STEMkey

Teaching standard STEM topics with a key competence approach

Higher Education Course Material

Module 01 - Introduction

Developing Key Competences in STEM Education

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Summary

The European Commission has identified the urgent need to develop its citizens' key competences in certain areas of living and working with the intention to ensure personal fulfilment, a sustainable lifestyle, employability, social inclusion, and active citizenship. **A key competence is defined as a combination of knowledge, skills and attitudes** by the Council of the European Union (2018); the European Commission, Directorate-General for Education, Youth, Sport and Culture (2019) and the European Commission (2020).

STEMkey[1] provides options to implement the EU's Framework for Key Competences for Lifelong Learning in STEM education.

The core of STEM[2] education traditionally delivers fundamental subject knowledge like functions, human anatomy, and chemical reactions. Learners' skills to apply gained knowledge and attitudes to set it in context with their life and societal decision-making processes have received less attention so far. Thus future STEM teachers need to be empowered to teach subject knowledge and to support their students to acquire skills and attidudes needed to apply this knowledge and make informed decisions. Only then can STEM education support our society, environment, and Europe with its full potential.

Module 01 lays the foundation for a set of altogether 13 modules to be used in Higher Education programmes for future STEM teachers. The Modules 02-12[3] cover the STEM disciplines biology, chemistry, physics, (digital) technology and engineering, and exemplify topics from each discipline with regards to the development of key competences in each of them (e.g. light representing physics education, algorithms representing informatics, or the periodic system representing chemistry). **The set supports the development of learners' knowledge, skills and attitudes in different STEM subjects and shows how critical thinking, problem-solving and creativity can be fostered through specific STEM learning activities.** Foci hereby are on an interdisciplinary perspective on each covered STEM discipline, and on the implementation of an integrated STEM approach.

To enable others to take up on key competence-based teaching and thus apply the EU's Framework for Key Competences, a model for the application in STEM subjects is presented.

[1] https://icse.eu/international-projects/stemkey/

[2] STEM stands for science, engineering, maths and technology and in this project also refers to digital technology

[3] These modules were created as part of the STEMkey project, involving STEM education researchers and practitioners from 12 different European countries, and running from 2020 to 2023.

1. Introduction

Europe is confronted with a shortfall of scientific knowledgeable people and underachievement in science (OECD 2016). But to secure its technological leadership, Europe's labour markets need skilled employees in all STEM related sectors, on all professional levels and with a diverse range of technological knowledge (European Union, 2019). A large majority of European countries have recently experienced recruitment difficulties due to a substantial lack of suitable candidates in science sectors (STEM Alliance, 2017).

To overcome this dilemma, the Commission has been running several education initiatives under the umbrella of the European Education Area to overcome growing skills gaps (especially in STEM and related sectors). One of these initiatives is a framework for the acquisition of key competences in a lifelong learning process.

Acquiring key competences in a lifelong learning process is one major element to enable Europe's citizens to continuously partake in civic and social life; as well as to be able to successfully operate on Europe's labour markets, and contribute to its innovation chains (Council of the European Union 2018; DG EAC 2019). Developing key competences furthermore is an essential element for the achievement of the European Education Area and forms the basis for personal fulfilment and a sustainable lifestyle (European Commission, 2020). Being key competent in STEM subjects considerately improves students' employability as particularly in rapidly changing digital and technological environments, employers increasingly are looking for employees which are able to adapt to transforming job positions (COM 2016).

A key competence hereby is defined as a combination of knowledge, skills and attitudes. To tap the full potential of a competence all three elements have to be fostered likewise (EAC 2019). Education consequently must refrain from the sole purpose of (isolated) subject knowledge delivery. This simply does not measure up to today's and tomorrow's challenges anymore. Instead, **STEM education must deliver subject knowledge and allow the development of skills and attitudes to use this knowledge in various societal and real-life contexts** in equal measure. Consequently, future STEM teachers must be empowered to deliver knowledge in their future STEM classrooms without neglecting the skills and attitudes of their students to be developed likewise.

To this end, **interdisciplinary learning has been identified as an important source for the development of key competences** (COM 2019a). Schools sometimes offer interdisciplinary STEM teaching. However, the needs analysis conducted among partner institutions showed that, most teachers do not feel prepared to pursue integrated approaches across disciplines, as they have been educated subject-specifically.

This module 01, as part of a set of altogether 13 modules, serves as introduction into the comprehensive field of key competence development in STEM education. Higher education teaching staff in programs for future STEM teachers, as well as in-service STEM teachers, will be provided with insights into the field, with explanations on main concepts and ideas, and with ideas to take it up into their teaching.

2. Key competences for lifelong learning

The Council of the European Union adopted a Recommendation on Key Competences for Lifelong Learning in May 2018 (European Council, 2018). The Recommendation identifies eight key competences essential to citizens for personal fulfilment, a healthy and sustainable lifestyle, employability, active citizenship, and social inclusion:

- Literacy competence
- Multilingual competence
- Mathematical competence, and science, technology, and engineering competence
- Digital competence
- Personal, social, and learning to learn competence
- Citizen competence
- Entrepreneurship competence
- Cultural awareness and expression competence

Figure 1 Key Competences for Lifelong Learning (DG EAC 2019)

Each key competence is a combination of knowledge, skills, and attitudes. Knowledge is composed of the concepts, facts and figures, ideas, and theories that are already established and support understanding a specific area or subject. Skills are defined as the ability to carry out processes and use the existing knowledge to achieve results. Attitudes describe the disposition and mindset to act or react to ideas, persons, or situations.

The STEMkey project deals with mathematical, science, technology, engineering, and digital competence, comprised to *STEM key competences*, which are further described in the following.

2.1 Mathematical competence

"Mathematical competence is the ability to develop and apply mathematical thinking and insight to solve a range of problems in everyday situations. Building on meaningful knowledge, and a sound mastery of numeracy and geometry, another emphasis is on processing the knowledge. Mathematical competence involves, to different degrees, the ability and willingness to use mathematical modes of thought and presentation (formulas, models, constructs, graphs, charts) (DG EAC 2019, p.8). Some concrete examples follow:

Knowledge - *individual*

- Knowledge of numbers, measures and structures, basic operations, and basic mathematical presentations
- Understanding of mathematical terms and concepts
- Awareness of the questions to which mathematics can offer answers

Skills - *individual*

- To apply basic mathematical principles and processes in everyday contexts
- To follow and assess chains of arguments
- Reason mathematically, understand mathematical proof, and communicate in mathematical language

Attitudes – *in a context*

- A positive attitude in mathematics is based on respect for truth and a willingness to critically look for numerical and geometrical claims or reasons and to assess their validity. Math shall be appreciated as a means to create, evaluate and validate facts and thus as a means to take part in decision-making processes in any real-world situation.

2.2 Science, technology, and engineering competence

"Competence in science refers to the ability and willingness to explain the natural world by using the body of knowledge and methodology employed, including observation and experimentation, to identify questions and draw evidence-based conclusions. Competences in technology and engineering are applications of that knowledge and methodology in response to perceived human wants or needs. Competence in science, technology, and engineering involves understanding the changes caused by human activity and responsibility as an individual citizen" (DG EAC 2019, p.9). Some concrete examples follow:

Knowledge - *individual*

- Knowledge of the basic principles of the natural world, fundamental scientific concepts, theories, principles and methods, technology and technological products and processes
- Understanding of science, technology, engineering, and human activity in general in the natural world
- Understand the advances, limitations, and risks of scientific theories, applications, and technology in societies

Skills - *individual*

- The ability to use logical and rational thought to verify a hypothesis and the readiness to discard one's own convictions when they contradict new experimental findings
- The ability to use and handle technological tools and machines

Attitudes – *in a context*

- An attitude of critical appreciation and curiosity towards science, technology, engineering and its potential, a concern for ethical issues and support for both safety and environmental sustainability, in particular as regards scientific and technological progress in relation to oneself, family, community, and global issues.

2.3 Digital competence

"Digital competence involves the confident, critical and responsible use of, and engagement with, digital technologies for learning, at work, and for participation in society. It includes information and data literacy, communication and collaboration, media literacy, digital content creation (including programming), safety (including digital well-being and competences related to cybersecurity), intellectual property-related questions, problem-solving and critical thinking" (DG EAC 2019, p.10). Some concrete examples follow:

Knowledge - *individual*

- Understand how digital technology can support communication, creativity and innovation, and be aware of their opportunities, limitations, effects and risks
- understand the general principles, mechanisms and logic underlying evolving digital technologies

Skills - *individual*

- The ability to use digital technologies to support their active citizenship and social inclusion, collaboration with others
- The ability to use and handle technological tools and machines

Attitudes – *in a context*

- Engagement with digital technologies and content requires a reflective and curious yet critical, open-minded, and forward-looking attitude to their evolution. It also requires an ethical, safe, and responsible approach to the use of these tools.

The examples above indicate that knowledge and skills are interpreted as individual qualifications and that attitudes express themselves in a context. This distinction between individual qualifications and that attitudes express themselves in a context is essential in an assessment context. We will return to that in section 2.6.

2.4 Educational practices

The development of key competences can be supported by a variety of educational practices in a lifelong learning continuum. Practices which have proven to be supportive of key competence development (DG EAC 2019; DG EAC, McGrath, Hougaard, O'Shea 2020) and which are applied in STEMkey project and its 13 modules are:

- Framing the learning and activities through real-life contexts
- Giving learners an active role

- Applying inquiry-based learning (IBL), project-based learning (PBL) and engineering design processes (EDP)
- Involving digital learning environments and tools
- Considering girls' needs and students' diversity
- Individual and collaborative learning
- Pursuing an integrated STEM approach

2.4.1 Integrated STEM education

Traditional science and mathematics education delivers fundamental subject knowledge like functions, human anatomy, and chemical reactions. Too often, such subject knowledge delivery is isolated in two ways. On the one hand, knowledge is not connected to any contexts of learners' real life, which makes it difficult to recognize its relevance (and thus reduces the interest to gain such knowledge). On the other hand, knowledge is not connected across science subjects let alone STEM disciplines, making it even more difficult to use it to solve real-world problems, as these real-world problems often require more than what one discipline has to offer.

With this in mind, it is intelligible that, **interdisciplinary learning has been identified as an important means for the development of key competences**, as these bear a strong connection to real-life problem-solving (DG EAC, McGrath, Hougaard, O'Shea 2020). Each STEMkey module therefore indicates options to approach activities with an interdisciplinary perspective, referring strongly to real-world problems which require interdisciplinary solutions. These problems refer to the system-character of the "real world", making learners understand that, dealing with problems in an isolated way often does not live up to their complexity.

But what exactly is meant by interdisciplinary STEM education? The following chapter 2.4.1.1 tries to shed some light on terminology and concepts of interdisciplinarity in STEM education.

2.4.1.1 Definitions & Terminology

In the first instance, *STEM* is no more than an acronym for science, technology, engineering and math. Equally, at first instance, the term *STEM education* might be used for the sole purpose of having a summarizing phrase to refer to teaching science, technology, engineering and mathematics. Moreover, as *STEM* is rarely implemented as course subject (other than mathematics or chemistry, for example) or practiced in schools (Mustafa et al, 2019), the term *STEM education* does not necessarily refer to a certain level of integration.

In STEMkey, integration is explicitly targeted with regards to supporting mathematics, science, engineering and (digital) technology key competence development as explained in the chapters above. The activities in the STEMkey modules 2-12 ask learners to solve problems by integrating contents from science, technology, engineering, and mathematics with various degrees. However, there is a lack of consensus about terminology and concepts related to the level of integration in STEM education (Thibaut et al., 2018). In the following, different perspectives on and facts of the case are presented to allow for a common understanding and to provide impetus to contribute to the still ongoing discussions.

One framework for integration was proposed by Vasquez et al. (2013). It sets increasing levels of interconnection among STEM disciplines. Starting with disciplinary approaches (each discipline taught separately) the framework moves to multidisciplinary forms of integration in which concepts and skills in each discipline are learned separately but linked by a common theme. Next is interdisciplinary integration that intends to connect knowledge and skills learned from two or more disciplines to deepen the learning outcome and extend scopes of results. It goes beyond a common theme and focuses on interdisciplinary content. The final is transdisciplinary integration, utilising real-world problems as the context to integrate the knowledge and skills of two or more disciplines. Martín-Páez et.al. (2019) propose a similar yet extended framework to design, interpret, and implement STEM education activities. They describe interdisciplinary integration as a way of combining contents from the STEM disciplines to achieve learning goals that have implications in several subjects/disciplines. The learning goals are (predominantly) curriculum oriented and guided by the teachers. Transdisciplinary integration also combines contents from the STEM disciplines, to achieve learning goals that also go beyond individual disciplines/subjects. These learning goals focus on the problem (rather than the curriculum), preferably a real-world problem. Hereby also contents from other subjects from, for example, social sciences or arts come into consideration, to solve a problem. At this point, the STEAM approach gains importance, which explicitly involves contents (knowledge, skills, mind-sets) from beyond science, technology, engineering and math. In STEMkey, learning evolves around real-world problems on the one side, but for the purpose of realistic practice transfer, the problems and learning goals also are strongly oriented to the partner countries' curricula on S, T E and M subjects. However, teachers are strongly encouraged to go beyond STEM perspectives with the offered activities (and for example, include design and arts to present results or shed light on social aspects by involving socio-scientific issues into the discussions as explained in *https://icse.eu/ensite/*), should the level of performance or interest of the students allow it.

There are other ways to look at how integration can be done in STEM teaching, mainly discussed in literature are content, pedagogy and context (Johnson et al., 2015; Margot & Kettler, 2019; Cheng & So, 2020; Hourigan et al., 2021). Moore et al. propose "to combine all or part of the disciplines of Science, Technology, Engineering and Mathematics into a class, unit or lesson based on the relationship between the subject and context of the real-world problem". Kelly and Knowles (2016) describe integrated STEM education as "the approach to teaching the STEM content of two or more STEM domains, bound by STEM practices within an authentic context for the purpose of connecting these subjects to enhance student learning". In addition to that, context integration involves the use of various STEM contexts to make the content more meaningful, primarily focusing on the content of one discipline, and using the contexts from others to make the content more relevant (Stohlmann, 2019). English (2017) and Stohlmann (2019) pointed out that, science often receives the main focus in carrying out integrated STEM education while engineering and technology are considered the silent members. STEMkey gives a voice to these silent members with activities for (digital) technology and engineering subjects. All researchers agree that integrated STEM education should use real-world contexts to engage students in authentic and meaningful learning. STEMkey takes up on this and sets all its tasks explicitly in real-life contexts. As for the pedagogy part, Cheng and So (2020) introduce pedagogical integration as various pedagogical methods or activities for STEM learning, for example problem-based learning and inquiry processes. Already in 1998, Rakow and Vasquez wrote that "Project-based integration may be the most authentic form of cross-curricular integration because it involves students in real-world learning experiences". Thibaut et al. (2018) did a comprehensive review on instructional practices which are suitable for integration in STEM education and identified five key principles: integration of STEM content (hereby meaning the explicit assimilation of learning goals, content and practices from different STEM disciplines), problem-centered learning, inquiry-based learning, design-based learning and cooperative learning. In addition, Aguilera et al. (2021) did a comprehensive literature review and identified four different methodologies which are mostly associated with STEM education which is integrated to a certain level: inquiry-based learning, project-based learning, problem-based learning and engineering design.

Based on the facts of the case, a *framework for interdisciplinary STEM education*[4] *in the STEMkey project* was set up. Its implementation closely addresses the recommendations given by DG EAC (2019); DG EAC, McGrath, Hougaard, O'Shea (2020), Thibault (2018) and Aguilera et al (2021) and has the following elements.

2.4.2 Using real-life contexts

In STEMkey learning sessions, problems from real-life contexts are the starting point or subject of consideration in tasks; referencing problems embedded in real-life situations and everyday activities (Stylianides & Stylianides, 2008). In other words, problems embedded in real-life situations have no ready-made solution procedure, are non-routine, open-ended, and include social dimensions (Cheng, 2013). Tackling these problems (e.g. energy transition or waste reduction) often requires an approach which draws from more than one discipline. We believe that these problems allow students to learn to connect disciplines and to apply their knowledge in complex situations that may further their understanding of each discipline, their critical reflections on affordances and limitations of the disciplines and help them transfer skills and knowledge across disciplines.

2.4.3 Inquiry-based Learning

Inquiry-based Learning (IBL) and inquiry-based mathematics education (IBME) refer to a student-centered paradigm of teaching mathematics and science. At the beginning of an inquiry-based approach learners generally with identifying a problem, choosing an adequate experimental approach to produce reliable data, collection and analysis of data, and coming up with results based on the analysis (Kolodner et al., 2003). Students are invited to work in ways similar to how mathematicians and scientists work. This means they have to observe phenomena, ask questions, look for mathematical and scientific ways of how to answer these questions (like carrying out experiments, systematically controlling variables, drawing diagrams, calculating, looking for patterns and relationships, and making conjectures and generalisations), interpret and evaluate their solutions, and communicate and discuss their solutions effectively (Dorier & Maass, 2020).

2.4.4 Design-based learning/Engineering design

Engineering design can provide a foundation for pursuing an integrated approach in STEM learning. Scientific inquiry (see 3.4.2) and engineering design have in common that they require learners to investigate an (open-ended) problem, and typically involve collaboration,

[4] In this project, we use the terminology: interdisciplinary STEM education.

questioning, and application of what was learned. However, the steps to be followed to come to a solution differs (King & English 2016).

Typical steps to be followed in the engineering design process (EDP) are: definition of the problem, development of a possible solution and then implementing, testing and optimizing it to come up with the possibly best version of it (Cakmakci 2022, Wells 2016, Bryan et al. 2015;). Learners thereby are controntec with risk, uncertainty and failure (Bryan et al. 2015), being put in the position to reflect and apply critical thinking to succeed. Solutions are iteratively tested and can be justified by mathematical and scientific concept and thus can enhance learners' ability to apply science and mathematics concepts in solving real-world problems significantly (English & King 2015). However, the goal of engineering design is to produce a functioning model which not necessarily requires that learners develop an understanding of scientific principles. More to the point, it is important to balance the cognitive and affective components along the whole process, allowing for empathy and insights into potential users' perspectives and needs, problems, emotions, and motivations. Here the obvious connection to the attitude component n competence-based learning becomes clear. From an instructional point of view, observation, immersion and engagement are commonly used approaches to predict user behaviour. Observation helps us investigating user behaviour in natural settings. Immersion includes the engineer's active participation of a set of experience the user may have. In this process the learners- in their role as engineers - see, feel and experience the issue at hand. In the engagement phase, users are questioned about their behaviour to uncover their meaning-based needs and elicit stories to connect to the real-world and the humans in it (Cakmakci 2022).

Over the last couple of years, one of STEMkey's project partners has been concentrating on integrating epistemic practices of engineering in education and implementing EDP in STEM education (Aydeniz & Cakmakci 2017). As one result of these efforts, STEMkey module 10 offers materials to use EDP to approach the topic of household appliances in the classroom. STEMkey moule 8 introduces Reverse Engineering on the topic electricity.

2.4.5 Project-based Learning

In project based learning (PBL), as in IBL and EDP, learners take active roles, while teachers offer guidance rather than providing "pre-constructed" knowledge. Learners are supported in following an investigative process engaging in real-world and personally meaningful projects or finding an answer to a complex question. A project typically covers an extended period of time in which learners use their competences and experiences to increase their competences, gaining new knowledge and skills by creating a public product, presentation or possibly artefact. As a result, students develop deep content knowledge and critical thinking, collaboration, creativity, and communication skills. Project-Based learning contributes to increased creativity, collaboration, and problem-solving skills. (Rusek, Tóthová & Vojíř 2021)

PBL employs learning which is determined by trial-and-error, encouraging learners to try multiple approaches and to reflect on their successes or failures. It is important to mention that "failures" hereby do not refer to a learner's performance but belong to the overall process, being a stage on the way to a possible solution to successfully complete the project at hand (Hall & Miro 2016).

With its real-world context, and the focus on creating a solution by means of various steps which are similar to the engineering design process and require similar skills (e.g.

collaboration, critical thinking and creativity), it becomes clear that PBL can be applied with an engineering design process to set up activities in STEM education contexts (Kolodner et al 2003).

2.4.6 Using digital tools to deepen the insight into standard topics

According to Mayer (2014), three assumptions describe why learning with digital tools can be beneficial for learning. According to the dual-channel assumption, learners can organise information into two different cognitive structures: the visual and the auditory channels. The second assumption is the limited capacity of information processing in one channel. Therefore, it is favorable if learning environments stimulate the activation of both visual and auditory channels to prevent cognitive overload. This is possible, for example, by presenting sound images or spoken texts in combination with written texts or visual images. The third assumption is that learners need to engage actively with learning content in order to comprehend new information (Mayer, 2014). This is possible by the use of interactive learning environments, where the learner can actively and directly influence their own learning processes. In other words, "the defining feature of interactivity is responsiveness to the learner's action during learning" (Moreno & Mayer, 2007).

2.4.7 Considering students' diversity

Fear of confirming negative stereotypes of a group one belongs to (gender, race, etc.) can undermine performance and contribute to a lack of sense of belonging. Girls' sense of belonging is an increasingly important moderator for their intent to pursue a career in STEM fields and their math or science performance. Sense of belonging refers to "students' sense of being accepted, valued, included, and encouraged by others (teachers and peers) in the academic classroom setting and of feeling oneself be an important part of the life and activity of the class" (Goodenow, 1993, p. 80). Additionally, external cues, such as the low representation of one's group, can influence the sense of belonging, particularly for women in male-dominated fields, such as most STEM disciplines (Murphy et al., 2007). Thus, as a basic condition, STEMkey modules try to establish learning environments which embrace diversity and support gender-neutrality to support for positive learning experiences.

2.4.8 Individual and collaborative learning

The diversity of learners must be addressed by a diversity of approaches and tools, to provide targeted and also individualised learning when necessary.

Great diversity in student abilities may create difficulties in managing STEM learning. One way to consider girls' needs and students' diversity is to let the students work together in groups, provide cognitive support, and facilitate interaction through group work (Y. C. Cheng & So, 2020).

It is recommended to use a combination of individual (autonomous and self-managed) and collaborative learning for competence development.

Furthermore, attitudes are often socially constructed, they "are versions of the world that are constructed by people in the course of their interactions with others." (Bidjari 2011). These include negotiation of ideas and the understanding of the role of different perspectives in generating new possibilities. Thus, competence-based learning is supported by activities which involve interaction among learners, and also between learners and teachers.

The single modules take up these practices and lay them out by means of covering various exemplary STEM topics.

2.5 Transversal competences

Transversal skills such as critical thinking, creativity, problem solving, teamwork, communication, negotiation, analytical and intercultural skills which are relevant in many different contexts and settings of life, have to be supported throughout one's own lifelong learning process and thus are embedded throughout the key competence framework (DG EAC 2019). Learners are recommended to "become informed critical consumers of scientific knowledge – a competency that all individuals are expected to need during their lifetimes" (OECD, 2013, p. 5). STEMkey activities allow for the development of such skills, for example, following engineering design thinking processes or inquiry-based learning approaches increases problem-solving skills. The following sections describe how STEMkey supports the development of Critical Thinking (CT) and Creativity (CR) in particular.

2.5.1 Critical thinking

Critical rationalism and the associated attitude of systematically questioning and objectifying the process of knowledge development serve to ensure the quality of scientific research. Critical thinking thus serves the purpose of quality assurance for one's own thinking processes as well as those of others. Critical Thinking (CT) is highly relevant in STEM settings and contexts in general (for example, due to the complexity of modern age technologies, the severity of environmental and social challenges and the enormity of available data), but also, vice versa can be developed and refined through STEM education.

Looking into CT philosophy and research, it has become clear that the idea of "how to think critically" has been among society for many decades, probably even centuries. However, no universal definition for CT has been established yet. Definitions and emphases are continuously sharpened (Hitchcock 2017). Robert H. Ennis, Richard W. Paul, and Harvey Siegel are among those who have been engaging on the forefront to introduce CT in education. The three of them have provided helpful literature on the case. In 2011, Hitchcock shed light on the most common perspectives, and identified **a set of skills which is most relevant for CT**: clarifying meaning, analyzing arguments, evaluating evidence, judging whether a conclusion follows, drawing warranted conclusions (Hitchcock 2017). Furthermore, he identified **a set of attitudes which are needed to follow a process of CT through**: open-mindedness, fair-mindedness, willingness to search for evidence, willingness to be well-informed, responsiveness to others' views and their reasons, willingness to weigh belief against evidence, willingness to consider alternatives and revise beliefs.

Hitchcock (2017) emphasized that **education needs to support learners to develop the knowledge, skills, and attitudes which makes them critical thinkers. This is where STEMkey can spud in, providing a framework and modules to support CT in STEM education**.

Based on his research, Hitchcock (2017) also provided an instructional framework to support CT in education which we highly recommend to use for further reading (Hitchcock 2017).

2.5.2 Creativity and innovation

In 2020, the World Economic Forum (WEF) defined new education models for The Fourth Industrial Revolution. **Innovation and creativity** appear in second place among the key skills. They refer to constantly changing conditions and the need to rapidly generate new ideas, processes and products so that future human capital contributes to the future economy (WEF, 2020). At the same time, the OECD agrees and supports the development of key competences and soft skills for future generations. However, the problem is the insufficient implementation of these requirements by higher education institutions. STE(A)M education can develop creativity and creative thinking through various forms and methods of teaching such as problem-based teaching, project-based teaching, playful learning, research-oriented teaching, or through trial-and-error teaching and brainstorming.

At first sight, it might seem that creativity has no place in science. The contrary is true. New inventions, models and theories require extremely imaginative solutions, but also finding and solving problems, generating hypotheses and modeling are based on creative thinking. The literature generally understands creativity as "the interaction between skills, process, and environment through which an individual or group produces a perceptible product that is both novel and useful as defined in a social context" (Plucker, Beghetto, & Dow, 2004). Several theories of creativity recognize the importance and interaction of relevant knowledge and skills, divergent and convergent thought processes, task motivation, and a rewarding environment to support creative engagement in each task (Amabile, 1983; Amabile and Pratt, 2016; Lucas et al., 2013; Lucas, 2016; Sternberg and Lubart, 1991, 1995; Sternberg, 2006).

Currently, we distinguish three levels of creativity: "Big-c" creativity, "Little-c" creativity and "Mini-c" creativity (Craft, 2001; Kaufman and Beghetto, 2009). Only a small percentage of the population achieves "Big-c" creativity, which is typical of geniuses who have a high level of expertise, skills. Their product is highly recognized by the society for its originality and social contribution, it can be intellectual or technological, but also artistic mastery. On the contrary, all people have "Little-c" creativity. Professional sources agree that "Little-c" creativity can be developed through practice and education. It is about everyday creativity, such as thinking about possibilities, or discovering the right path, a solution that involves an "aha" moment. It is not creativity with a socially significant new contribution, but it can to some extent influence the functioning of a narrow circle of society or the context (Craft, 2000). The concept of creativity, including the process, was summarized by Vygotsky (1967/2004) as follows: "Any human act that gives rise to something new is called a creative act, regardless of whether what is created is a physical object or some mental or emotional a construct that lives in the person who created it and is known only to him". In this sentence, the last level of creativity is described, i.e. "Mini-c" creativity, which is part of the learning process (Beghetto and Kaufman 2007). So, a person experiences "Mini-c" creativity only when acquiring knowledge and skills, specifically when understanding.

Big-C creativity	large scale contributions; product oriented
Little-C creativity	everyday creativity; product oriented
Mini-C creativity	intrapersonal creativity; progress oriented

Summary of the three levels of creativity

2.5.3 Critical Thinking and Creativity in STEMkey

For schools and universities to promote Critical Thinking and Creativity, teachers and trainers need a tangible explanation and recommendations for instruction and designing learning environments.

The notion of Critical Thinking is complex and consists of many components. The ability to think critically, and by doing so reflecting on the quality of one's own thinking process, is crucial to participate in societal discourse and democratic debate. In addition, the skill to reflect on the opinions and statements of various stakeholders and, if applicable, to include them in the learning process, indicates critical thinking. Critical thinking enables people to quality check their own decision-making process. Most students, teacher students and teachers will agree that learning how to think critically is an education goal everybody is supposed to achieve. However, for all those involved, critical thinking is an umbrella term, and individually, as well as culturally, shaped. We use the term to refer to a process of judging available resources and information to make decisions in a particular situation by activating personal values, knowledge and skills, from which new knowledge, skills and attitudes can further develop. Consequently, **in STEMkey, the person's ability to use Critical Thinking while solving problems in STEM topics is considered a central element**.

While trying to set up the framework for STEMkey, one of the project partners introduced the *Synergy Model of Critical Thinking* which they have developed. It can be used to visualise the complexity of Critical Thinking while considering the philosophy of science (Rafolt et al., 2019). The model is illustrated in **Fehler! Verweisquelle konnte nicht gefunden werden.** is part of the own research work of Rafolt et al and contributes to the ongoing debates on how to develop a shared understanding of higher-order thinking and judge the quality of one's own

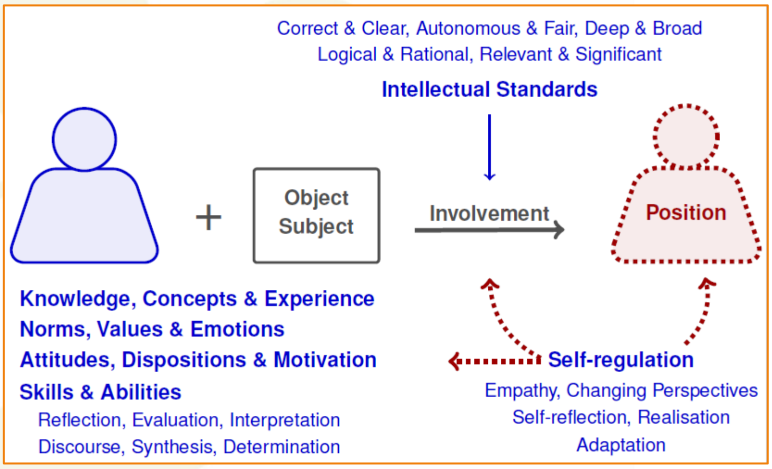

Figure 2 The Synergy Model of Critical Thinking in Science Education

thinking process in STEM education.

One of the principles of competence-based teaching is to show learners at the beginning what goals are to be achieved and how they can recognise what they can do already and what they still need to work on. The Synergy Model may help teachers and students to engage on how to recognise critical thinkers and to develop a shared understanding of what to achieve if they want to become critical thinkers. It furthermore helps teachers to monitor students learning progress and supports students to self-assess their achievements.

CT is contextual which makes it necessary to put a focus on the tasks, problems and issues in the science curriculum (Bailin 2002) and to identify the ones which require critical thinking and to carefully choose the ones which will be used in educational settings. The topics chosen for the STEMkey modules offer various starting points. Learning opportunities for CT are pointed out in each of the subject modules 2-12 while referring to the above introduced Synergy Model. Another focus of the project is put on CT in a real-world STEM context and how it can link activities across disciplines. It is therefore made explicit how CT can be promoted in each module and in the classroom. In the following, some examples are given, more can be found in the accordant modules 2-12:

- Using 'every day' data, data which is easily accessible to students, using sources they are familiar with, to find and back-up solutions
- Encouragement to assess validity of used data, e.g. through engaging in argumentation on mis-information and tricks to disguise data
- Questions and reflection among the learner group on how a consideration or an algorithm has led to a particular conclusion
- Involving discussions on ethical implications of STEM and found results, supporting concern for it and discussing possible stands and actions towards it
- Involving argumentation on environmental implications of STEM and found results, supporting concern for it and discussing possible stands and actions towards it
- Go into possible implications of CT itself, e.g. by making clear what it means to take leadership for making a decision (based on used data and drawn conclusions)
- Support an awareness that reflections of solutions to complex problems can create new problems

As we mentioned earlier, creativity exists in every individual, only its form is different. The STEMkey modules develop "mini-c" creativity in the primary framework of education and thus newly acquired knowledge from the given issue that the given module deals with. At the same time, they have a high potential to develop "little-c" creativity, which is necessary for social progress. They are composed to arouse students' interest in learning, to develop clear technical knowledge in one or more areas of the study program, involve the development of a visible product or artefact. Furthermore, they focus on solving the given problem from different points of view, leaving room for unexpected solutions and especially leaving time and space for students to reflect and provide feedback (Vincent-Lancrin, S., et al., 2019).

Students cannot be turned into critical and creative thinkers at the push of a button. Moreover, future teachers need to develop an elaborated understanding of CT and CR to be able to give feedback to individual students' stages of development and to become a useful example for students to learn how to shape and foster these competences. The above listed examples can also help to shape an assessment framework for key competence development in STEM education, as briefly explained below.

2.6 Assessment

Appropriate and flexible ways to assess and validate key competences is one major element to their successful development (DG EAC, McGrath, Hougaard, O'Shea 2020). To make it possible for teachers to support competence-based learning and use the STEMkey framework in their STEM classes, they need to be able to assess in how far learners succeed in developing certain competences. The challenges here are skills and attitudes mainly, as knowledge assessment is typically covered through traditional assessment methods. On the other hand, it has to be kept in mind that assessment influences the progress of learners and their successful performances (Black & Wiliam, 1998). An adequate assessment framework can help learners to gain, assimilate and process new knowledge, skills, and attitudes and help them understand their preferred learning styles and become autonomous and confident learners (European Commission 2018). A competence will always be context-bound, and competence is demonstrated through action in a specific and complex situation (Salganik & Stephens, 2003). Competences must be assessed in a context; failure and defeat are not necessarily considered to be an expression of a poor performance.

Assessing transversal competences can also be very subtle as learners never 'reach an end' and, as discussed earlier, it is already complex to explicitly define those competences. For clarification and illustration, the project partners have developed a set of exemplary tools which the teachers may use and adapt to their needs to assess Critical Thinking and Creativity. To support the implementation of **each STEMkey module 2-12 and the included activities in STEM education, concrete elements of assessment are provided that (prospective) teachers and their students in the classroom may use for evaluation and self-evaluation of Critical Thinking and Creativity: a rubric, evaluation table and (self-)evaluation questions**.

The outline of different levels in a rubric will help to set a common ground, while the suggested questions enable students, teacher students and teachers to engage in a discussion about what makes a critical thinker or a creative individual. The rubric is given in terms of three levels: basic, intermediate and advanced.

Each level is described according to different dimensions, which can be evaluated jointly or separately, depending on the aims and the scope of the activities in which the students are engaged. Some of these dimensions are:

- Quality check of resources
- Variety of methods
- Originality of ideas and approaches
- Argumentation and coherence of conclusions
- Use of tools and data
- Understanding and consideration of different norms and values
- Communication of the results
- Presence of goal-orientation and perseverance
- Richness of reflection

Table 1 Rubric – levels of Critical Thinking and Creativity

Basic level	The basic level is characterized by modest use of critical thinking and creativity while solving a problem: - no quality check of external sources of information - almost no appearance of contextual knowledge - alternative methods are taken into consideration - tools are used with systematic errors - explicit arguments for a decision not given - visible lack of motivation or perseverance - presentation is sloppy and incoherent - no reflection about the answer

Intermediate level	The intermediate level is characterized by solving a problem with certain elements of critical thinking and creativity, without using its full potential: - only limited sources of information used, and sources are poorly checked - the variation of methods is limited to procedures shown by others in similar contexts - arguments are given, but with limited knowledge and potential to be generalized - use of tools and data processing follows standard procedures, but it is flawed or misinterpreted - all steps of the process presented, but the structure, coherence or attractivity of the presentation could be improved - occasional understanding of norms and values - in the reflection, the solution is checked, and the answer is evaluated inside the context, but the metacognitive relation to the whole process is rather weak
Advanced level	The advanced level is characterized by solving a problem based on extensive experience and a professional approach, exhibiting critical thinking and creativity in every aspect: - multiple sources are considered and selected based on quality checks - a variety of methods is used or even invented for the purpose of analyzing and solving the problem - conclusions are coherent, logical and supported by theoretical and empirical arguments, based on sources and considering norms and values relevant for the problem - tools are used efficiently and in original ways - goal-orientation is continuously present and capability to act reasonably and rationally is exhibited throughout the process - reflection is rich, includes the higher aims of the activity and the possibility to evaluate findings in a wider context

To achieve more flexibility during assessment, the teachers may select those dimensions that they find relevant at a certain moment and add levels according to their aims and needs.

Table 2 Evaluation table for rubric adaptation

	Basic	Intermediate	Advanced
Quality check of resources			
Variety of methods			

Originality of ideas and approaches			
Argumentation and coherence of conclusions			
Use of tools and data			
Understanding and consideration of norms and values			
Communication of results			
Presence of goal-orientation			
Richness of reflection			

Based on this rubric, teachers can plan to use the following (non-extensive) list of questions while preparing the lessons or pose these questions to students to support their problem-solving process and improve their skills:

- Do we understand the problem and its context?
- Which competences might help us in investigating the problem further?
- Do we know similar tasks and methods to solve them?
- How many different approaches can we come up to solve the given problem?
- Have we allowed ourselves to think ‘outside of the box’?
- Which sources of information we consider using?
- Have we checked the information from multiple sources and checked their reliability?
- Have we included all the key information that is available to us?
- Do we have enough measurements or might our sample be biased?
- How precise are our measuring tools?
- Do we respect the prescribed procedures for using the tools and processing data?
- What kind of an answer do we accept and which solutions we consider to be good’?
- Which values and norms condition our reasoning?
- Do we understand social values, norms and rules to act properly?
- Do we understand the motivation of the subject or object we are confronted with?
- Are we motivated to complete the task? What is our motivation?

- Do we have enough evidence for our conclusions?
- How do we make sure that our reasoning is correct?
- How much time did we invest in the solving process?
- How to present our solution to others?
- Do we respect the norms and principles that our community uses in communication?
- Is the solution that we reached understandable and meaningful to us? Does it make sense with respect to the context of the problem?
- Are we able to reflect, interpret and evaluate?
- Could a more general viewpoint provide us a deeper understanding of the solution?
- Are there more aspects/dimensions we can consider in our reflection?
- What have we learned from the interaction with this problem?

Each particular topic brings more specific questions that are explicated in the modules. The above discussion ends with two examples.

Example 1 related to IO3: Measurement

Mobile phones have an activity meter that measures the number of steps during the day and the distance covered. A couple of students walked around the school yard to measure its circumference. They were asked to hand in their findings. These were the collected results: 100 steps, 98 steps, 93, steps, 103 steps, 100 meter, 97.45 meter, about 1 km. What would you do with these results to determine the circumference? What would you advise these students when they had to perform another measuring task?

Level	*Measurement*
Basic level	*The basic level is characterized by absence of critical thinking and creativity while solving a problem:* - *In the calculation no reference to different dimensions & one number being more precise than possible* - *No use of knowledge about school yards (or personal ref. points)* - *In the advice no reference to other measuring tools/strategies* - *No underpinning of the advice* - *No reflection on a circumference that differs significantly from 100 m.*
Intermediate level	*The intermediate level is characterized by solving a problem with certain elements of critical thinking and creativity, without using its full potential:* - *A reference to different dimensions, or to one number being more precise than possible* - *Calculation is basically adding results with same dimension and dividing by the number of results.* - *The advice includes a reflection on the limitation of step counting as a measuring strategy*

	- *The answer also includes a reference to what is possible for a real school yard (e.g. why 1 km needs to be excluded).*
Advanced level	*The advanced level is characterized by solving a problem based on extensive experience and a professional approach, exhibiting critical thinking and creativity in every aspect:* - *Explicit reflection on different dimensions & to one number being more precise than possible* - *Calculation selects only steps (underpinned) and includes a reference to possible variation in lengths of a step* - *The advice includes a reflection on the limitation of step counting as a measuring strategy, and suggestions for alternative measuring strategies* - *The answer includes a reference to what is possible for a real school yard, and positions the size in a wider context (e.g. by referring to other yards or the size of the school).*

Example 2 related to IO5: Material cycles

The task is to explore the school garden or any garden environment nearby and identify possible carbon sources and sinks (e.g. plants, animals, fungis, ponds, soils, potting soils, composts, petrol- or diesel-powered gardening tools and synthetic fertilisers, the production of which releases carbon dioxide). Depending on the prior knowledge of the group, relevant objects can be marked beforehand or have to be recognised by themselves. The teacher collects the ideas about carbon sources and sinks and discusses their decisions in the plenary. The follow up task for the students is to transfer components of the carbon cycle as shown in a schematic representation to a photo of the school garden.

Levels	*Material cycles – exploring carbon sinks and sources in a garden environment*
Basic level	*The basic level is characterized by absence of critical thinking and creativity while solving a problem:* - *Teacher guided understanding of the concept of sinks and sources* - *general contextual knowledge about the reasons why plants need carbon* - *Appearing of common pre-conceptions on material cycles* - *general argumentation about the reasons why different objects appear either as source or as sink* - *teacher guided reflection on why the objects are sinks or sources*

Intermediate level	*The intermediate level is characterized by solving a problem with certain elements of critical thinking and creativity, without using its full potential:* - *Referring to the concept of photosynthesis* - *Finding the solution by just comparing different sinks and sources* - *Arguments are given, but without connecting the solution to the material cycle of carbon* - *Understanding the concept of sinks and sources without being aware of the importance for one´s own life* - *Sources and sinks are named, but the synopsis remains unclear*
Advanced level	*The advanced level is characterized by solving a problem based on extensive experience and a professional approach, exhibiting critical thinking and creativity in every aspect:* - *Explicit reflection on the concept of carbon sinks and sources and connection to the carbon cycle* - *Ability to reflect the role of different objects (sinks and sources) in the carbon cycle* - *Connecting Carbon sinks and sources to the material cycle and understanding the role of material cycles in our global system* - *Ability to reflect and compare the results, transferring them to the carbon cycle, understanding the connection to climate change education* - *The answer includes a reference to the role of oneself in the carbon cycle and what actions are possible and required to reduce the carbon footprint of oneself*

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Annex 1 Further subject topics which can provide a base for additional activities to develop key competences in these subjects

a. Energy

b. Astronomy

c. Climate change

d. Calculus

e. Chemical bonding

f. Photosynthesis

g. Additional idea: for example, IO on water management system which now applies IBL could then instead apply EDP

h. Biodiversity

i. Probability

j. Statistics

k. Financial literacy

l. Geometry

m. (Geometrical) optics

n. Chemical language

o. Particle models