Good Practices Using Digital Technologies in STEM Education with a Focus on Mathematics

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Introduction

When Dudley Herschbach, a Nobel laureate in Chemistry for 1986, delivered a lecture to high school students with a potential for doing science, he surprised them with his opinion about the difference between the scientists and the students. Here is what he said (I am quoting by memory): *The difference between the scientists and the students is in fact very small – it consists in the way they react to a question they don't know the answer to. Whereas the students feel embarrassed and miserable thinking of a possible failure on a test, the scientists feel enthusiastic – they see food for reflection and explorations!*

Enstein, in a classical humble brag, once remarked (as quoted in Ryan, J., 2017, p. 41): "I have no special talents. I am only passionately curious." … "The important thing", the great physicist observed, "is to not stop questioning. Never lose a holy curiosity". Then Ryan continues: *Curiosity begins with asking "I wonder why?"* and he further suggests that we should take the time to look around us and remember to ask "I wonder why?" – a question that launches discoveries and leads to remarkable insights.

One of the most important aspects of education towards a creativity-based society deals with provoking teachers to become authentic co-learners joining their students in creative explorations. Such a goal requires for the education (traditionally teacher-centered in Bulgaria) to provide appropriate strategies, methods and environments, which nurture, enrich, and stimulate learner's creativity (Henriksen, Henderson, Creely, et al., pp. 418-419)

Supporting the inborn curiosity of children and encouraging them to act like scientists during all the stages of the school system has been the motivation behind the development of learning environments in support of the inquiry-based STEM education by a research team at the Institute of Mathematics and Informatics at the Bulgarian Academy of Sciences (IMI-BAS).

There exist various interpretations of STEM but in our further considerations we shall stick to the one in (Ackay, 2018, p.138), which is in harmony with our understanding:

> STEM education is the intentional integration of science, technology, engineering, and mathematics, and their associated practices to create a student-centered learning environment in which students investigate and engineer solutions to

problems, and construct evidence-based explanations of real-world phenomena with a focus on a student's social, emotional, physical, and academic needs through shared contributions of schools, families, and community partners.

Our focus will be on mathematics education by an intensive use of digital technologies as laboratories for experiments – a phenomenon typical for the natural sciences but not for mathematics some decades ago…

The inquiry-based learning in a digital setting in Bulgaria has been closely related to the principles of an experimental Research Group on Education (RGE) functioning in the period of 1978-1989 (Sendov, Bl., 1987; Sendova, 2017) and has recently being developed within a series of recent European educational projects dealing with innovative education. Among these projects it is worth mentioning InnoMathEd – *Innovations in Mathematics Education on European Level* (Chehlarova et al., 2011), Fibonacci - *Disseminating Inquiry-Based Science and Mathematics Education in Europe* (Sendova, Chehlarova, 2012; Kenderov, Sendova, Chehlarova, 2012), KeyCoMath - *Developing Key Competences by Mathematics Education* (Zehetmeier et al. (2015), MaSciL – *Mathematics and Science for Life*, Scientix – *The community for Science Education in Europe* (Kenderov, Sendova, Chehlarova, 2015), STEM PD Net - *The Network of **S**cience* (Maass et al., 2019; Maass & Engeln, 2019).

Research Group on Education – an educational experiment launched 40 years ago

The Research Group on Education (RGE) experiment was launched jointly by the Bulgarian Academy of Sciences and the Ministry of Education. It comprised 2% of the Bulgarian K-12 schools, the main goal being to design and implement a novel, ICT-prompted curriculum (Sendova, 2013). The guiding principles of RGE were *learning by doing*, *guided discovery* and *integration of the school subjects*. During the first four years, Informatics was introduced as a part of an encyclopedic education.

The educational materials developed specially for the experimental schools included textbooks, teacher guide-books, a bulletin Informatics and mathematics for teachers, and unified (Logo-based) computer environments tuned to specific subject domains and still allowing exploratory activities in a broader context.

One of the main integrated disciplines in the primary cycle was "I read, write and calculate". A good example of activities under this subject would be creating a situation in which children would decode a letter (matching numbers with letters), read, write, and code a return message in a context of interest to them.

An innovative idea for integrating the study of Mathematics, natural languages (Bulgarian, English and Russian), and computer language (Logo in this case) was launched in 1984 with the publication of the textbook *Language and Mathematics* (for 5th and 6th grades). Designed to show the intersection of language study with mathematical thinking in the context of Informatics, this experimental textbook included problems of translating from a natural to a formal language, of algorithmic description of basic grammar rules, and of ways to extend the Logo vocabulary to several languages. Informatics notions, such as *coding, decoding, tree-graphs, algorithms, variables, tables, procedures, recursion, data*, etc. were applied in the context of playing, editing and creating linguistic games, coding and decoding secret texts, describing and executing algorithms in the subjects of Mathematics, Language and Music (Figure. 1).

Figure 1. The *Language and Mathematics* Textbooks for the RGE 5- and 6-graders

Specifically designed microworlds were provided for students to deal with these new notions from a procedural rather than a declarative point of view. This has already had an impact on the way we started teaching Mathematics, Literature, Science, Art and Music (Nikolov, 1987).

Building *Geomland*, a microworld for explorations in Euclidean geometry (Sendov, Dicheva, 1988), was another important step toward inquiry-based learning. It was launched in 1986 as a language-based computer laboratory enabling students to construct and experiment with Euclidean objects, to investigate their properties, and to formulate and verify conjectures, i.e. to *act as mathematicians rather than learn about mathematics* (to paraphrase Papert, 1971).

Our experience showed that students mastered their mathematical language; they looked for patterns, formulated hypotheses, posed problems and were highly motivated to prove their own theorems.

As far as the teachers are concerned, Geomland empowered them to a great extent to act like researchers, something they would hardly dare to do otherwise.

Expanding the RGE positive results beyond the pilot schools turned out to be difficult not only for economic and political reasons but also due to the fact that the assessment instruments (for students and teachers alike) were not relevant to its basic principles. Still, some of the main constructionists' ideas (Sendova, 2014) that outlasted the RGE experiment and were reborn in EU projects on STEM education, are as follows:

- IT are a means for self-expression, not an object of education;
- When learning by doing students construct something meaningful to them which could be shared.

Furthermore, the lesson learned was that the learners' and teachers' creativity potential can be stimulated by developing specific ICT-enhanced methodologies and educational resources in support of the inquiry-based learning and creativity.

Examples of Good STEAM Practices in Support of IBL in Mathematics

The current activities of the Institute of Mathematics and Informatics at the Bulgarian Academy of sciences (IMI-BAS) as a center for inquiry-based learning (IBL) include developing and providing an open access to learning environments related to STEAM (the letter **A** standing for art in our case) as well as delivering various types of PD courses for primary and STEM teachers.

A good repository of such educational resources is the *Virtual School Mathematics Laboratory* (VirMathLab, http://www.math.bas.bg/omi/cabinet) being developed by IMI-BAS which contains over 1200 scenarios with dynamic files transparent for the users (Kenderov, Chehlarova, 2016).

Mathematical notions such as *rotation, translation, reflection and compositions of those* are presented in the context of modeling natural phenomena and artifacts (Chehlarova, Sendova, 2010). Some examples are given in Fig. 1. The design and the implementation of these scenarios are just elements of a more ambitious goal − we expect our students to look for manifestations of geometric congruences, discover them and use them in various activities, and thus – to be able to find patterns and relationships deepening their knowledge and understanding of the world around them.

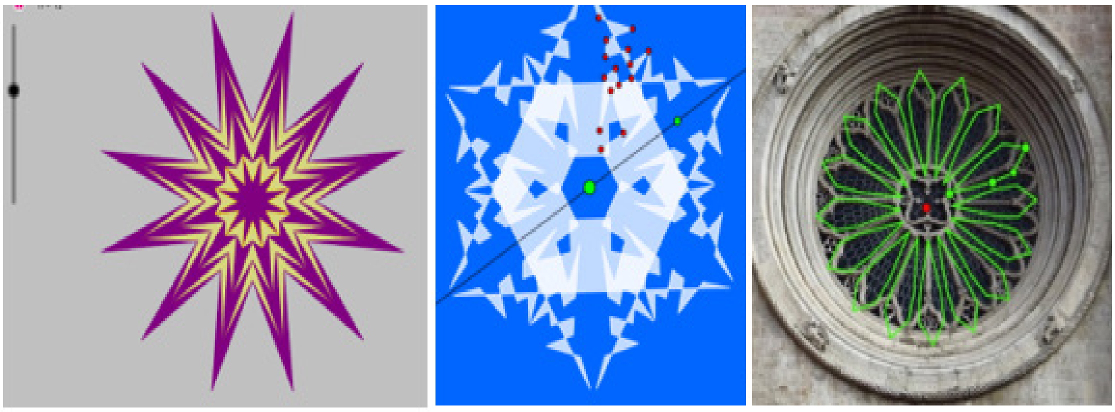

Figure 2. VirMathLab: Dynamic Files for Rotational Symmetry

The Art component of STEAM is considered by providing dynamic applets for: studying fine-art compositions (Sendova, Chehlarova, 2013); facilitating the creation of virtual models in the style of Mondrian, Warhol, Escher (Chehlarova, Sendova, Stefanova, 2012); adding special effects to photographs by artistic explorations based on play with mathematics functions (Chehlarova, T., Chehlarova, K., 2014). Examples are shown in Figure. 2-5.

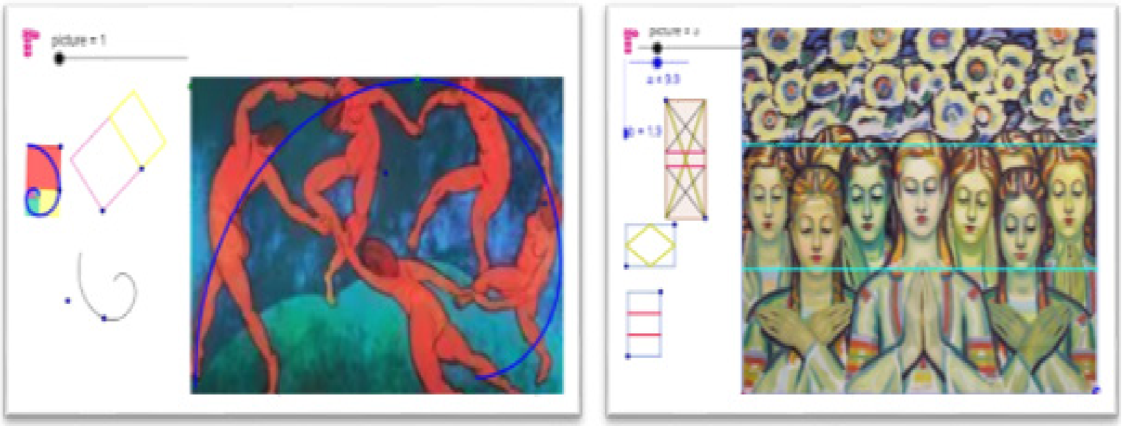

Figure 3. Dynamic Geometric Constructions for Studying Art Compositions

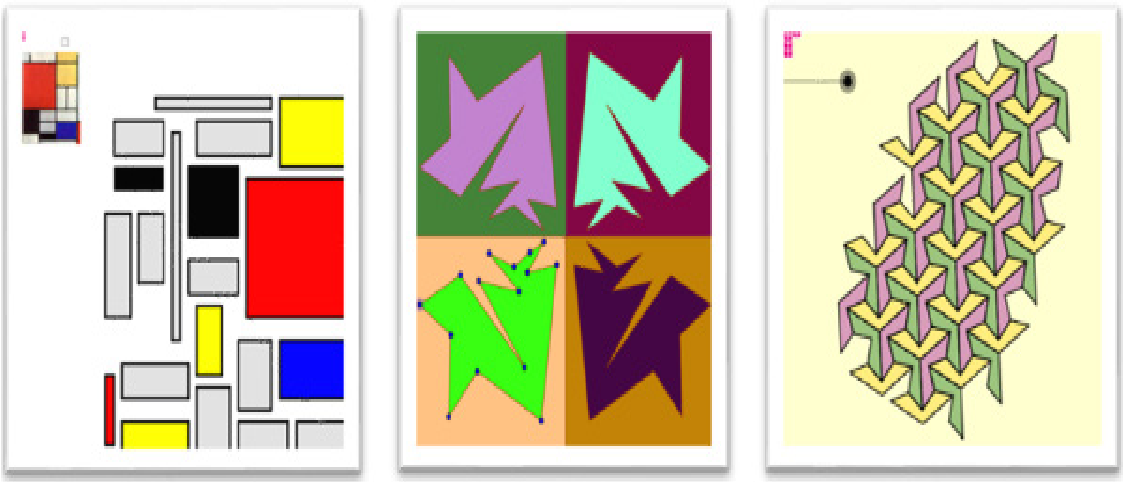

Figure 4. Dynamic Files for Modeling in the Style of Mondrian, Warhol, Escher

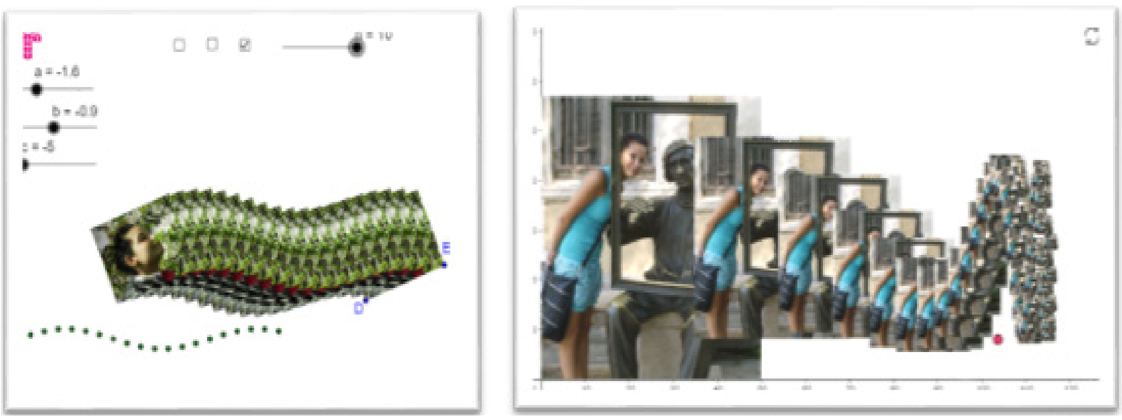

Figure 5. Art Photos Based on Mathematics Functions

Professional Development (PD) Courses for Teachers in Mathematics and IT

The inquiry-based learning, its connection with the world of work, good practices and problems in its implementation in a class- and out-of-class setting have been the focus of our work with teachers.

This approach requires experienced scientific reasoning and domain competences from students, which in turn poses specific challenges for the teachers and the teacher educators.

We encourage teachers to use the VirMathLab resources so as to stimulate students to behave like working mathematicians: to make experiments, to look for patterns, to make conjectures, to verify them experimentally, to apply "what-if" strategies so as to modify/generalize the problem, and even to use them as a preparation for a rigorous proof. To do this without leaving their comfort zone, the teachers enter the role of their students and experience the same type of activities during our courses, and when working on their own. Thus, it would hopefully become quite natural for them to work jointly with the students as a research team.

With this in mind a team of IMI-BAS scientists (including the author) has been involved in organizing novel PD courses in support of such an approach. These PD courses are being organized by IMI-BAS in the frames of European projects (InnoMathEd, Fibonacci, Mascil, KeyCoMath, STEM PD Net and Scientix), as well as by the Union of Bulgarian Mathematicians (UBM), by the Ministry of Education and Science, by publishing houses for educational literature, and by PD centers. The main goal of the courses is in harmony with the most recent educational strategies for updating the math and science education in the EC countries: the development of key-competences by implementing the inquiry-based learning in integration with the world of work. The courses are based on a team work (of the lecturers and the participants alike) and implement educational models adaptable to various school settings. The crucial part of the courses is for the participants to experience different stages and levels of IBL. They first use the dynamic files supporting the scenarios as a ground for explorations. The next step for them is to propose appropriate modification of the files for similar problems, or to use them as a model for creating one of their own from scratch. Typically, the teachers work on pedagogical problems related with: reformulating of math problems in IBL style so as to enhance the development of specific key competences; formulating their own math problems reflecting real-life situations, not solvable with the current math knowledge of the students but allowing for explorations (by means of dynamic geometry models) leading to a good enough approximation of the solution; studying and proposing methods for tackling problems which are unstructured, or whose solutions are insufficient or redundant; solving "traditional problems" with "non-traditional" data, for which the use of a computing device is necessary; applying game-design thinking so as to engage better the students in the problem solving; formulating more relevant evaluation criteria for the students' achievements; assessment of learning resources in terms of formation and development of IBL skills and key competences; project-based work with presentation of the results (Chehlarova, Kenderov, Sendova, 2015).

The key feature of these PD courses is that the teachers do act as partners in a research team −they enter the shoes of their students in an IBL environment. They work in groups, use brainstorming technique to generate ideas for solving specific tasks and present their ideas to the rest of the participants.

New Types of Mathematics Contests

Changing the very character of the learning process by implementing an inquiry-based education and taking into account the new realities in the world of work is not easy in the context of a relatively conservative educational system. To challenge and motivate students on a larger scale to *see through the eyes of professional mathematicians* by exploring problems of mathematical nature with tools available in out-of-class setting, a two novel contests have been launched a couple of years ago (Chehlarova, Kenderov, 2015; Kenderov, Chehlarova, Sendova, 2015). These are *Mathematics with a computer* and *Theme of the month*, based on the *VivaCognita* computer platform (Figure 6).

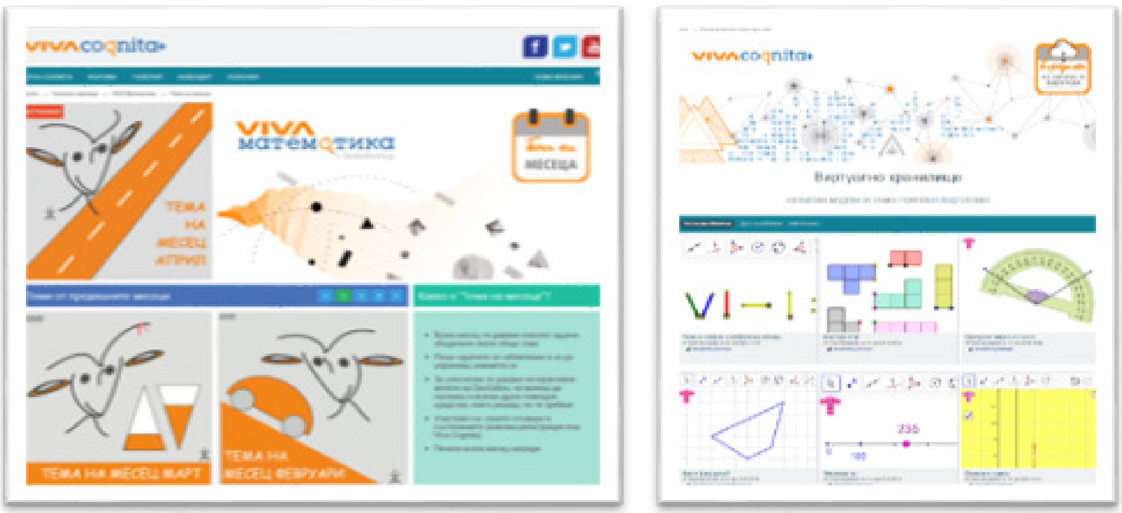

Figure 6. *Theme of the Month*: (Left) and *Virtual Repository* of Math Problems (Right)

Students (3-K12) are invited to work on a chain of problems in increasing difficulty and based on a unifying mathematical idea. Some of the problems in both competitions are accompanied by auxiliary dynamic geometry files (*GeoGebra* files in our case) so that the students could explore a specific mathematics situation, discover relevant properties, try out various strategies and find (possibly an approximate but practically acceptable) solution. Thus, the digital competence the students are developing is expected to go beyond the one of traditional IT users, and to reach its most crucial part – *algorithmic thinking and programing.* Furthermore, the students are expected to develop new mathematical competences thanks to their explorations of mathematical constructions, and observations of mathematical phenomena

The students work on the problems on-line. The data they are expected to enter as solutions are related with essential characteristics of the mathematical objects involved and are acceptable within certain error bounds. Grading the submitted solutions is automatic and the points for every solution depend on its closeness to the correct solution (Gachev, 2015).

On regular basis, the IMI-BAS delivers courses and seminars with teachers got preparing their students for these contests.

Conclusions

With all our efforts we have been trying to help teachers create an atmosphere where the students would experience the excitements of the genuine learning: *How interesting, I wonder what will happen if… I wonder why… I am ready to try something nobody has tried before…*

Our impressions of the work with teachers so far make us optimists about the future of education. One of the main achievements is the organization of communities of teachers who implement and spread the inquiry-based learning of mathematics and informatics. They participate in pedagogical experiments not only as a reality-proof of researchers but as members of a research team. These teachers implement, modify and develop from scratch educational resources in support of IBL, share their good practices at seminars, conferences and in professional journals. Some of them organize public events at a school and regional level for popularizing the inquiry-based mathematics education. Teachers are also key figures in organizing the new contests *Mathematics with a computer* and *Theme of the month*, in making them known to a broader audience. A significant number of teachers already are serving as multipliers of implementing the IBL with the world of work at a school level. These multipliers are further educating new groups of teachers by the cascade method. Some of the multipliers have already developed resources at a level high enough to be included in the repository of the VirMathLab. Others have suggested problems which were included in the contests *Mathematics with a computer* and *Theme of the month* and published on the Viva Cognita portal.

In conclusion, instead of complaining that the STEM (and particularly the math) education is in crisis, let us, the people who care about its destiny (researchers, educators, policy makers), join our efforts to identify, implement and disseminate styles and practices of learning which makes the teachers and students enjoy the explorations on their own right.

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Citation:
Sendova, J. (2019). Good practices using digital technologies in STEM education with a focus on mathematics. In M. Shelley & S.A. Kiray (Ed.). *Education Research Highlights in Mathematics, Science and Technology 2019* (pp. 243-253). ISRES Publishing, ISBN:978-605-698540-9.