Creating Experiments to connect Science and the Outside World

STExperiMents Design Guidelines

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Project Team

Charles University, Czech Republic (Coordinator): Martin Rusek, Dominika Koperová, Tadeáš Matěcha, Marta Kuhnová

University of Jyväskylä, Finland: Maria Fisk, Kristof Fenyvesi, Josephine Lau

Bahçeşehir University, Türkiye: Nilay Ozturk, Sezin Esfer, Ayse Gul Celenk, Mehmet Sencer Corlu

Johannes Kepler University, Austria: Cecília Russo, Abril Armenta-Franco, Eva Ulbrich, Zsolt Lavicza

Images: From the participants of the project team

Further resources and information about the STExperiMents project can be found at: https://STExperiMents.pedf.cuni.cz/

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Executive Summary

This document provides a set of design guidelines describing how experimental learning tasks (Experiments) within the STExperiMents project are developed. The aim is to support teachers, educators, and project partners in creating structured experiments that connect scientific concepts with real-world contexts while remaining feasible in classroom and workshop environments.

The guidelines were developed through collaborative work within the project consortium. Initial brainstorming sessions, discussions among partners, and analysis of existing STEM and inquiry-based learning approaches were used to identify overarching design principles for educational experiments. These principles were translated into a structured framework that supports the development, documentation, and comparison of experimental activities across participating countries.

The resulting framework contains essential dimensions for experiment design, including contextual relevance, conceptual focus, feasibility of materials, measurement and observation strategies, and opportunities for reflection and discussion. These dimensions aim to ensure that experiments are scientifically meaningful and pedagogically accessible and adaptable to different educational settings as well as support the goals of the project.

The document provides a template describing the experiments and illustrates how the design principles can be applied in practice to support implementation in schools. This structure supports partners to document their experimental activities in a comparable way and facilitates the exchange of ideas within the project.

The guidelines are intended to support the development of new experimental tasks and the refinement of existing activities. The document contributes to a coherent approach to experimental learning within the STExperiMents project and supports the creation of transferable educational practices by providing a shared framework.

Introduction: The STExperiMents Project

The aim of the STExperiMents project is to create a collection of STEM learning activities that enable teachers to incorporate meaningful, evidence-based STEM education into their practice. Beyond this central goal, the project pursues several interconnected objectives.

The development of experiments will enrich participating schools and research groups by integrating diverse perspectives from different disciplines. The iterative, evidence-based refinement will generate findings valuable also to the STEAM education research community. The project experiments emphasize the development of skills and competencies and visualise deeper learning goals of experiments beyond content delivery to pre- and in-service teachers, teacher educators, and decision makers. These experiments, framed by the STExperiMents project, are implemented across two different formats: hands-on and digitally supported activities. In hands-on settings, students engage directly with materials and measurement processes, such as temperature investigations (Figure 1a), while digital environments allow students to explore scientific concepts through simulation, for example, by investigating pH values using an online tool (Figure 1b). The STEAM approach provides the interdisciplinary connections emphasized in national curricula but often neglected in classroom practice.

The collaborative exchange of ideas, experiences, and pedagogical strategies has the potential to transform practices at university and secondary school levels: project partners represent diverse educational environments with varying approaches to STEAM integration and inviting pre-service teachers to embrace STEAM approaches into lesson planning and classrooms.

a) **b)**

Figure 1: In *a)*, students measure temperature. In *b)*, students explore the pH values of substances using an online simulator.

This document presents the resulting design guidelines. It introduces the theoretical foundations that inform the framework, formulates operational design principles, and provides a structured model for task development and refinement. The purpose is to inspire teachers and teacher educators in analysing, constructing, and adapting experimental tasks. The structure should support inquiry processes and make facilitation explicit to create a task design supporting:

- inquiry competence
- and facilitation awareness.

The focus lies on the internal structure of tasks: how problems are formulated, how degrees of freedom are constrained, how measurement structures guide reasoning, how uncertainty is handled, and how reflection supports conceptual consolidation. Experimental activities are a common component of STEM education across European school systems. Their educational value can depend on how they are designed, structured, and facilitated. Experimental tasks differ in the extent to which they engage students in hypothesis generation, variable control, measurement-based reasoning, and evidence evaluation. For this reason, the design of experimental activities requires explicit pedagogical and epistemic consideration. The Design Guidelines for the STExperiMents project addresses the design dimension of experimentation in STEM education. Across participating countries, curricula emphasise inquiry competence, transversal skills, digital integration, and the ability to engage with complex socio-technical challenges.

Project Context

STExperiMents is an Erasmus+ KA220-SCH cooperation partnership in school education that positions its work within current European priorities around STEM/STEAM learning, digital transformation, and the development of transversal competences. The selected programme priorities include promoting interest and excellence in STEM and the STEAM approach, as well as addressing digital transformation through digital readiness, resilience, and capacity.

European education policy currently situates school development within broader digital and socio-economic transformation processes. Digital readiness is framed as a systemic requirement. The ongoing digital transition of society and labour markets requires education systems to prepare learners for environments in which digital tools, data practices, and technological infrastructures are embedded in nearly all professional fields. Projections of widespread demand for digital competences, particularly in IT and STEM sectors, position digital capacity as a structural precondition for participation in future labour markets and for maintaining European economic stability. STEM education is therefore linked to questions of competitiveness and innovation. Shortages in STEM-qualified professionals are understood as constraints on research, technological development, and sustainable economic growth. Strengthening interest and performance in science, technology, engineering, and mathematics is framed as a means of reinforcing Europe’s innovation capacity and its ability to respond to technological and environmental challenges. STEM education is treated as an interconnected field that combines scientific reasoning, technological literacy, and applied problem solving.

The integration of arts and social perspectives within a STEAM orientation reflects a related policy emphasis on interdisciplinarity. European frameworks frequently refer to transversal competences such as problem solving, collaboration, creativity, and the ability to apply knowledge across domains. These competences are associated with flexible learning pathways and with the capacity to navigate complex, real-world contexts. Educational initiatives are therefore encouraged to move beyond subject-specific content delivery and to structure learning environments that connect conceptual understanding with contextual application.

Sustainability appears in policy discourse as part of the broader green and digital transitions shaping European societies. Educational systems are expected to contribute to sustainable economic development and to prepare learners for participation in environmentally and technologically evolving contexts. This orientation links STEM competence with societal responsibility, technological innovation, and long-term economic resilience.

Digital readiness, STEM capacity, transversal competences, and sustainability form an interconnected policy framework. Education is positioned as the central mechanism through which Europe seeks to strengthen innovation potential, respond to labour market demands, and navigate ecological and technological transformation.

Project Aims

Experimental tasks can support analytical reasoning, structured documentation, teamwork, and data interpretation. However, the extent to which transversal competencies are systematically assessed or linked to experimental design depends on school level implementation.

The STExperiMents project focuses on the development of structured experimental task designs for STEM education. These tasks are conceived as deliberately designed learning environments in which the internal structure of experimentation is made explicit. Attention is given to how problems are formulated, how variables are organised, how measurements are integrated into reasoning processes, and how reflection phases are embedded. The project aims for a coherent set of experimental designs that can be implemented, analysed, and refined across contexts. The primary users of these task designs are teachers and teacher educators. The project addresses pre-service and in-service teachers, positioning experimental tasks as tools for classroom implementation and as objects of professional reflection.

Target Outcome

The project's main ambition is to develop transferable, research-informed experimental task designs that can be adapted to different educational conditions across partner countries while supporting inquiry-related competence development and making facilitation demands explicit.

This guidelines document defines the framework for designing the experimental activities developed within the STExperiMents project. They serve as a common reference for all partners involved in the creation, testing, and refinement of both hands-on and virtual STEM experiments. They can also be used by teachers to better understand the experiments, their structure, and what to look out for when adapting activities or generating experiments themselves.

The document translates the project commitments into operational design criteria that guide task development across work packages and partner countries.

- The project contains the development of eight piloted experimental activities, four physical and four virtual, which will be included in a freely available toolkit. These activities are conceived as structured experimental formats that can be implemented, analysed, and revised in different educational contexts. Each experiment should be designed in a way that adapts to national curricula while preserving its core conceptual and methodological structure.
- A second project outcome is the development of a methodology for examining students' learning performance when working with the experimental activities. For this reason, the design of each task should include an explicit measurement and evaluation structure. Experimental formats are required to generate observable evidence of student reasoning processes, variable handling, data interpretation, and conclusion formation. Evaluation tools are to be aligned with these structural elements for a systematic analysis during classroom trials and revision phases.

The development process follows an iterative design logic. Experimental tasks are analysed, designed, reviewed, implemented in classroom settings, and revised based on documented feedback from pre-service teachers, in-service teachers, and students. Cross-country implementation is an important component of this process. Task designs should be described with sufficient precision for proper replication while remaining flexible to accommodate contextual differences in materials, time allocation, and curricular emphasis.

The guidelines also require that each experimental activity make its epistemic structure transparent. This includes clear articulation of the problem framing, specification of variables and constraints, definition of measurement procedures, and structured reflection phases. The intention is to ensure that the experimental design supports inquiry processes and helps facilitators to anticipate and manage classroom dynamics.

This guidelines document operationalises the project's commitments:

- the development of a validated experimental toolkit,
- an accompanying evaluation methodology,
- and structured dissemination outputs.

It provides the shared design criteria through which experimental activities are constructed, tested, adapted, and prepared for broader use across European educational contexts.

STEM and STEAM

In educational practice, the distinction between STEM and STEAM can be fluid. Both frameworks share certain principles:

- learning through inquiry and experimentation
- problem-based and project-based learning
- integration of knowledge across disciplinary boundaries
- development of transversal competences such as the four Cs of the 21st century, namely critical thinking, collaboration, communication, and creativity
- connection between theoretical knowledge and real-world applications

STEM-oriented approaches typically focus on scientific reasoning, technological literacy, and engineering-oriented problem solving, often emphasising analytical and quantitative methods. These approaches are closely connected to innovation, technological development, and the demands of modern labour markets (National Research Council, 2012; Bybee, 2013). They maintain these foundations while incorporating creative design processes, visualisation, prototyping, and aesthetic exploration (see Figure 2 a-c). This can support different forms of engagement with scientific concepts, including alternative ways of modelling phenomena, representing data, or exploring technological ideas (Henriksen, 2017).

In this sense, STEAM can be understood as an expansion of STEM. It introduces additional perspectives that may support creativity, design thinking, and broader forms of innovation, see Figure 2 d-f, for examples of STEAM activities. The relevance of STEAM can be seen in the inclusion of artistic perspectives and the humanities in STEM-related learning environments. This is increasingly discussed in educational research and policy contexts. One reason is that many contemporary technological and societal challenges require integrative thinking that combines analytical reasoning with creativity, design, and communication (European Commission, 2018).

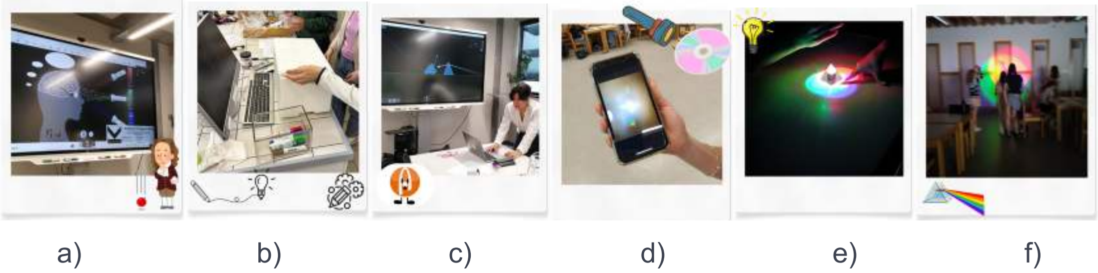

a) b) c) d) e) f)

Figure 2: Pictures a–c show STEM-oriented activities: Pictures d–f represent STEAM-oriented activities, where students explore light refraction and RGB color addition/subtraction through an artistic lens.

In educational settings, STEAM approaches can support learning by encouraging multiple forms of representation and explanation

- connecting scientific concepts with design, visualisation, and creative expression
- supporting motivation and engagement among diverse groups of learners

facilitating the exploration of complex socio-technical phenomena from multiple perspectives. STEAM can therefore provide additional pathways for learners to engage with scientific concepts, particularly in contexts where experimentation, modelling, prototyping, or design processes are involved (Henriksen, 2017; Yakman & Lee, 2012) from a pedagogical perspective. For the purposes of the STExperiMents project, STEM remains the initial reference framework because the experimental activities are grounded in scientific and mathematical inquiry. However, the project acknowledges that creative design elements, visualisation practices, and interdisciplinary perspectives associated with STEAM may enrich experimental task design and support broader engagement with STEM-related phenomena.

Educational Context Across Participating Countries

The design of STEM activities and experimental guidelines within a transnational partnership involving Finland, Czechia, Türkiye, and Austria requires attention to differences in educational structures and classroom conditions. While all four countries include science education and experimental work in their curricula, the implementation context varies.

Factors include availability and maintenance of laboratory infrastructure, access to consumable materials, class size, instructional time allocated to practical work, and the organisation of teacher education and in-service training. In some settings, laboratory sessions might be formally scheduled; in others, experimentation is integrated into regular subject periods. Degrees of curricular flexibility, assessment practices, and safety regulations may shape how experiments are structured and conducted. These contextual characteristics influence whether experiments are primarily teacher-led, guided, or more open in format. These differences shape the development of guidelines that can be interpreted and implemented across diverse institutional environments without assuming uniform material, temporal, or pedagogical conditions.

National STEM Priorities

Based on national curriculum frameworks and official system profiles, Finland, Czechia, Türkiye and Austria all include science and mathematics as compulsory components of basic education, and all formally reference experimental or inquiry-related elements within science teaching.

- In **Finland**, the National Core Curriculum requires multidisciplinary learning modules and emphasises inquiry and experimental work in science subjects (Finnish National Agency for Education, 2016).
- In **Czechia**, the Framework Educational Programme for Basic Education defines science subjects within the educational area “Man and Nature” and includes practical activities and observation as part of science instruction (Ministry of Education, Youth and Sports Czech Republic, 2021).
- In **Türkiye**, the national Science Curriculum specifies inquiry-based learning, experimentation and engineering design skills within centrally defined curriculum standards (Ministry of National Education Türkiye, 2024).
- In **Austria**, subject-based curricula for primary and secondary education explicitly refer to experimentation and scientific inquiry within competence-oriented science education (BMBWF, 2004, 2012).

System profiles indicate differences in governance structures and levels of school autonomy across the four countries, which shape how STEM and experimental activities are implemented at school level (Eurydice, 2023a, 2023b, 2023c, 2023d; OECD, 2020).

Finland

The Finnish basic education curriculum is defined by the National Core Curriculum for Basic Education (Perusopetuksen opetussuunnitelman perusteet 2014; POPS 2014) providing a nationwide framework guiding local curriculum development. Municipalities and schools have considerable pedagogical autonomy in the Finnish educational system.

The Finnish National STEM Strategy and Action Plan (Ministry of Education and Culture, 2023) strengthens competence in natural sciences, mathematics, and technology across education and society supporting socially, ecologically, and economically sustainable development and innovation capacity (Ministry of Education and Culture, 2023).The broad concept of LUMATE (natural sciences, mathematics and technology), aligns Finnish education with the international STEM/STEAM framework connecting to interdisciplinary learning and technological competence for future working life and societal challenges (Ministry of Education and Culture, 2023).

Curricula include inquiry-oriented methodologies, transversal competencies, and diverse learning environments and methods into all subject areas. Science education is competence-based (in-depth and broad-based) and emphasizes experimentation, phenomenon based and learner center learning. The curriculum emphasises a learning approach in which students engage in hands-on investigation individually and in groups, apply problem-solving strategies and learn to apply topics to real-world contexts (POPS, 2014). It also encourages the expansion of learning environments beyond the school through collaboration with external partners (Fisk, 2024), enriching inquiry-based learning and linking education to real-world contexts. (POPS, 2014).

Phenomenon-based learning modules often integrate science, mathematics, technology, and arts perspectives in ways comparable to STEAM approaches. These modules can be organised as project weeks or distributed interdisciplinary learning units across the school year (Opetushallitus, 2014). The national STEM strategy further reinforces these curricular orientations by emphasising multidisciplinary STEM learning, collaboration between educational institutions and external stakeholders, and the development of scientific literacy as a key civic competence (Ministry of Education and Culture, 2023).

1. Learning builds on **subject-specific competence**: In-depth and broad-based disciplinary understanding forms the basis for scientific inquiry.
2. **Hands-on and problem-based**: Students investigate, experiment and solve problems individually and in groups in real-world contexts.
3. **Broad-based competence** integrates with **subject specific in-depth competence**: Thinking skills, collaboration are developed through and with subject-specific knowledge, creating a unified competence base supporting deeper inquiry and real-world application.
4. Multidisciplinary (STEAM) modules bridge subjects with **phenomenon-based learning**: Shared phenomena are explored through multiple subjects via project weeks or distributed modules across the school year.
5. Learning environments **extend beyond school**: Partnerships with museums, science centres, experts and organisations enrich inquiry and link learning to authentic settings (e.g. can be used for the multidisciplinary module).
6. STEM competence is linked to **societal wellbeing and sustainable development**.
7. STEM learning is part of a continuous learning pathway.

The national STEM strategy shows the role of STEM education in addressing global challenges such as climate change, digital transformation, and sustainable economic growth (Ministry of Education and Culture, 2023).

Czech Republic

The Czech education system provides a national curricular framework through the Framework Educational Programme for Basic Education (FEP BE), which defines the general learning objectives and competencies for compulsory education. Science education there is organised under the educational area “Man and Nature”, which includes subjects such as physics, chemistry, and biology. The curriculum builds on observation, experimentation, and the interpretation of natural phenomena as central elements of science learning (Ministry of Education, Youth and Sports Czech Republic, 2021). The Czech system combines national curricular guidelines with a degree of autonomy at school level. Schools develop their own School Educational Programmes, adapting their teaching methods and learning activities to local conditions to integrate experimental activities, practical investigations, and inquiry-oriented learning approaches with available resources and institutional priorities (Eurydice, 2023b).

Science education in Czech schools emphasises the development of scientific literacy through observation, experimentation, and reasoning about natural phenomena. Practical activities often involve measurement, comparison of results, and interpretation of evidence. Experimental work therefore functions as an instructional format to connect theoretical knowledge with empirical observation and develop reasoning about variable relationships. Based on the Czech curricular framework and system characteristics, the following principles can be identified for effective STEM education with inquiry-oriented experimentation:

- **Learning connects theory with empirical observation.** Students investigate natural phenomena through structured observation and experimental activities.
- **Scientific reasoning is developed through experimentation.** Learners collect measurements, analyse data, and interpret evidence in order to explain observed phenomena.
- **Inquiry processes are embedded**. Experimental tasks encourage students to formulate questions, explore variable relationships, and evaluate results.
- **Flexibility at school level supports contextual adaptation.** Schools adapt experimental activities related to available materials, laboratory infrastructure, and instructional time.
- **Collaboration and discussion support conceptual understanding.** Students compare observations and interpretations to refine explanations and to connect results to concepts.

Türkiye.

Türkiye provides a curricular framework in which scientific inquiry, engineering design, competence-oriented learning, and real-world problem solving are interconnected (Ministry of National Education Turkiye, 2024). The degree of flexibility in implementation is more limited than in decentralised systems, but these elements are formally embedded in national curriculum documents and educational policy. Science education is structured through centrally defined curricula in primary and lower secondary education, particularly through the Science Curriculum, which includes experimentation, inquiry processes, analytical thinking, and application to everyday life as core components.

STEAM-focused education has been strengthened through curriculum reforms and national policy initiatives, especially since the 2018 and 2024 curriculum updates. Engineering and design skills were explicitly incorporated into science education, linking experimentation with problem solving, product development, and evaluation. STEAM learning is generally embedded within science and technology-oriented activities rather than implemented as a separate subject area. Inquiry-based learning is promoted through structured activities in which students formulate questions, conduct investigations, interpret data, and connect findings to real-life situations.

Compared to more decentralised systems, implementation is more standardised, with textbooks and national guidelines playing a strong role in shaping classroom practice (Eurydice, 2023c). However, this also ensures that inquiry processes and experimental activities are consistently included across schools. Based on curriculum documents and STEM policy developments, the following principles can be identified for effective STEM education in Turkey at secondary level:

- Learning is **structured and guided**. Inquiry processes are guided by predefined tasks so students can engage with experiments while always being supported by teachers.
- Experimentation is **linked to engineering design**. Students investigate phenomena and also develop and test solutions, integrating scientific knowledge with practical application.
- **Real-world relevance** is embedded. Tasks are connected to everyday problems and societal needs, supporting the application of knowledge beyond the classroom.
- **Scientific process skills** are explicitly developed. Observation, hypothesis formation, data interpretation, and evaluation are systematically included in task design.
- **Interdisciplinary connections** are often anchored in science. Mathematics and technology are integrated primarily through application within science contexts.
- Resources and implementation are **standardised**. Textbooks and national materials provide structured experimental activities to enhance inquiry in practice.

These principles reflect a model in which inquiry-based STEM learning is embedded within a centrally guided curriculum, combining structured experimentation with elements of engineering design and real-world application.

Austria

Austria provides a curricular framework in which experiments, transversal competencies, inquiry-oriented methodologies, digital tools, and sustainability themes are interconnected. The degree of integration and the depth of implementation vary across educational settings, but all elements are formally embedded in national policy documents and subject curricula. Science education is structured through subject-based curricula in primary and secondary education, including physics, chemistry and biology, with competence-oriented formulations that reference experimentation and scientific inquiry (BMBWF, 2004, 2012). The Austrian system combines nationally defined curricula with school-level pedagogical autonomy (Eurydice, 2023d). STEM-focused education is often implemented through specialised profiles within existing school types. General secondary schools and vocational and technical secondary schools provide structured laboratory-based instruction within technical programmes (BMBWF, 2011). Schools may choose to focus on MINT education and can be awarded by a MINT seal. The national MINT-seal of approval certifies schools that demonstrate structured and sustained engagement in mathematics, informatics, natural sciences and technology (MINT).

Based on the mintschule network, (MINT Best Practices, 2021), these principles can be identified for effective STEM education in Austria with inquiry-based learning at secondary level:

1. Learning is **application-oriented**. Students engage in hands-on investigation. Practical experimentation, problem-solving tasks, and real-world contexts are central components.
2. **Inquiry** is structured and student-active. Learners are encouraged to develop hypotheses, plan investigations, collect and interpret data, and reflect on findings.
3. **Interdisciplinarity** is embedded. STEM subjects are connected across disciplinary boundaries so students can address complex phenomena from multiple perspectives.
4. **Partnerships** extend learning environments. Collaboration with universities, research institutions, companies, and STEM initiatives supports research experiences.
5. **Teacher professionalisation** is continuous. Schools with sustained STEM profiles invest in ongoing subject-specific and pedagogical development to facilitate inquiry processes.
6. **STEM** is institutionally anchored. Inquiry-based STEM education is embedded in the school development plan with long-term goals.
7. **Digital tools** are integrated meaningfully. They are used for data collection, modelling, simulation, and documentation, supporting investigative processes.

Shared Educational Foundations

Competencies such as critical thinking, collaboration, communication, creativity, and digital literacy are explicitly referenced across subject areas. In STEM subjects, experiments are one of the main instructional formats through which these competencies are addressed. Experiments are intended to support conceptual understanding and to connect theoretical knowledge with empirical observation. In practice, the frequency and format of experimental activities vary by school type, subject, and local conditions. Demonstrative experiments are common in Physics to visualize natural phenomena and help build an intuitive understanding of concepts. In Chemistry, structured experiments follow predefined procedures so students develop technical skills and scientific rigor through observation, measurement, and recording. In Biology, experimental work often takes the form of observation, measurements, or simple investigations.

Sustainability themes are structurally anchored in the curriculum as cross-curricular principles and within specific subjects such as Biology or Chemistry. Topics include climate change, energy systems, resource use, and environmental protection. Experiments relate to sustainability areas such as renewable energy, material properties, ecological systems, and environmental measurements. Sustainability serves as a thematic context that frames experimental tasks and problem-based scenarios, linking STEM content to societal and environmental questions.

The principles derived from the comparison of participating countries and following theoretical considerations will generate a set of principles on which the experiments will be developed. The set of principles will be connected to theories we derived from national contexts and then be explained with an example each to display how the design principle could look like in praxis.

Theoretical Foundations for Experimental Task Design

Experimental task design in science education draws on several theoretical perspectives that explain how learners engage with knowledge construction and how instructional environments shape this process. Inquiry-based learning provides a starting point in which learning happens during hypothesis generation practicing, variable control, and evidence evaluation. In inquiry settings, learners formulate questions, interpret evidence, and revise their reasoning in response to experimental results. Research in science education emphasizes that experimentation becomes educationally meaningful when tasks require learners to engage with uncertainty, interacting variables, and iterative decision-making (Minner et al., 2009; Pedaste et al., 2015).

Within this perspective, experiments can be understood as structured epistemic environments. The design of experimental tasks determines whether learners encounter experimentation as procedural execution or as a process of investigation. Studies on laboratory instruction distinguish between verification-oriented activities, in which procedures and results are largely predetermined, and inquiry-oriented designs that distribute epistemic responsibility to learners (Domin, 1999; Hofstein & Lunetta, 2004). Inquiry-oriented tasks expose learners to interacting variables and uncertain outcomes, requiring systematic reasoning and the coordination of evidence. Research on scientific thinking shows that practices such as controlling variables in multicausal systems are often hidden and therefore require structured opportunities for investigation and reflection (Kuhn, 2002).

The structure of experimental tasks also influences the instructional demands placed on teachers. Inquiry-based environments require teachers to balance epistemic openness with guidance while supporting collaboration, managing cognitive load, and connecting experimental observations with conceptual understanding. Cognitive load theory explains how poorly structured tasks can overwhelm learners, while carefully designed constraints help focus attention on relevant conceptual relationships (Kirschner et al., 2006; Sweller, 2019). Facilitation in inquiry settings therefore depends on the epistemic structure of the task itself, since design decisions shape how learners interact with variables, evidence, and collaborative processes.

Inquiry-Based Learning

The design of experimental tasks in science education requires consideration of how learners engage with knowledge production. Inquiry-based learning positions students as active participants in epistemic practices such as hypothesis generation, variable control, and evidence evaluation (see Figure 3). Learners are expected to make decisions about experimental design, interpret uncertain results, and adjust their strategies in response to emerging evidence. These practices connect experimentation with scientific reasoning, as learners coordinate observations, variables, and measurements to construct explanations. Research on inquiry-based science education suggests that such epistemic engagement depends strongly on how tasks are structured and how opportunities for reflection and interpretation are embedded in the learning process, not always emerging from hands-on activity (Minner et al., 2009; Pedaste et al., 2015).

Experimental learning can be understood as the design of structured epistemic environments. Laboratory activities differ depending on whether learners verify known results or investigate open problems. Verification-oriented laboratories typically prescribe procedures and expected outcomes, positioning learners primarily as executors of predefined steps. Inquiry-oriented experiments shift epistemic responsibility to learners, requiring them to formulate hypotheses, identify and control variables, and evaluate evidence under conditions of uncertainty. Such environments expose the complexity of interacting variables and require iterative decision-making. The design of experimental tasks can determine whether learners engage with experimentation as procedural execution or as a process of knowledge construction. Material constraints, measurement tools, and comparison criteria define the structure of the problem space and influence how learners interpret evidence and revise their reasoning (Domin, 1999; Kuhn, 2002; Lazonder & Harmsen, 2016).

Facilitation in Inquiry Settings

The structure of experimental tasks also shapes the facilitation demands placed on teachers. Inquiry-based settings require teachers to manage multiple processes simultaneously:

- maintaining productive uncertainty,
- supporting variable control strategies,
- coordinating collaborative work,
- and guiding reflection that connects empirical observations to conceptual understanding.

These facilitation demands emerge from the epistemic architecture of the task. Poorly structured activities may increase extraneous cognitive load and hinder reasoning processes, while carefully designed constraints can make relevant variables visible and support systematic comparison (Kirschner et al., 2006; Sweller, 2019). Teachers therefore require awareness of how design decisions influence cognitive load, collaboration dynamics, and conceptual consolidation.

Participation in inquiry-oriented experiments can make these facilitation demands visible in teacher education contexts. Embodied participation exposes aspects of inquiry that often remain implicit when teaching is only observed. Role shifts between learner and teacher perspectives can support the development of facilitation awareness and professional noticing if participants recognize how specific task features generate cognitive challenges, collaboration demands, and opportunities for conceptual insight (Sherin, 2007; Kolb, 1984; Schön, 1983).

a) b)

Figure 3: Pictures *a)* and *b)* illustrate activities in which students are encouraged to formulate a hypothesis in response to an inquiry-driven design challenge.

Based on these theoretical considerations, the experiments in the project are designed as structured inquiry environments that balance epistemic openness with manageable constraints. The principles derived from the comparison of participating countries and the theoretical foundations outlined above inform the design of experimental tasks.

Each principle addresses a specific aspect of experimental learning, such as the distribution of epistemic responsibility, the visibility of interacting variables, or the role of systematic measurement in evidence evaluation.

Self Determination Theory

Experimental task design also interacts with motivational processes during learning activities. Self-Determination Theory describes how learning environments support engagement when learners experience

- autonomy,
- competence, and
- relatedness.

Inquiry-oriented experimental tasks can provide such conditions by containing decision-making within constrained problem spaces and by fostering collaborative interpretation of results (Ryan & Deci, 2000).

In this project, students' motivational responses during experimentation were measured using the Intrinsic Motivation Inventory (IMI), which operationalises motivational dimensions derived from Self-Determination Theory (McAuley, Duncan & Tammen, 1989).

Contextual and Interdisciplinary Learning

Experimental learning in science education in broader contexts connect disciplinary knowledge to real-world phenomena and problem situations and can support meaning-making by linking abstract concepts to observable or relevant situations, provided that tasks maintain a clear epistemic focus (Hmelo-Silver, 2004; Gilbert, 2006). In this sense, context defines the problem space, the relevance of variables, and the interpretation of results.

Interdisciplinary approaches discussed under the terms STEM or STEAM often describe ways of connecting knowledge domains when addressing complex phenomena (Liao, 2016). These approaches provide a framework for organising content and perspectives. In experimental task design, interdisciplinary connections are relevant when they influence problem structure, considered variables, or how solutions are evaluated. For example, design-related decisions, modelling processes, or data interpretation may draw on multiple domains without always requiring explicit integration of all disciplines.

The inclusion of artistic or humanities-oriented elements, as emphasised in STEAM approaches, can support processes such as visualisation, modelling, connection to local culture, and representation (Henriksen, 2017). These elements can contribute to learning when they are epistemically connected to the investigation and not treated as separate creative activities. The relevance of interdisciplinary perspectives therefore depends on their function within the experimental task by shaping reasoning processes, representations, and the interpretation and contextualisation of evidence. These perspectives act as a framing layer influencing how tasks are constructed and how learners engage with complex, real-world phenomena.

Design Principles for Experimental Tasks

The experimental activities are based on shared curricular orientations across participating countries. National curricula across the participating countries contain overlapping orientations in science education, particularly regarding inquiry-based learning, transversal competencies, digital integration, and contextualised problem solving. These shared orientations provide the basis for formulating common design principles for experimental tasks.

The following principles define how experimental tasks are to be constructed within the project. They translate curricular commonalities into operational design criteria. The intention is to ensure that each experimental activity developed in the project meets shared structural requirements. Each partner will develop a hands-on experiment that may integrate digital tools and one virtual experiment keeping those requirements in mind:

Cross-Country Principles

1. Every experiment connects the scientific concept to a recognisable **real-world situation**. The phenomenon is embedded in a practical context showing why the concept matters.
2. Experiments combine **conceptual understanding** with structured **inquiry cycles**. Students formulate predictions, test them, analyse results, and compare them with others.
3. The design of each task should **ensure knowledge transfer** and thus include an explicit measurement and evaluation structure.

Each experiment should be designed along these dimensions as general outlines.

1. **Conceptual focus:** The experiment should identify the scientific or mathematical concept it addresses. The conceptual objective should guide the design of variables, materials, and measurements.

2. **Competence focus:** The experiment should specify which competences are structurally embedded in the task. These may include critical thinking, problem solving, collaboration, creativity, and digital literacy. Competences should be supported through task structure.

3. **Contextual relevance:** The experimental problem has to be connected to real-world or authentic scenarios. The contextual framing should support transfer between disciplinary knowledge and everyday applications.

Format-Specific Considerations: Hands-on experiments should enable physical interaction with materials or tools. The design should ensure that manipulation is epistemically relevant. Virtual experiments support structured manipulation of variables within digital environments. The digital interface should encourage exploration and measurement, and active participation.

Technology Integration: Experiments should integrate digital tools as part of the reasoning process. This may include programming elements, digital design, data collection tools, or simulation environments. Digital components should support conceptual understanding.

Adaptability: Experiments have to be adaptable to local contexts including flexibility in materials, differentiation options for diverse learners, and alignment with national curricular requirements.

Sustainability: Where applicable, sustainability considerations are reflected in the design of experiments, for example through the use of reusable materials or task constraints such as limited material availability that require deliberate resource use.

Methodological Design Requirements: All experimental tasks developed in the project should follow common methodological principles:

- **Engagement and autonomy**: Students should manipulate variables, make decisions, or construct artefacts connecting to Self Determination Theory by a degree of autonomy.
- **Inquiry**: The task should require hypothesis formation, testing, observation, and interpretation. This connects to the competence level of Self Determination Theory.
- **Collaboration**: Experiments should include phases for groupwork to share reasoning and compare outcomes connecting to relatedness of Self Determination theory.
- **Reflection**: Each experiment should contain a structured phase for analysing results, discussing interpretations, and considering alternative explanations or improvements.
- **Feasibility**: Materials, time requirements, and technological demands should be realistic for classroom implementation.

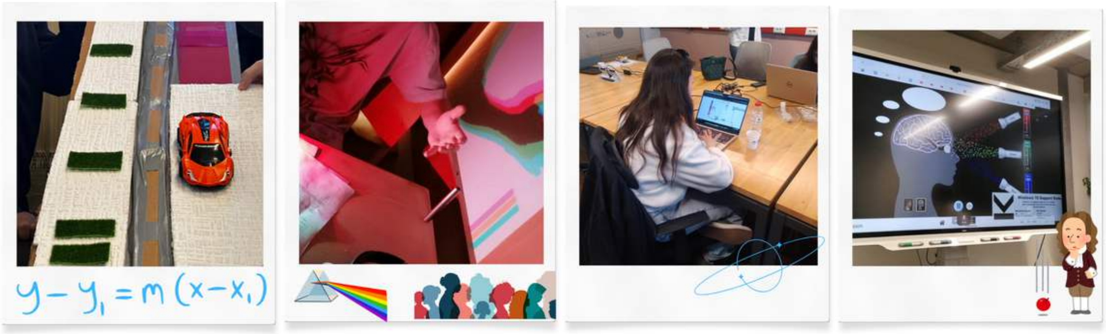
Derived Set of Dimensions

The following dimensions operationalise the principles in the structure of individual experiments. Each experimental activity is described along a set of shared design dimensions. These dimensions make the structure of the tasks comparable across countries and formats.

Hand-on Experiments

1. *Experiments start from a concrete scenario.*
    - Theory: Contextualised problem framing can support epistemic engagement in inquiry-based learning environments. Learners can connect disciplinary reasoning with observable phenomena and everyday contexts through scientific concepts if they are introduced through practical problems (Minner et al., 2009; Pedaste et al., 2015).
    - Design implication: School connects to every life of learners. A STExperiMents experiment is based on everyday situations or reflection is used to connect the experiment to life outside of schools and complex scenarios (See Figure 4 a).
    - Indicator: The task is framed as a mission, challenge, or narrative situation that requires solving a practical problem.
2. *Students build or modify a physical artefact that produces measurable effects.*
    - Theory: Learners are active participants in knowledge construction in experimental learning environments. Manipulating artefacts and observing resulting changes can support hypothesis testing and understanding the impact of variables (Domin, 1999; Kuhn, 2002).
    - Design implication: Hands-on experiments should contain physical artefacts and their creation, use, or modification should have a measurable effect.
    - Indicator: The experiment includes observation and constructing or configuring something that influences the phenomenon.
3. *Groups generate comparable results that should be exchanged across teams.*
    - Theory: Scientific reasoning can be developed through comparison of evidence and interpretation of results(Pedaste et al., 2015; Kuhn, 2002).
    - Design implication: Experiments should produce outcomes across groups for collaborative evidence evaluation and discussion of alternative explanations.
    - Indicator: Data comparison between groups is structurally embedded.
4. *The experiment contains at least one open design parameter that changes the outcome.*
    - Theory: Inquiry-based learning invites learners to investigate variable relationships and evaluate their effects under conditions of uncertainty. Experimental tasks therefore should expose interacting variables that can be manipulated and compared (Domin, 1999; Lazonder & Harmsen, 2016).
    - Design implication: Learners should be able to create unique, personalised learning experiences with the provided materials. Their choice should matter.
    - Indicator: Students are encouraged to modify materials, configuration, or conditions that directly influence the phenomenon (See Figure 4 b).

5. *Students should publicly represent their results.*
    - Theory: Representing results publicly supports interpretation of evidence, comparison of explanations, and conceptual consolidation through discussion (Minner et al., 2009; Pedaste et al., 2015).
    - Design implication: Students should compare their results with either the entire plenum or other groups. Discussions should always be encouraged and time allocated.
    - Indicator: Results are externalised through posters, artefacts, displays, or presentations exceeding written answers.



a) b) c) d)

Figure 4. In a) and b), students engage in hands-on challenges, manipulating variables such as surface materials and ramp configurations to observe and compare outcomes. In c), pre-service teachers test pH values, and in d), through simulations, they explore RGB colour addition and subtraction.

Virtual Experiments

1. *A phenomenon is explored through interactive simulation, never observation of a fixed demonstration.*
    - Theory: Digital inquiry can support experimentation and observation by manipulation of variables dynamically (Lazonder & Harmsen, 2016).
    - Design implication: Options to change the experiment's outcome representing the dimensions of the experiment should be available.
    - Indicator: Students manipulate variables and observe system responses dynamically (See Figure 4 c).
2. *Simulations are used to model various phenomena that are difficult or unsafe to reproduce physically in school laboratories.*
    - Theory: Virtual environments extend experimental possibilities by exploration of phenomena that are impractical or unsafe in classroom laboratories while supporting hypothesis testing and evidence evaluation (Pedaste et al., 2015).
    - Design implication: Virtual experiments contain benefits of either safety, showing otherwise hidden information, or use otherwise expensive or time-consuming materials (See Figure 4 d where the effects in brains are made visible).
    - Indicator: The virtual environment supports experimentation with parameters inaccessible in a classroom.
3. *Digital tools can be measurement devices and part of the learning task itself.*
    - Theory: Digital environments should integrate tools for observation, modelling, and data collection that support systematic investigation of variable relationships (Kuhn, 2002; Pedaste et al., 2015).
    - Design implication: Digital tools should always connect directly to the experiment by for example providing measurement options and the virtual environment itself should be part of skill development of for example digital competencies.
    - Indicator: Students use software environments (simulation platforms, app builders) as part of the experimental process.

Showing the principles and dimensions in an example

Design principles are distributed across different elements of the experiment description and activity structure. Each principle is operationalized through specific components such as problem framing, activity instructions, measurement tasks, or reflection prompts.

Example structure

Open-Ended Problem Framing: The open ended and real world anchoring of experiments is introduced in the general objectives or in the guiding questions that initiate the activity. For example, students may be asked to design an object influencing the experiment, requiring them to explore different materials and measure different results than another group.

Constrained Complexity: Adaptations and complexity is reflected in the definition of a limited set of variables that students can manipulate during the activity. For instance, experiments may restrict exploration to specific parameters such as surface material or the intensity of light sources within a simulation.

Measurement-Based Evidence Anchoring: Evidence-based reasoning is supported through structured data collection during the experiment. Students may record measurements such as time, pH values, observed color outcomes, or simulation results and use these observations to compare designs or evaluate their initial predictions. Tables for data collection can be found in accompanying student worksheets that can be either adapted or printed out as they are.

Structured Reflection for Conceptual Consolidation: This is done through structured reflection tasks that follow the experimental activity. These may include guided questions, group discussions, or poster presentations in which students interpret their results and connect them to the underlying scientific concepts.

Feasibility and Context Adaptability: Elements such as grade-level specification, duration estimates, resource lists, and suggestions for adaptations for other grades so teachers can adjust the activity to different classroom contexts, age groups, or available materials.

Task Design Template

Each experiment follows a certain structure so teachers can quickly orient themselves regarding the experiment's purpose, structure, and practical requirements to adapt it to their needs. Hands-on and virtual experiments follow the same structure so teachers will always find relevant information in the same areas and sections. The general parts of the experiments are:

1. Metadata: grade, duration
2. Pedagogical framing: objectives, competencies, concepts, learning outcomes
3. Requirements: prerequisite knowledge, resources
4. Activity description: experiment / development
5. Teaching support: adaptations, assessment
6. Student support: worksheets
7. Optional additions: teacher preparation, media

An overview provides structural information about the target group the experiment is designed for to learn about the connected subjects and competencies so teachers know when in the curriculum the experiment is suitable. After that, teachers find a detailed step-by-step description of the experiment to help them identify where they should adapt the experiment, which kind of resources are used where, and which learning materials are available out of the box such as student worksheets for data collection. The experiment description provides a narrative overview of how the activity unfolds, what students do, and what kind of learning experience it creates.

Overview Area

1. Each experiment opens with the **Grade Level and Activity Duration**, giving teachers an immediate sense of the intended audience and the time required.
2. This is followed by the **Competencies** the experiment addresses such as critical thinking, creativity, communication and collaboration, to more discipline-specific ones such as scientific inquiry and data analysis.
3. The **General Objectives** frame the experiment as an open problem or challenge.
4. A **Prerequisite Knowledge** section explains what students should already know to be able to complete the experiment. This can help teachers to adapt their introductions to the topic depending on the national curriculum.
5. A **Resource List** is provided to know what students should bring to the experiment and what materials teachers should organise or prepare in advance.The **Concepts for STEAM Disciplines** and **Learning Outcomes** help teachers to gain a good picture of the conceptual and competency landscape of the experiment, organised by discipline.

Narrative Step-by-Step Description

The Experiment itself is described in a step-by-step guide that includes instructions, questions, timing suggestions, and scientific explanations. In the Experiment section, the five design principles are put into practice in the following way:

- **Open-Ended Problem Framing is done** by starting each experiment with a real-world problem or provocative question, such as why a candle stops burning or how materials affect the speed of a car. The first design principle which gives students a meaningful reason to investigate without prescribing what they will find.
- From there, the activity guides students through a constrained set of variables, specific materials to test, particular parameters to manipulate in a simulation, or defined motion scenarios to measure, keeping complexity manageable while preserving genuine inquiry; this is what **Constrained Complexity** looks like in practice.
- **Measurement-Based Evidence Anchoring** takes shape when they collect and record observables, and comparable data in structured tables, whether that means timing a toy car, logging gas concentrations, or reading acceleration graphs.
- A structured reflection moment then closes the activity, through guided questions, group discussions, poster presentations, or engineering improvement tasks, helping students interpret their results and connect them to the underlying scientific concepts; this is **Structured Reflection for Conceptual Consolidation.**
- **Sustainability, Feasibility,** and **Context Adaptability** is addressed through accessible, low-cost materials and simple measuring tools such as handmade paper protractors or stopwatches that can be used across different countries as well as contextual anchors connecting the activity to local realities such as a reference to the Großglockner mountain road for Austria in the ramps experiment which teachers in other participating countries are equally encouraged to replace with a locally meaningful example.

This is followed by the **Assessment** section and the **Adaptations for Different Levels**, which offers alternative versions for younger or more advanced students. The **Teacher Preparation section** compiles additional resources such as videos, readings, and background explanations, to help teachers feel confident before the lesson. Each experiment also includes learning materials such as **Student Worksheets** that guide students through predictions, data collection, and reflection, supporting their learning process and the teacher's assessment.The worksheets make the process of data collection visible and comparable to other groups.

Iterative Refinement

The initial versions of the experimental activities are developed based on the design principles following the shared template and aligning them with the pedagogical and disciplinary goals of the project and their respective national goals. These draft prototypes help explore how the design principles could be translated into classroom activities. Next, experiments are reviewed by other project partners to examine each other's activities from different curricular and pedagogical perspectives. The experiments are then adjusted to improve clarity, feasibility, and alignment with design principles. They are then implemented with pre-service teachers, who provide feedback (see Figure 6) from a teacher preparation perspective, and also piloted with students in classroom settings. This will help ensure experiments are workable, understandable, and suitable for classroom use.

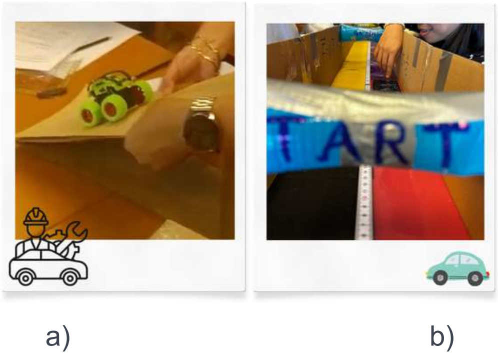


Figure 6. In a) and b), pre-service teachers are piloting and refining a hands-on experiment, improving a ramp iteratively.

Teachers developing their own experimental activities using the template should treat the initial version as a draft that can be improved through reflection and testing with for example colleagues or teachers of subjects part of the experience.

After designing the activity, teachers should make sure whether the task contains a clear problem to explore, manageable variables that students can manipulate, opportunities for collecting observable evidence, and moments where students reflect on their results. Based on this review best done by colleagues, the activity can be refined by simplifying instructions, adjusting materials or time requirements, and clarifying guiding questions so that the experiment remains feasible while still supporting meaningful exploration of the underlying scientific concepts.

Example Task

The experiment "Keeping Vaccines Cool" uses a real-world design challenge in which students develop and test solutions for maintaining necessary temperatures under constrained conditions as can be seen on Figure 7.

- **Open ended problem framing:** the experiment begins with an open-ended, real-world question: how vaccines can be kept cool in warm environments with limited power supply. Students are asked to design and test their own approaches making it meaningful, contextualized, and open to multiple valid solutions.
- **Constrained Complexity:** the variables students can manipulate are limited. Students work within defined parameters such as available insulation materials, container types, or cooling strategies. This keeps the task manageable while preserving genuine inquiry, since different design choices still lead to different measurable outcomes.
- **Measurement-Based Evidence Anchoring:** students systematically collect data such as temperature changes over time, cooling duration, or performance differences between designs. These observations are structured through measurement tasks and data tables, for comparison across groups and linking design decisions to empirical results.

- **Structured Reflection for Conceptual Consolidation:** guided interpretation is part of the experiment. Students analyse data, compare solutions, and relate findings to underlying scientific concepts such as heat transfer, insulation, and energy efficiency. This reflection phase transforms raw observations into conceptual understanding and supports articulation through discussion or presentation.
- **Sustainability, Feasibility and Context Adaptability:** accessible, low-cost materials and simple measurement tools are used, making it transferable across different educational contexts. The structure helps teachers to adapt the task to available resources, student age, or local relevance, while maintaining the core inquiry logic.

a) b)

Figure 7: *a)* Students and pre-service teachers testing their isolation materials' hypotheses during a hands-on activity, b) while a second group takes temperature measurements to test their hypothesis.

Task Design template in practice follows the structure for quick orientation and adaptation:

- In the **overview area**, teachers find grade level and duration, which define the scope of implementation. Competencies include both transversal skills such as collaboration and critical thinking, and domain-specific skills like scientific inquiry and data analysis. The objectives introduce the open design challenge, while prerequisite knowledge clarifies required conceptual entry points. A resource list specifies materials, and learning outcomes outline expected conceptual and procedural gains across disciplines.
- The narrative **step-by-step description** operationalizes the design principles. It starts with the open problem, guides students through constrained experimentation, embeds structured measurement, and ends with reflection and interpretation. Each phase is explicitly linked to what students do, what they observe, and how they reason.
- The **teaching support section** includes assessment strategies and adaptations for different levels for variation in complexity without changing the core structure. The student support-materials, such as worksheets, guide prediction, data collection, and reflection, ensure that inquiry remains structured.

Expected Educational Contribution, Recommendations

For Students

Working with the experimental activities engages students in structured inquiry processes in which reasoning is closely connected to observable phenomena. The tasks require learners to formulate predictions, manipulate variables, generate measurable evidence, and interpret results in relation to scientific concepts. Experimentation becomes a context for developing inquiry competence through these processes.

The design of the activities also supports structured reasoning practices. As illustrated in Figure 8, the experiment is structured to encourage students to compare results across groups, interpret differences in measurements, and connect their observations to the underlying physical, mathematical or chemical mechanisms at play, making the reasoning process explicit and fostering evidence-based discussion. Reflection phases are included to consolidate conceptual understanding and to make the reasoning process explicit. These elements encourage students to articulate explanations, evaluate evidence, and revise initial assumptions. Students encounter scientific concepts in relation to practical problems because the experimental tasks are embedded in contextual scenarios and interdisciplinary themes. This contextual framing can support transfer between disciplinary knowledge and broader STEM contexts. In this way, the activities connect conceptual understanding with the interpretation of real-world phenomena.

For Teachers

The guidelines support teachers in recognising how the internal structure of experimental tasks shapes classroom learning processes. The framework makes the epistemic structure of experiments visible by describing elements such as problem framing, variable organisation, measurement procedures, and reflection phases. This perspective can help teachers understand how task design influences student reasoning and collaboration during inquiry activities.

The framework also strengthens facilitation awareness in inquiry-oriented settings. Experimental tasks often require teachers to manage multiple processes simultaneously, including student collaboration, interpretation of results, and conceptual clarification. By making the structure of tasks explicit, the guidelines support teachers in anticipating these facilitation demands and responding adaptively during classroom implementation. In addition, the framework contributes to teachers' design literacy. Teachers can use the described dimensions to analyse existing experiments, adapt activities to local classroom conditions, or develop new experimental tasks that follow similar principles. This orientation positions experiments as instructional activities and objects of professional reflection within teacher education.

For Policy and Curriculum Development

The principles provide a structured approach for developing experimental STEM tasks that can be implemented across diverse educational systems. The guidelines guide adaptation to different curricular frameworks, laboratory infrastructures, and classroom conditions by focusing on the internal structure of experiments.

The design dimensions described in the framework also support comparability between experimental activities developed in different contexts. They can be analysed and refined across partner institutions because tasks are structured around shared elements such as conceptual focus, measurement structures, and reflection phases. This enables collaborative development and evaluation of experimental activities within international STEM education projects.

More broadly, the framework contributes to discussions about how inquiry-based learning can be operationalised within STEM education. The guidelines offer a practical reference for initiatives that seek to integrate structured experimentation into classroom practice across European educational contexts by translating curricular orientations toward inquiry, transversal competences, and contextualised problem solving into concrete task design elements.

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