STEMplus: The Foundation of an Education in the 21st Century

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The STEM subjects have a special role to play in our increasingly technology-driven world. That is why it is important to introduce children and adolescents to the basics in a targeted way, especially in school lessons. However, this should not only be about declarative knowledge, about testable terms and facts. Rather, it is important to stimulate their motivation and interest, to let them experience science through their own actions, and to encourage them to conduct their own experiments, to question them critically, and to discuss the results. Likewise, STEM subjects must be seen in terms of their role in the society, which comes with a special responsibility in terms of the consequences of actions. Here, too, children and adolescents must be able to have experiences that prepare them for participation in society. This includes being open to creative ways outside their own environment, engaging with different aspects of knowledge and respecting other cultures. Thus, it is not enough to limit oneself to the technical aspects of STEM. Rather, a holistic approach is required, which is what is at the bottom of the acronym STEMplus.

1. The Challenges

Fifty years ago, the Club of Rome issued warnings about the consequences of the uncontrolled growth of the world's population, the lack of nutrition for mankind, progressive industrialization, the exploitation of raw material reserves, and the destruction of the biosphere in the high-profile publication "The Limits to Growth" (Meadows, Meadows, Randers, & Behrens, 1972). This was based on computer simulations that examined a range of different scenarios. Since then, we have learned from other studies that the predictions were correct and that current developments – such as population figures – are by and large in line with the standard scenario the report presented (Turner, 2014). Even though the report was widely acclaimed and met with great deal of attention, relatively little was actually done worldwide as a result to protect the environment and therefore mankind.

Meanwhile, the problems have by no means diminished. In recent years, we have very clearly been forced to acknowledge that climate change poses a threat to more or less every region on Earth, and we are experiencing periods of heat and drought or the melting of the polar icecaps and glaciers with a resultant rise in sea levels. We are also now very aware of the threat to human health and life that a pandemic can inflict.

The risks caused by the changes in our natural environment are central challenges for the 21st century that we and the generations to come will have to deal with. However, compared to the situation fifty years ago, we are also faced with very different framework conditions. Globalization has taken another marked leap forward. This situation may be associated with risks, but it also offers opportunities that should be seized. We know better than ever that we need global solutions for the greatest problems and therefore we need to reach an agreement between the most different of views, requirements, and assessments with all due consideration of the respective concerns. Increasing digitization is a further vital factor that also poses risks, but – used in the right way – also opens up opportunities for effectively tackling problems. Again, this requires us to think holistically and to implement and make full use of a digital culture.

It is clear that solutions for complex issues need to not only be addressed by short-term policies, but also necessitate very long-term considerations. It is here that education enters the picture. The aim must be to make an active contribution to solution approaches. It must be ensured that the younger generations receive the best possible state-of-the-art education and are prepared for the challenges they will face. Various organizations are taking action to contribute to this. In 2015, the United Nations defined sustainable development goals, and also placed education center stage (United Nations, 2015). Literacy and mathematics were explicitly mentioned as a foundation here, but ultimately the goal was a more comprehensive "Quality Education", as explained in the "Education 2030 Agenda" (UNESCO, 2015). The latter states "By 2030, inclusive and quality education for all as well as options for lifelong learning" are to be ensured. The report by the International Commission on the Futures of Education (UNESCO, 2021), set up by UNESCO, follows similar lines. The focus here is on ecological, intercultural, and interdisciplinary learning that conveys an ability to take action and look at things from an international perspective. Explicitly, this means reconfiguring education and upbringing to ensure a sustainable future in just and peaceful societies. In terms of education specifically, the OECD created the Learning Compass 2030, a framework concept for learning oriented towards key competencies in an ever-changing world. It specifies levels of learning that make it clear how comprehensively education must be thought through. Learning to know is, of course, a central aspect, but that alone will not suffice. It should be complemented by learning to do, which includes problem-solving skills in particular as well as critical thinking and collaboration, learning to be, which includes acquiring social and cross-cultural skills, personal responsibility, and self-regulation, and learning to live together, which includes teamwork in a global and political context shaped by digitization (OECD, 2019, with reference to Scott, 2015). The goals also consider the sustainable development requirements set by the United Nations and cover areas such as health, safety, civic engagement, or the environment (OECD, 2019).

Although the OECD publication in particular makes it clear that learning and education should not be restricted to school, but should be considered a task for society as a whole, this institution should be attached particular significance. Perhaps, one could learn to read or to speak another language at home or in another private environment, but mathematics or natural sciences would be less likely. Additionally, the concept of equal opportunities requires every young person to be offered the opportunity of a good education regardless of their background. Responsibility for imple-menting this resides at the political level. It should be ensured in the public sector, and therefore primarily in schools, that an education is offered in which the formulated goals can be attained.

2. The Specific Role of STEM Subjects

What are the prerequisites for tackling the challenges? Without doubt education plays a central role here. The complexity of the tasks involved requires the cooperation of well-educated people capable of looking creatively for solutions and contributing to the current state of the art of science. But naturally, it is not about keeping this knowledge restricted to a tight circle. Rather, meaningful and required measures also need to be discussed, accepted, and implemented in a social context. The education of all members of society is a vital prerequisite for this.

Given the challenges of the 21st century, it is STEM subjects that are the main focus here, i.e. science, technology, engineering, and mathematics. Mathematics generally forms the foundation of the other areas and not only when it comes to calculations. It is by no means an ancillary discipline. The COVID19 pandemic, for example, has clearly shown how important knowledge of statistics and the rational handling of uncertainty is. Mathematical modeling is as well an important tool when it comes to tackling real requirements (as seen, for example, in "The Limits to Growth" as mentioned above). In particular, mathematics forms the foundation for information sciences and technologies, the central importance of which – in the digital age – hardly needs to be emphasized. A basic understanding is also helpful here, for example when it comes to the critical use of digital technology. Progress in science has increasingly shaped everyday life over the last few decades, for example in terms of health or nutrition. Finally, though engineering sciences are less evident in most schools, the impact of technical developments and the assessment of their possibilities and limits are very pronounced for society as a whole.

What applies to society as a whole can then clearly be applied to each individual member of that society. Social participation requires solid knowledge of the STEM disciplines. People need skills based on these subjects in order to form opinions about climate change, environmental issues, health, or digitization and to justify these opinions in order to shape the solutions accordingly in a professional and private context. The central component is not declarative knowledge of facts, but rather flexible knowledge that can be applied in an interdisciplinary context. Application does not just mean technical implementation but rather includes reviewing and questioning proposals, answers, and results, weighing up the pros and cons appropriately, and thinking about integration into the social environment (see also UNESCO, 2021).

A sound STEM education must take the specific roles of the subjects into consideration and therefore prepare people to assess situations and understand the context and its wider development, above and beyond purely factual knowledge. To put it another way: such a STEM education aims beyond the purely factual and should be perceived as comprehensive preparation for broad areas of everyday private and professional life. It would help to concentrate on 21st century skills here, where creativity, critical thinking, cooperation, and communication play central roles (OECD, 2020). In this context, creativity is particularly considered to be the ability to develop new solutions for complex challenges; critical thinking includes reviewing sources and checking information independently yourself; cooperation means working in a team and relying on other people; communication is the means being able to communicate your own way of thinking and working as well as your own way of learning to others.

3. From STEM to STEMplus

So, what are the concrete consequences of these ideas of education beyond STEM subjects? We live in a society that is more influenced than ever by processes based on STEM knowledge and insights. However, it is certainly not enough to limit ourselves to a purely technical perspective. Rather, the subjects must be embedded in the societal environment, addressing creativity, critical thinking, cooperation, and communication as much as the subject content. The four letters STEM are not necessarily sufficient for this.

In an Anglo-Saxon context, the term STEM for "science, technology, engineering, mathematics" has been turned into STEAM, adding "arts" to the mix. The underlying idea is attributed to American designer John Maeda, who has worked at the Massachusetts Institute of Technology and Rhode Island School of Design (https://en.wikipedia.org/wiki/John_Maeda#cite_note-38). The added "A" covers a broad area comprising various arts, as well as languages, media, and humanities, as perceived within the context of STEM. However, the essential factors are considered to be less the contents and more the methods of access to knowledge that are problem-based, intended to encourage innovative approaches, and support creative working. STEM+H, used sometimes in a Latin American context, is taking things in a similar direction (Cano, Bermúdez & Arango). Here, it is “Humanidades" that has been added. But again, this is ultimately about more than that, namely, the encouragement of critical thinking, collaborative working, and consideration of social context when solving problems (cf. also UNESCO, 2021). Bascopé and Reiss (2021) also use STEM4S ("STEM Education for Sustainability"). This means ensuring that STEM competencies and skills contribute to creating an understanding of global problems and supporting social actions to address these challenges in a sensible and knowledge-based way. STEM4S follows the approach of encouraging critical thinking while keeping sustainability in mind and understanding the value of STEM education for society as a whole.

Although the approaches are different, they all have one important thing in common: Good STEM education has to take a perspective into account that is more than the canon of a given subject. This education is clearly based on specialist, disciplinary knowledge. But an expanded STEM education ("STEMplus") is oriented toward problems that do not necessarily have disciplinary limits, while opening up creative ways to solve them, and focusing on common initiative in doing so. A central component is that possible benefits for society as a whole are given as much attention as the social responsibility associated with a solution. Ultimately, it should be recognized that there can be very different needs within a society and therefore consequences can also be very different for individuals. The issue here is about addressing real actions that can convey an idea of benefits and risks, but can also show that these are not always easy to evaluate, and certainly not in a standardized manner (cf. the specified learning levels, OECD, 2019).

There is no simple definition for the term STEMplus. Rather, it needs to be characterized by looking at the pathways to holistic STEM education within the subjects. It is the targeted competencies of students, the associated learning opportunities, and the specific role of learners in the classroom that add up to a picture of what constitutes STEMplus.

4. Education in STEM subjects: How to implement STEMplus?

Education is a social task that involves various institutions as much as the family or your peers. It is not limited to childhood and youth, but instead is increasingly perceived as a vital and necessary life-long component. Nevertheless, school is of crucial significance. It is after all the task of school to teach students the basics (not just) of STEM education. Particularly given that the requirements imposed on the younger generations over the coming decades are likely to undergo profound and far-reaching change, it is of central importance to prepare them to the best of our knowledge and ability.

This task is not easy. The image of the STEM subjects is complex and certainly they are not simple to tackle. There are still a lot of clichés associated with them. Chemistry and physics tend to be regarded as difficult, with girls in particular often showing less interest in them (Schiepe-Tiska, Simm & Schmidtner, 2016). Mathematics is also not considered to be an easy subject and can furthermore be seen as polarizing: you either like the subject or you don't (Henn & Kaiser, 2001). Engineering and computer sciences are not always part of the curriculum in every form of school organization and Federal State (Ständige Wissenschaftliche Kommission der KMK, 2022). Above and beyond these individual subjects, there is a fundamental problem that interest in STEM often takes shape from very early on and changing someone's attitude at a later date is not always possible. There is a tendency towards decreasing interest in these subjects in particular during the course of school life (Daniels, 2008; Gottfried, Fleming & Gottfried, 2001). However, in terms of performance in STEM subjects, both interest and self-efficacy play important roles (cf. the metastudy by Grimalt-Álvaro & Couso, 2022).

Can the issues be overcome? There have been plenty of attempts to do so in recent years. Education returned to public focus after the sobering results of the PISA 2000 survey in which students in Germany were rated below the average of the OECD states in all areas, particularly in mathematics and science (Baumert et al., 2001). Educational standards were identified that no longer defined learning opportunities for students, but rather consisted of competencies to be achieved (cf. Kultusministerkonferenz most recent version for secondary level, 2022). The focus should no longer be on a curriculum oriented towards input, but rather the output, the way knowledge is handled or – to put it another way – the desired competencies to be achieved by children and young people in the long term.

Although the road is not an easy one and reforms always take time, particularly in terms of schools and curriculums, there are early signs that the proposed direction looks promising in principle: Student competencies in Germany were below the average of the OECD states in mathematics and science in PISA 2000 (Deutsches PISA-Konsortium, 2001), while in PISA 2018 they were significantly above this average in both areas (Reiss et al., 2019). Of course, there is "room for improvement", given that states such as Estonia, the Netherlands, or Poland are achieving significantly better results than Germany in mathematics, while Estonia and Finland are better in science. The measures also need to be subjected to constant review, as there has been a slight downturn despite good results over the years. This has also been confirmed for Germany, particularly in a study by the Institute for Educational Quality Improvement [Institut für die Qualitätsentwicklung im Bildungswesen] (Stanat et al., 2022).

Stronger orientation to the desired competencies of the students has a significant impact on education and teaching in STEM subjects. Two aspects are worth highlighting here in particular. Firstly, the way in which knowledge is handled and applied plays a far more prominent role than ever before – and thus it is an important component of STEMplus. The competencies for biology, chemistry, and physics – unanimously – consist not just of content knowledge, but also the acquisition of knowledge, communication, and evaluation. In mathematics, differentiation is made between content-based competencies that reflect the specialist aspects and process-based competencies that focus on actively engaging with content (Kultusministerkonferenz, 2022). On the other hand, the interdisciplinary level has been reinforced. In the education standards for general higher education entrance qualifications in science, explicit reference is made to a decision by the Standing Conference of the Ministers of Education and Cultural Affairs [Kultusministerkonferenz] from 1972, which stated that education and teaching at upper-grade secondary school level should be about "mastering basic knowledge in the subject as a prerequisite for opening up connections between fields of knowledge, working methods for systematic procurement, structuring and using information and materials, as well as learning strategies, independence and personal responsibility, and team and communication skills" (Kultusministerkonferenz, 2020a; p. 3f.). This creates a comprehensive picture of the sciences that is intended to also be addressed in education and teaching, pursuing far-reaching goals: "Competency in science thereby contributes to overarching goals such as education for sustainable development, education relating to media, values, consumers, and democracy, and therefore education in general" (Kultusministerkonferenz, 2020a; p. 10.).

At this point, an idea should at least be touched upon that once again takes up the "learning to live together". STEMplus by no means implies seeing the subjects exclusively from the perspective of one's own culture. It is precisely the intercultural approach, which should also include traditional knowledge, that should be suitable for building an understanding of and appreciation for other ways of looking at STEM. For sustainable development, such broad acceptance of different approaches is likely to be an important component (see, for example, Sato, Chabay & Helgeson, 2018).

5. STEM Competencies and Learning Opportunities

Weinert (2001, p. 27f.) defines competencies as a complex construct. They are "the cognitive abilities and skills that are available to or can be learned by individuals in order to solve certain problems, as well as the associated motivational, volitional, and social dispositions and abilities to make successful and responsible use of problem solutions in variable situations". In short, it is about the application and flexible use of knowledge. However, broken down in detail, competencies are based on a broad range of cognitive and non-cognitive fundaments.

What are STEM competencies? The general description clearly needs to be defined in concrete terms and elaborated. This always means looking at the specialist contents that play a role in all education standards (for example: Bildungsstandards der Kultusministerkonferenz in Germany; National Council of Teachers of Mathematics, 2000, and Common Core States Standards Initiative, 2017, in the USA; Ministerio de Educación de Colombia, 2003, in Colombia). Subject-related ways of thinking and working methods are also a central focus here, under a variety of headings. These are the specific processes for generating knowledge, such as inductive or deductive conclusions in mathematics, experimental methods or working with models in science, or the development of algorithmic problem solutions in computer science.

These specialist and methodical building blocks must now be combined so that they can be used to solve real, everyday problems. It is clear that this requires suitable curriculums and teaching. In terms of the various educational standards, it is therefore not just about conveying content and methods, but also about encouraging the motivation and interest of students just as much as their ability and willingness to successfully engage with problems. Ultimately, if we follow Weinert (2001), competent problem-solving also involves taking responsibility for implementing one’s own ideas. Here we come full circle to the aforementioned formulations of the OECD or UNESCO for modern education.

To summarize in brief, the acquisition of competencies essentially means learning how to independently engage with problems, identify ways and means to solve them, and proceeding to do so in a motivated and responsible way. Suitable learning opportunities need to be created for this, particularly in the context of school education and teaching. The central focus is clearly not on the learning of facts. While this is undoubtedly important, it is more about the working methods that often lead to insightful access to the content.

An approach focused on natural sciences is particularly suitable for the STEM subjects: You observe a phenomenon (often repeatedly), you identify patterns, and you therefore develop a theory. You test this theory – also using new examples – and confirm or reject it. The result could be a prototype, for example, that could be more broadly applicable. Here, the goal of teaching should be to make such a working method explicit. It encourages an individual's engagement with the world, has a preparatory function, and may also be suitable for independent learning experiences. In this context, it is vital to identify age-appropriate and accessible phenomena, thereby encouraging students to carry out their own investigations, experiments, and conclusions, as well as discussing the phenomena and their critical reflections.

There are plenty of simple or complex questions in science that would be suitable: Does ice melt differently in a stainless-steel bowl or in a plastic bowl? What is the greenhouse effect? How do we obtain drinking water? The scenario can also be applied to mathematics in principle: Is a number always divisible by 3 if its checksum is divisible by 3? What is the relationship between the volume of a cylinder, a circular cone, and a hemisphere with the same radius and height? What does "incidence" mean? Finally, there are also tasks in technology or engineering that can be approached at very different levels: What does it mean to program a computer? What algorithms run our everyday lives? What is protection of data?

Learning opportunities in STEM education must also look at the specifics of the subjects from a point of view that is based on the philosophy of science. Again, this is not so much about the knowledge about a phenomenon as it is about subject-specific work with this. Both computer science and mathematics work with processes where a certain input leads to a similarly certain output. The processes are generally universally applicable, but one can question the quality of the input in order to evaluate the quality of the output. The sciences are experimental subjects that develop theories based on observations. Such theories can be entirely provisional and may be refined, expanded, or even corrected at a later date.

What does all this mean for education, curricula or formal learning? Firstly, it should be about active learning, showing students the route to acquiring and constructing knowledge rather than just conveying facts. Naturally, there are times when direct instruction is the right choice. In particular, it should not be about "constantly reinventing the wheel". However, if it is our goal to turn today's students into creative people in the future, sufficient scope has to be given to free work. Furthermore, suitable content needs to be selected and offered for access to learning. Basic knowledge is required in every subject, and there are essential principles in every subject. But this knowledge, too, should usually be based on the observation of phenomena. Tracking these processes is an important aspect of education and teaching. It is entirely possible to use an everyday reference in order to generate creative applications that can then lead to or confirm basic knowledge.

It should be emphasized that STEM education clearly cannot just focus on providing simple learning opportunities, nor can it entirely refrain from (time-efficient) knowledge transfer. Preparation for – as-yet unknown – future requirements cannot stop at trivial problems, but must create the prerequisites for independent further learning through engagement with complex issues. This requires a solid subject-matter basis. Education and teaching should therefore look for everyday references, while also preparing students in the basics. After all, creative applications are also based on specialist knowledge and should be accessible and compatible.

6. Active Learning and Its Prerequisites

The provision of good learning opportunities is an essential requirement for sound education and teaching, but is by no means a sufficient condition for success. Teachers play a vital role here. A synthesis by Hattie (2009) of over 800 metastudies on learning demonstrated the huge impact that teachers have on the successful acquisition of competencies by students. An update of the meta-analysis confirms that the highest value is placed on the variable collective teacher efficacy (https://visible-learning.org/hattie-ranking-influences-effect-sizes-learning-achievement/). This concerns the collective conviction of teachers at an institution that they can have a positive impact on their students.

Alongside these more pedagogical-social aspects, other studies also consider the pedagogical content knowledge of teachers to be a major component in the success of education (Kunter et al., 2011). Based on the division of teachers' professional knowledge into school-related content knowledge, pedagogical content knowledge, and pedagogical knowledge (Shulman, 1986), a study accompanying PISA 2003 for mathematics showed that although content knowledge is central for education and teaching, it only becomes truly effective when moderated by pedagogical content knowledge.

It is hard to summarize in a few words what constitutes pedagogical content knowledge in STEM subjects, but there are specific components that have proven to be significant in current discussions and practice, even if the related empirical findings are not necessarily consistent. Naturally, lessons should help students in developing content-based competencies, but they should also develop to be constructive, engaged, and reflective citizens, as stated above (OECD, 2019). In turn, this goal is to be achieved through active and self-directed learning. For teachers, this means using corres-ponding working methods and implementing problem-based lessons that facilitate explorative learning. However, it also means offering targeted help and, in particular, identifying students' specific problems with the subject and their misconceptions.

Concrete implementation in STEM subjects can be expediently oriented towards the specific working methods for the individual subjects. For example, PISA 2015 differentiates between three sub-competencies in basic scientific education, namely, explaining phenomena scientifically, evaluating and designing scientific enquiry, and interpreting data and evidence scientifically (OECD, 2016). They clearly reflect the activities that form the central building blocks of scientific work.

In mathematics, argumentation is a fundamental working method. It is used to formulate problem solutions, describe the approach to solving the problem, and interpret the solution (OECD, 2019). Furthermore, academic work in STEM subjects is mostly based on problems where the search is for a specific or also a general solution. Pedagogical content knowledge is important not only for identifying suitable problems for education and teaching, but also for operationalizing at various competency levels.

Of course, it's not about preparing every student to engage in active STEM research or a STEM profession in general. Rather, good preparation mainly serves as the foundation for an understanding of academic working methods and therefore an understanding of the complex and constantly changing world around us. It is generally impossible to predict what is likely to become important in detail. As a concrete example: The polymerase chain reaction method (PCR) was introduced in 1983 by the biochemist Kary Mullis, who won the Nobel Prize in chemistry for this achievement in 1993. In the meantime, the term itself has not only become known to the general public as a term for testing the human body for certain viruses, but the actual process is still carried out in school laboratories to this day.

7. STEMplus: The task is to connect the components

STEMplus is a comprehensive concept that is not limited to the STEM subjects, but attempts to shape learning and teaching with a view to future requirements. Accordingly, STEMplus needs a collective effort of different actors for its implementation. The goal is to familiarize students with a holistic view of STEM subjects, to motivate them to actively and reflectively participate in STEM competencies. This can be achieved and, in particular, must be achieved in regular school lessons. Such teaching, which is geared toward STEMplus, conveys a comprehensive picture of mathematics, computer science, natural sciences and technology and is suitable for better recognizing and understanding the role of these disciplines for the world of the 21st century.

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