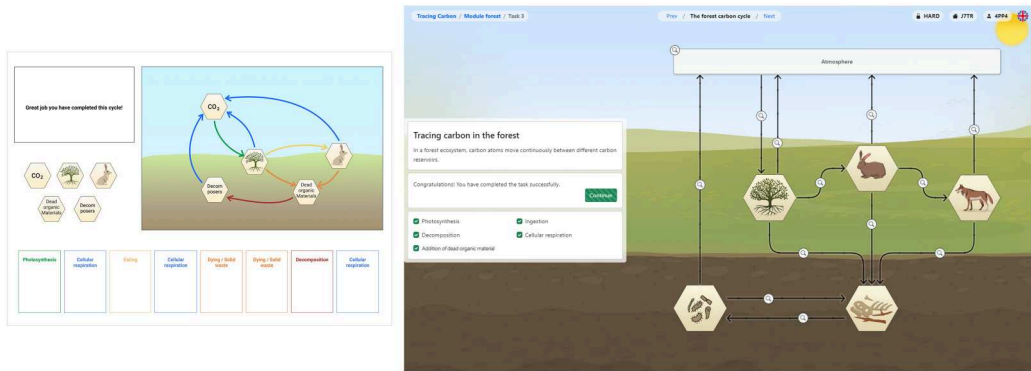


Figure 7. Initial sketch (left) and final version (right) of a task with arrow drawing.

detailed analysis of how pupils approached these tasks suggested that understanding the links between the arrows and the processes was challenging in the global carbon cycle module. We responded to this challenge through two strategies. Firstly, we decreased the task's perceived difficulty by adjusting the order of the modules – starting with the forest carbon cycle followed by the global carbon cycle – with the intention to allow pupils to become more familiar with the content and the arrow-drawing mechanism through more straightforward tasks. Our second strategy involved manipulation of the three difficulty levels within the task by allowing some of the arrows to be pre-drawn when the task starts and adding a checklist of the required arrows on the lower-difficulty levels.

5.4.3. Clicking to reveal more information

The third interactive mechanism that we adopted for interactive learning tasks involved clicking on specific parts of the diagrams to reveal more information (Figure 8). Chunking and structuring the information could potentially facilitate learning through the segmenting effect (Mayer, 2021). Therefore, this approach aims to increase interaction with diagrams while reducing cognitive load (Sweller et al., 2011) by presenting information in multiple layers. Initially, this feature was designed as a card-flipping function. However, the results of the classroom test indicated that the pupils did not flip the cards much, if at all. We simplified the initial interaction and added iconic click targets to make the additional information more accessible.

5.4.4. Interacting with charts and tables

Making sense of carbon cycle data (e.g. atmospheric carbon dioxide concentration) and reasoning about carbon reservoir and flux magnitudes are essential for understanding how the carbon cycle is connected to climate change (Covitt et al., 2021). As reflected in the quote below, some teachers also expressed a desire to incorporate scientific data from reliable sources such as IPCC and NASA in their teaching. These motivations resulted in an interaction mechanism that involved interacting with charts and completing tables (Figure 9):

“To address human intervention, the global carbon cycle, and dynamic systems behaviours, I think it is important to simulate things with data. Then we can discuss what the data is and how it is calculated.” (Teacher F, individual interview)

Interacting with multiple forms of representations, such as diagrams or graphs, can facilitate learning about complex scientific content (Ainsworth, 2008, 2006). By utilising different forms of data visualization, these learning tasks aim to encourage pupils to access reliable data and derive meaning from it. This form of interaction requires reading data from charts and infographics and completing tables to fulfil the tasks.

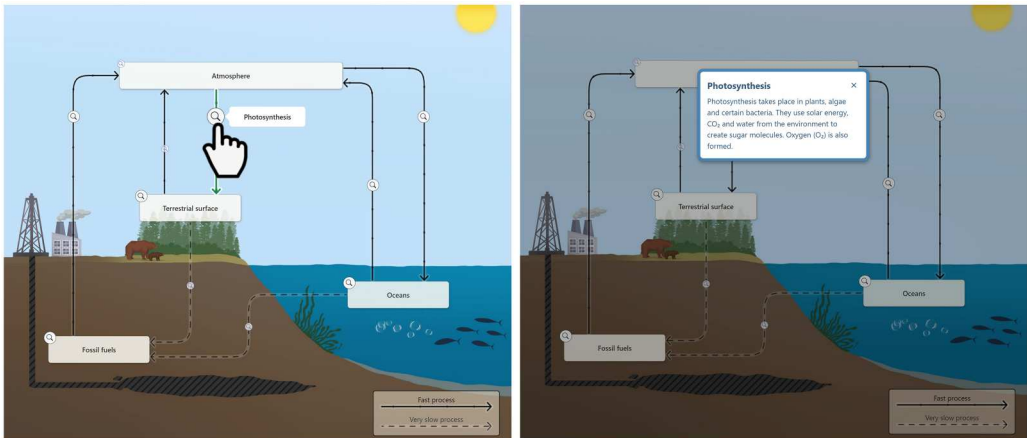


Figure 8. Clicking to reveal more information.

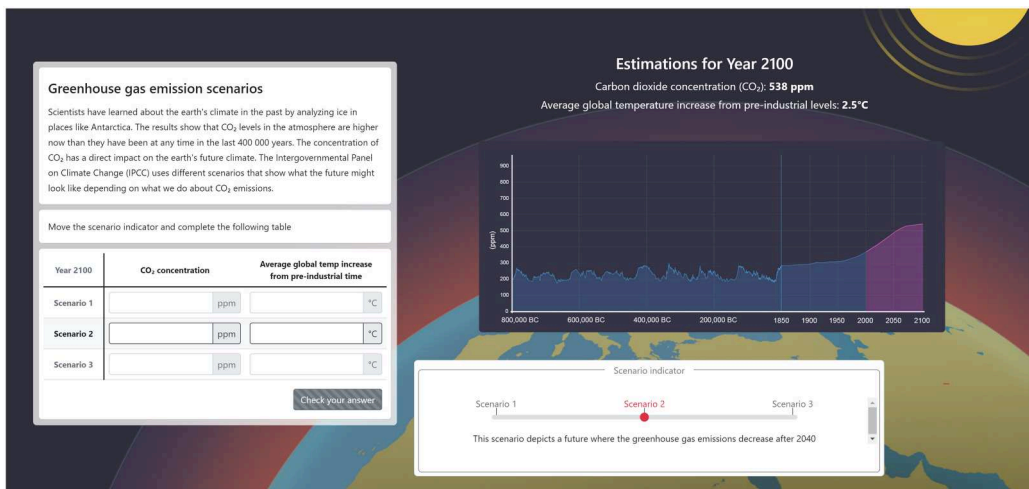
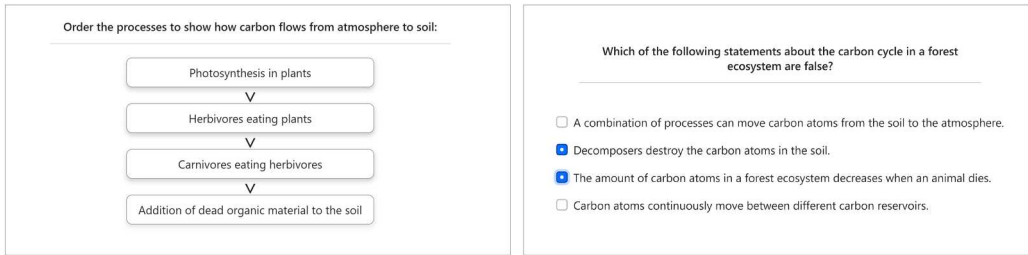


Figure 9. A task with chart interaction and table completion.

5.5. Learning quizzes

Quizzes are generally found to affect learning positively (Spanjers et al., 2015), and quiz testing can serve as an effective learning method when part of digital environments (e.g. R uth et al., 2021). We constructed and introduced learning quizzes as parts of the modules. The motivation for adding them to the learning system emerged from teachers' feedback in individual interviews (see section 5.4.1). This incorporation aimed to encourage deeper learning and foster reasoning skills among pupils. Quiz questions were designed to encompass various levels of systems thinking skills. They were designed in two distinct difficulty levels – easy and hard – with future incorporation of adaptivity in mind.

During this process, diverse question formats were considered and developed, including single/multiple-choice questions, assertion-reasoning questions, sorting and sequencing options, and fill-in-the-blanks (Reynolds et al., 2010). The format of each question was selected depending on the nature of the target knowledge. For example, multiple-choice format was considered for the questions addressing misconceptions, while sequencing was selected when the pupils needed to focus



Order the processes to show how carbon flows from atmosphere to soil:

Photosynthesis in plants

Herbivores eating plants

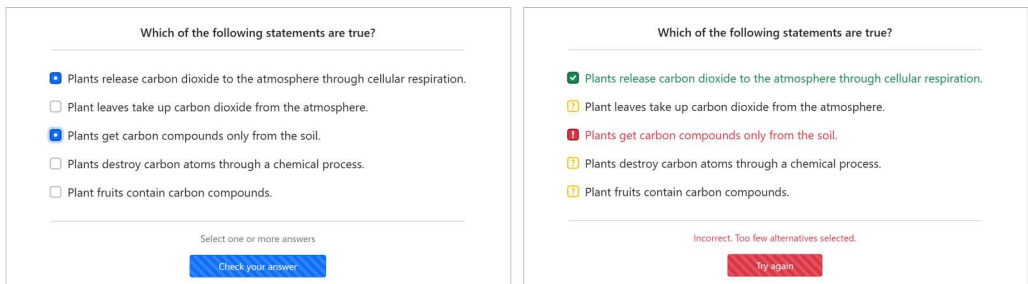
Carnivores eating herbivores

Addition of dead organic material to the soil

Which of the following statements about the carbon cycle in a forest ecosystem are false?

- A combination of processes can move carbon atoms from the soil to the atmosphere.
- Decomposers destroy the carbon atoms in the soil.
- The amount of carbon atoms in a forest ecosystem decreases when an animal dies.
- Carbon atoms continuously move between different carbon reservoirs.

Figure 10. Two different question formats in quizzes.



Which of the following statements are true?

- Plants release carbon dioxide to the atmosphere through cellular respiration.
- Plant leaves take up carbon dioxide from the atmosphere.
- Plants get carbon compounds only from the soil.
- Plants destroy carbon atoms through a chemical process.
- Plant fruits contain carbon compounds.

Select one or more answers

Check your answer

Which of the following statements are true?

- Plants release carbon dioxide to the atmosphere through cellular respiration.
- Plant leaves take up carbon dioxide from the atmosphere.
- Plants get carbon compounds only from the soil.
- Plants destroy carbon atoms through a chemical process.
- Plant fruits contain carbon compounds.

Incorrect. Too few alternatives selected.

Try again

Figure 11. Delayed feedback on quiz questions before (left) and after submitting answer (right).

on the order of the elements (Figure 10). All questions were designed according to the learning context and the learning objectives of each learning module (Nicol, 2007), aiming to address various learning challenges in relation to the carbon cycle (Asshoff et al., 2010; Covitt et al., 2021; Düsing et al., 2019; Mohan et al., 2009).

We integrated delayed feedback for each quiz question to facilitate pupils' progression. This feature requires pupils to submit their answers first. Then, the feedback validates the correct answers or guides the pupils towards finding them. Figure 11 demonstrates the feedback function for a multiple-choice question. After submitting the answer, the green symbol validates the correctly selected option, the red symbol signifies the wrong answer, and the yellow symbols highlight that additional correct answers should be identified. This form of feedback does not reveal the correct answer immediately and encourages the pupils to find it on their own.

To construct the quiz items, we developed an approach by integrating systems thinking hierarchical levels (see Table 1) with the carbon cycle context. We validated the difficulty levels by presenting a set of questions to the teacher panel, and subsequently by analysing the pupils' performance in the classroom test quizzes.

6. Tracing carbon: outcome of the design process

The outcome of the design process yielded Tracing Carbon, an adaptive interactive visual learning environment comprising twenty-one learning tasks and six quizzes embedded in three progressive learning modules for grades 7–9 aligned with the STH framework (Assaraf & Orion, 2005) and the Swedish school curriculum. Readers are invited to consult the Supplementary video for an overall visual communication of the resulting Tracing Carbon environment (see supplemental data). Pupils are foreseen to commence the learning experience in the first module by exploring how carbon circulates within a forest ecosystem. In the second module, they delve into the global aspects of the carbon cycle, and in the third, they focus on how various human activities affect the natural balance of the carbon cycle.

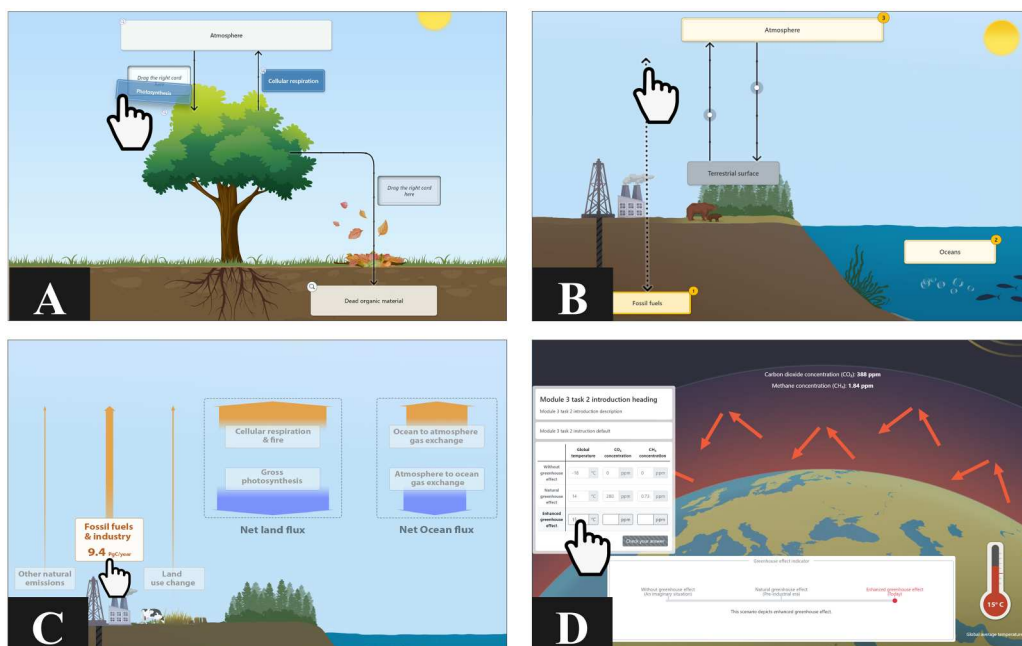


Figure 12. Integrated interaction mechanisms: dragging and dropping cards in module 1 (A), drawing arrows in module 2 (B), revealing more information in module 3 (C), and completing the tables in module 3 (D).

Tracing carbon aims to support the development of systems thinking skills through interactive visual-based tasks. This interaction is offered through four core mechanisms (Figure 12), including (A) Dragging and dropping cards to complete a diagram, (B) Drawing arrows to complete cycles and sub-cycles, (C) Clicking to reveal more information (e.g. about carbon fluxes), and (D) Interacting with charts and filling the tables.

All learning modules include two quizzes, each with six questions that target all three levels of systems thinking skills. These quizzes aim to provide a broader context for the recently covered materials and engage pupils' reasoning abilities (e.g. via assertion-reasoning items) by incorporating problem-solving elements.

Tracing Carbon aims to provide an adaptive, personalised learning experience by adjusting the difficulty of the tasks and questions according to each pupil's real-time performance. As pupils engage with Tracing Carbon, the environment will track their progress, evaluate their performance, and adjust the presented difficulty of the tasks and quiz questions accordingly. It additionally provides immediate and delayed feedback (e.g. highlighting the correct answers and signalling the errors either immediately or at the end of the task) to validate pupils' responses and supporting them in addressing their errors during the tasks and quizzes.

7. Results from the interpretive analysis

This section provides findings from our interpretive analysis – using reflexive methods (Alvesson & Sköldbäck, 2017) – of the design process, which is considered the empirical data of our work. We first provide an overview of the design process, then revisit each research question (RQ) in relation to the design phases of Tracing Carbon, and close by describing how a multiple perspectives approach informs the design of interactive learning environments. Figure 13 visually demonstrates the connections between various research questions and the design phases.

	Framing design space	Domain ontology & modular structure	Learning objectives	Interactive learning tasks	Learning quizzes
Using a theoretical framework as a design driver (RQ1)					
Multiple interactive visual representations and adaptivity (RQ2)					
Involving science teachers in the design process (RQ3)					
Involving pupils in the design process (RQ4)					

Figure 13. Connections between the research questions and the main phases of the design process.

Following an educational design research approach, we have presented a design case study of a multi-perspective design process of an adaptive learning environment for developing systems thinking skills called Tracing Carbon (also see Supplementary video). Our study describes an iterative design process that integrates multiple perspectives and design exploration while remaining practically applicable. Briefly, the design process consisted of five main phases described in turn. In **framing the design space**, the focus was on understanding the design situation and identifying key constraints and opportunities. We synthesised theoretical knowledge on systems thinking, subject knowledge, and adaptive learning environments into conceptual drivers. **Domain ontology and modular structure** were concerned with selecting the carbon cycle content and arranging it according to the STH framework and the national curriculum. This, in turn, formed the basis for a structure of six learning modules. **Learning objectives** were identified based on the Swedish national curriculum, existing learning resources, and existing science education research on learning challenges pertaining to the carbon cycle. **Interactive learning tasks** were detailed through interaction design processes combining existing research in science education and interactive learning environment design with general user interface design knowledge. **Learning quizzes** were detailed based on existing research in science education.

Given the five phases above, the primary ambition of involving multiple perspectives was fundamental to our study. Integrating multiple perspectives into the design process is a well-known strategy for opening new directions that is particularly valuable in explorative design approaches. For example, in participatory design research, the involvement of multiple stakeholder groups and their potentially non-aligned perspectives can be a driver of creative progress (Björgvinsson et al., 2012). Similar observations have been made concerning the design of innovative science education resources (Matovu et al., 2023; Mork, 2011).

7.1. Using a theoretical framework as a design driver (RQ1)

The Systems Thinking Hierarchical (STH) model was the primary conceptual driver of the design process for Tracing Carbon. This model was used as an organising principle for our design and impacted *Framing design space*, *Domain ontology and modular structure*, and the *Learning objectives*. Assaraf and Orion (2005) initially developed the STH model based on learners' understanding of the water cycle. They also advocated for the generalisability of their model and the transferability of systems thinking skills to other earth systems, including the rock and carbon cycles. In our design process, we utilised the framework for the carbon cycle in connection with environmental challenges. Since the three levels of systems thinking skills comprising the STH model can be applicable to other earth systems, we expect our design approach to be potentially applicable to developing learning resources for other earth cycles, such as the water or nitrogen cycle.

7.2. Multiple interactive visual representations and adaptivity (RQ2)

Tracing Carbon incorporates multiple interactive visual representations to guide learners through different levels of systems thinking skills in the context of the carbon cycle. Multiple representations allow for distributing visually communicated information across multiple displays rather than combining it in a single complex diagram, thus facilitating the learning of complex concepts such as the carbon cycle (cf. Ainsworth, 2018). Carbon cycle content is typically communicated through (one or a few) static diagrams accompanied by explanatory text. These diagrams frequently entail multiple layers of information, posing a potential challenge for novice learners (Düsing et al., 2019). However, to facilitate learning, Tracing Carbon segments this subject content and presents it through several interactive visual representations (learning tasks) organised according to the STH model and in thematic learning modules (cf. Assaraf & Orion, 2005; Mayer, 2021). Interacting with visualizations is afforded through four core interaction mechanisms (section 5.4), which aim to encourage pupils to actively engage in learning rather than merely passively receive the information. These interactions intend to involve pupils' completion or creation of visual representations, decrease pupils' cognitive load by presenting additional information on separate layers (e.g. Sweller et al., 2011), and engage pupils with carbon cycle data.

Adaptivity and the nature and delivery of automated feedback are features that contribute to personalised learning and have found traction in K-12 science instruction settings (e.g. Gerard et al., 2015; R uth et al., 2021). The adaptive behaviour of Tracing Carbon aims to adapt to pupils' pace by considering their level of understanding and providing automated feedback. All tasks and quizzes are designed with three difficulty levels, and the integrated scoring algorithm aims to suggest a suitable difficulty level based on individuals' recent performance. Reducing the difficulty of the tasks and quizzes for lower-performing pupils intends to facilitate their progression in the learning materials. However, for high-performing individuals, increasing the difficulty of the tasks and quizzes aims to keep them engaged throughout the learning process and to support their deeper acquisition of the science content.

Various forms of immediate and delayed automated feedback support pupils' interaction with Tracing Carbon. Although immediate feedback is generally considered valuable for learning, there remain some concerns about its effectiveness in educational research (Gerard et al., 2015). As exposed during the teacher interviews, immediate automated feedback could potentially hinder learning by encouraging trial-and-error behaviour. In fact, delaying feedback could reduce mindless clicking and encourage careful consideration of answers. Therefore, delayed feedback was incorporated into the quizzes and most of the tasks. However, providing delayed feedback for arrow-drawing tasks could allow learners' errors to enforce mistakes and pose negative consequences on learning. Therefore, immediate automated feedback is emerging as potentially promising for such instances.

7.3. Involving science teachers in the design process (RQ3)

The benefits of involving teachers in designing technology-enhanced learning are recognised (Kali et al., 2015) and adopted in educational technology research (e.g. Cober et al., 2015; Mavroudi et al., 2016). Tracing Carbon, as a design case study, exemplifies how teacher involvement in the design process impacted the quality of the designed learning environment. The teacher panel, consisting of 10 experienced and practising secondary science teachers, was a significant factor in informing the design of Tracing Carbon.

The teacher panel was involved in all phases of the design process through three types of activities, including one set of individual reflections on the teaching approach concerning the carbon cycle, three focus group meetings, and two sets of individual interviews. The feedback from these activities validated the design decisions and motivated further iterations to improve the quality of the design outcome. One challenge in this regard was involving the panel in a meaningful way, without imposing excessive demands on their valuable time. Therefore, in recognising the

significance of teachers' expertise in shaping effective educational tools in spite of their high teaching commitments, we carefully structured participation sessions in connection to all design phases as efficiently as possible. For example, we used short focus group meetings followed by individual follow-up interviews for framing the design space. Another example is that we presented the interactive learning tasks in prototype form and discussed them in individual interviews. This trade-off allowed us to integrate teachers' input in the design process while respecting the constraints of their schedules.

7.4. Involving pupils in the design process (RQ4)

In interaction design, it is common practice to involve intended users in the design process. The most established approach is to create prototypes and test them with intended users to validate design decisions and collect indications on how they can be further improved. Another typical approach is to involve intended users already in earlier, more creative phases in some form of co-design sessions. The overall intention is to ensure that the developed product appropriately addresses the needs of the intended users.

Involving learners as the intended users in the design process has a presence in science education research. For example, Merlino et al. (2015) involved feedback from 50 high school students in the design of an Android application (SeaCleaner) aimed at supporting waste management practices. Apart from the design of the artefact, networking with students in the design process also prompted the participating students to increase their own knowledge of pressing environmental issues. In another study, by implementing a design research methodology, Agbo (2022) worked with students in the co-design of an online learning environment to develop young university students' computational thinking, a key component of twenty-first-century STEM-related competence. Agbo's study serves as an example of how design methods and pedagogical approaches can be merged to develop new educational interventions through co-design processes with students.

In the present work, our task was to combine these practices with the perspectives of science education research. Specifically, we chose to involve pupils at two points in the design process: an eye-tracking study with six pupils and a classroom test with 97 pupils (the results of which go beyond the scope of this paper, which focuses on detailing the design process). In both cases, the pupils interacted with the developed prototypes. The collected data from their interactions contributed to the design process by validating the design decisions and highlighting instances where further iterations could improve the outcomes. As an example, the collected data from pupils' interactions resulted in modifying the adaptive properties of the designed scoring algorithm for providing a personalised learning experience. Another example referred to the drawing-arrow tasks where the data resulted in pedagogical adjustments concerning the different difficulty levels.

7.5. Multiple perspectives inform the design of interactive learning environments

To conclude our discussion, we return to the overall aim of the study. As indicated by other science education and educational design research scholars (Bopardikar et al., 2023; Hall, 2020; Mor & Winters, 2007; Nelson et al., 2005), the development of interactive learning environments can benefit from bringing multiple perspectives into play. Our approach has been to devise a design process where a design team representing science education research, interaction design and interactive learning technology collaborates with practicing teachers and with pupils, leaning on a foundation of theoretical frameworks and enabling technologies. This approach is certainly demanding in terms of time, resources and planning; however, we find that the outcome in the form of the Tracing Carbon interactive learning environment for developing carbon cycle systems thinking skills might in itself justify the investment. More importantly, though, we argue that a multi-perspective approach contributed to several unique insights in our design process.

In our case, a specific instance of a multiple-perspective design progression concerned the carbon cycle content. In the Swedish national curriculum, the topic is scattered across different subjects (see sections 5.1-5.3). Working with teachers in biology and chemistry enabled us to create a learning environment in a modular structure that can provide didactic opportunities for thematic learning approaches and subject integration. This described approach could potentially be adopted in other science didactic disciplines as well.

Another example of a multiple-perspective design progression concerns the interaction mechanisms of dragging cards and drawing arrows. It is generally held in interaction design that such approaches can stimulate engagement (Tidwell, 2010). Recent work has shown increased efficiency associated with drag-and-drop items (Ponce et al., 2021), while De Jong et al. (2014) showed how straightforward drag-and-drop interfaces integrated in online STEM labs can scaffold conceptual domain knowledge and inquiry skills. In our design case, however, teachers were able to identify the risk of trial-and-error strategies and recommend a feedback strategy to find a trade-off (see section 5.4.1). In other words, integrating multiple perspectives enabled us to make design decisions appropriate for this specific didactic use context.

8. Conclusions and implications

We present our work in this paper as a case study that utilises an explorative and iterative multiple-perspective design approach to develop Tracing Carbon, an adaptive, interactive, and visually oriented science learning environment tailored for fostering systems thinking skills within the carbon cycle.

Although our work focuses on the carbon cycle context, similar systems thinking skills are prevalent in various scientific domains ranging from the human body (Assaraf et al., 2013; Snapir et al., 2017) to ecosystems (Asshoff et al., 2020; Mambrey et al., 2022), and to other earth systems (Assaraf & Orion, 2005; Kali et al., 2003). In a recent analysis, Bielik et al. (2023) reviewed 255 published empirical studies in STEM education and identified a sharp increase in studies on systems thinking. While most studies have focused on higher education and biology, these scholars highlight a potential research gap in exploring systems thinking across other populations and disciplines. Hence, we expect Tracing Carbon (our designed learning environment) to help fill this gap by providing more opportunities to study teaching and learning systems thinking skills in the multi-disciplinary context of the carbon cycle for lower secondary pupils.

Additionally, literature in educational sciences emphasises the benefit of considering multiple perspectives to address the intricacies of complex educational contexts and highlights the scarcity of studies that explicitly detail the rationales underpinning key design decisions (Bopardikar et al., 2023; Hall, 2020; Howard et al., 2012). This work highlights the need for involving multiple perspectives in the design process of creating an adaptive and interactive learning environment for developing systems thinking skills. Given the complexity of our project's scope, we consider our work a valuable guiding methodological contribution. By providing a detailed account of our multiple-perspective design process, we aim to inspire the development of similar learning resources across various domains, fostering learners' systems thinking and related skills.

8.1. Limitations and future work

One limitation of our work concerns the adaptive algorithm in Tracing Carbon. The presented adaptive behaviour remains a work in progress and requires further refinement through additional iterations. The current adaptive behaviour was integrated through various difficulty levels in interactive learning tasks and quizzes. However, we were not able to implement the final scoring algorithm for the classroom test that was conducted in the final design phase. Instead, we analysed the collected data in this test to identify adaptivity parameters for refining our algorithm. The final algorithm will be tested in future educational studies in classroom settings.

Another limitation of our work relates to the extent of teacher involvement in the design process. We believe that co-design and participatory design processes could have enhanced teachers' pedagogical influence on the produced outcome (cf. Kali et al., 2015; Matuk et al., 2017). Although adopting such resource-intensive approaches were not feasible given the constraints of a realistic development process, we plan to involve teachers in a more co-creative approach in future research to appropriate our designed tools into real classroom practice.

Additionally, we involved students in the design process on only two occasions, mainly to validate and modify the design decisions. Although these two instances provided valuable feedback that resulted in multiple iterations within the scope of this project, exploring how pupils can be involved in the design process at a higher degree (cf. Agbo, 2022; Merlino et al., 2015) could be a meaningful direction for future research.

In the next phase of our research programme, we will integrate the Tracing Carbon environment in multiple science classroom settings. Implementing an educational intervention to teach the carbon cycle and explore pupils' and teachers' interactions with Tracing Carbon could lead to valuable design and pedagogical research avenues. One example of this is investigating how features and adaptive characteristics of Tracing Carbon impact learners' systems thinking in authentic settings.

In conclusion, this work represents a case study where design cooperates with science education research (Boda et al., 2024; Donnelly-Hermosillo et al., 2023). Building on methodological foundations of Constructive Design Research aligned with Educational Design Research, we have presented a design approach that accommodates multiple perspectives. Our work is intended to serve as a methodological contribution that other researchers can appropriate when developing interactive learning environments for similar science education contexts.

Acknowledgements

The authors thank the members of the teacher panel for their time and contributions to the design of the learning environment, and the pupils that participated in the classroom study.

Disclosure statement

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

Funding

This work was supported by Vetenskapsrådet: [grant number 2020-05147].

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