PROJECT TEACHING AND MATHEMATICAL MODELLING IN STEM[1] SUBJECTS: A DESIGN BASED RESEARCH STUDY

Wolfgang Bock and Martin Bracke

Department of Mathematics, University of Kaiserslautern

In this paper we introduce our concept of a design based research study on the implementation of a new course STEM. The idea is to create a 3-years course for students of lower secondary level that integrates several STEM subjects, e.g. mathematics, computer science and biology. The subjects are not taught separately but are working on the same overall topic, seeing through the eyes and using the techniques of the respective discipline. After motivation and introduction of our concept we explain the real-world problem for the current round of the study and outline some first results and experiences.

Keywords: Mathematical Modelling, Design Based Research, STEM subjects, Project Teaching, Active Learning

MOTIVATION

Beginning with the first Pisa study in 2000 (OECD, 2001) there is a worldwide discussion of an appropriate education in the so-called STEM subjects[1]. One cause was the alarming fact that in many countries the majority of secondary school students fail to reach proficiency in math and science (Kuenzi, 2008). Further studies showed that a lack of substantial subject matter knowledge of teachers is an important reason. Another trigger for the still growing interest in the discussion of education in STEM fields is the demand of industry for highly qualified young people with a degree in one of the STEM fields.

One significant reaction to the above mentioned debate was to strengthen the role of mathematical modelling in teacher training as well as in the curricula. In Germany, this can be seen from the fact that mathematical modelling is mandatory in most of the recently introduced master programs for academic training of mathematics teachers. Moreover, there is a strong increase in the number of publications on mathematical modelling of *real-world*, *realistic* or *authentic problems* over the past decade.

Definition 1: An *authentic problem* is a problem posed by a client, who wants to obtain a solution, which is applicable in the issues of the client. The problem is not filtered or reduced and has the full generality without any manipulations, i.e. it is posed as it is seen. A *real-world or realistic problem*, is an authentic problem, which involves ingredients, which can be accessed by the students in real life.

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[1] STEM = Science, Technology, Engineering, Mathematics (in German: MINT)

[2] The Felix-Klein-Center for Mathematics in Kaiserslautern (http://felix-klein-zentrum.de) is a

RESEARCH QUESTIONS

Along working on a real-world problem we want to study the following research questions:

- How can project teaching in STEM subjects be improved?
- How does project learning and modelling in a 3-years real world project affect the sustainability of the techniques and knowledge used throughout working on the problem?
- How can tablet computers be used effectively throughout such a project?
- How do real-world problems affect the intrinsic motivation of the students to learn mathematics/computer science? Here we use standard instruments as QCM, see e.g. (Rheinberg, Vollmeyer & Burns, 2001)
- How do real-world problems affect Self-Efficiency of the students? Here we use standard instruments as in (Jerusalem & Schwarzer, 1999)

Note that throughout the research project of the authors the tests will be compared to tests in other classes of highly-gifted students in three different schools. Note that of course the 3-years project can, due to organisational reasons, just be done in one school. The other classes therefore play the part of a control group. Of course to omit too big differences in the student group concerning knowledge and techniques it is crucial to compare highly-gifted students with highly-gifted students.

IDEA OF THE JUNIOR ENGINEER ACADEMY "STEM"

Although there seems to be an agreement on the importance of the incorporation of modelling problems into their math lessons on a regular basis teachers face several problems: Often, there is a lack of time since they need to cover the whole curriculum for final examinations. Secondly, many real-world problems are quite complex and do not seem to be suitable for young students (or students at school at all) or as short time projects, respectively. Moreover, many problems cannot be worked on just from a mathematical perspective because they make strong demands on other STEM disciplines – and this is challenging for both students and teachers! Of course, problems can always be simplified, but if this essential step of the mathematical modelling process is taken over by the teacher the students get no training in a very crucial point of the whole process. Later, when working as a STEM professional, nobody will be there to do this first step for them and hence, they will eventually fail to solve their real-world problem.

In summary, it seems to be very difficult to establish a meaningful education in the STEM fields just be modifying the way of teaching for single subjects. We have some experiences from a long-term experiment introducing a significant number of small but realistic modelling projects in regular math lessons (Bracke & Geiger, 2011). But during the study we were facing many of the above-mentioned problems, and this is why we started to make up a new concept for STEM lessons that is currently under evaluation as part of a pilot project between the Felix-Klein-Centre for Mathematics[2] and the Heinrich-Heine-Gymnasium[3] in Kaiserslautern, Germany.

Our concept for STEM lessons

In our pilot we did not just want to develop a new concept for math or physics classes but the idea was to use another organizational structure. Therefore, we chose the Heinrich-Heine-Gymnasium, a high school with a branch for highly gifted students. They already had a compulsory elective lesson called "MINT" which can be chosen by students entering 7th grade. The former concept was to divide the lessons of this 3-years course into three parts: During the first year the students were taught in computer science, during the second year they had additional math lessons and the third year was dedicated to one natural science, i.e. biology, chemistry or physics (in alternating order). Throughout the whole 3-years course the students had three hours of classes per week. It is important to note that the contents of the whole course was intended to have no intersection with the standard curriculum of 7th – 10th grades[4]. The main reason to choose this particular school was not the fact that they have a special branch for highly gifted students but the already existing organizational structure. In our opinion it is not a necessary condition to work with highly gifted students: In a similar project conducted by the TheoPrax Centre in Pfinztal, Germany, teachers work with ordinary school classes of grade 8–10 (TheoPrax, n.d.).

Together with the school's administration as well as with teachers of STEM subjects a new course "STEM" was set up: Of course, it is still a compulsory elective course and the time scope is three lessons per week throughout grade 7, 8 and 10. But there is a common topic for every 3-years course and every week there are lessons in mathematics, computer science and one natural science[5]. In the first round starting in 2010 – which is now in its third year – the topic was *Planning Sites of Wind Parks* and besides mathematics and computer science, the students get lessons in physics. The second round beginning in 2011 has the topic *Batteries, Accumulators and Fuel Cells: The Search for the Super-Storage* with chemistry as the natural science. The new topic for the third round is *Bioacoustics – Automatic Recognition of Bird Voices*

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[2] The Felix-Klein-Center for Mathematics in Kaiserslautern (http://felix-klein-zentrum.de) is a cooperation of the Fraunhofer ITWM (http://www.itwm.fraunhofer.de) and the Department of Mathematics, University of Kaiserslautern (http://www.mathematik.uni-kl.de).

[3] http://www.hhg-kl.de

[4] In the special branch of the school students skip 9th grade by concept, i.e. the lower secondary level consists of grades 7, 8 and 10.

[5] The natural science is chosen to correspond to the overall topic of the course.

and as the reader might guess, biology was chosen to be the natural science taught in that course.

Just reading those topics, the whole project sounds quite ambiguous for students of lower secondary level and of course there are always voices claiming that the topics were impossible to do! Our intention was to work on real-world STEM problems that are interesting for the students. The course is not about only learning techniques but about learning concepts and solving problems. The teachers are seen not only as instructors but also as co-workers on the STEM topic. For every course we have a team consisting of regular teachers and "external teachers": The external teachers are graduate students (for computer science lessons in round 1 and 2) and mathematicians for math lessons in round 2 and math/computer science lessons in round 3, respectively[6]. Additionally, each subject has an external consultant, an expert from the University of Kaiserslautern or the Fraunhofer ITWM.

The concept encompasses the regular lessons (three hours of classes per week as mentioned before) and additionally, there are excursions and workshops throughout the whole 3-years course. Examples for excursions are visits of university labs (to conduct own experiments) or other institutes/companies. The regular workshops are starting from *Team Building* and *Time/Project Planning* up to *Creativity Techniques* and *Conflict Management*.

An important part of the pilot is financing: For the first round the Felix-Klein-Centre and the Heinrich-Heine-Gymnasium have been awarded with a so-called Junior Engineer Academy by Deutsche Telekom Foundation. This covers the external teachers, excursions, workshops and some materials/devices that are not in the regular budget of the school. Since the first year was very promising both partners immediately decided to extend the pilot to have at least three rounds, i.e. in total a 5-years period.

Example: Bioacoustics – Recognition of bird voices

Since the topics of the first two rounds in our project were related to physics and chemistry, respectively, the obvious idea for the current topic was to find a challenging project involving biology.

While for the other topics we started from a concrete problem (planning sites of wind parks, optimal storage of electrical energy), the starting point for the current round was the external expert Hans-Wolfgang Helb[7], who is a specialist in ornithology and thus has no problem to distinguish between a whole variety of birds just by hearing them singing. For ordinary people, on the other hand, the identification of birds by

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[6] The second author teaches mathematics in the second round of the project and both authors do a team teaching of mathematics/computer science/physics in the third round.

[7] Hans-Wolfgang Helb was assistant professor for zoology, ecology, behavioral biology and ornithology at the University of Kaiserslautern for 35 years.

their voices is a very hard task and most people can only recognize a few very popular species by their sounds.

For similar tasks like plant identification where there exist tools – books and smartphone apps – that support amateurs in learning the identification process to a good level.

The recognition tools of birds are mostly books and even smartphone apps[8] that are based on visual features. but currently there is no application that relies on bird voices as the only (or at least main) feature for the identification. There is a very promising research project (WeBIRD[9]) that uses a huge database and claims a high accuracy for the recognition process but the corresponding smartphone app has not yet been published. Since it is based on an analysis performed on a remote server it does not seem to be ideal for in field use. Jerker Hammarberg, researcher at Alexandria Institute (Aarhus, Denmark) concludes in a blog report (Hammarberg, 2012) that there is some research on the automatic recognition of bird voices[10] but there seems to be no current approach that can be used for an application based on smartphone techniques.

Based on the above considerations we chose the topic *Bioacoustics – Automatic recognition of bird voices* for the current round of our project. The goal for the students is to generate methods and implement software to identify birds not by their visual appearance but by their songs. This is an actual problem in ornithology, where the ultimate goal - a smartphone app that simplifies the identification process - would provide two important contributions for clients from ornithology:

- Support for amateur ornithologists and those who are interested in that field.
- Produce a tool for monitoring biodiversity in ecosystems by non-invasive methods.

From the mathematical point of view the techniques required for this project such as *Fourier analysis* and *Hilbert space theory* are far beyond standard school mathematics. Therefore many mathematics teachers at first glance would maybe refuse to carry out the project. The same problem arises in computer science, where students do not at all know techniques as *machine learning, neural networks* and *smartphone programming*.

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[8] Audubon Birds, BirdsEye and iBird Pro (apps for iOS & Android based systems)

[9] WeBIRD: The Wisconsin Electronic Bird Identification Resource Database. Project leader is biologist Mark Berres, assistant professor at CALS, Madison, Wisconsin.

[10] C.f. (Jankovic and Köküer, 2011) or (Lopes, Lameiras Koerich, Nascimento Silla & Alves Kaestner, 2011)

We started the course with a presentation of the general, complex problem and the expert explained the ornithological background. We also highlighted the ultimate goal of a smartphone app having the features described above as a *nice to have*.

Since this real-world problem is a current research topic, i.e. a client is interested in a solution, we think that the students are more intrinsically motivated to work on this problem and to learn the things they need to know in order to do this (c.f. the section on teaching concepts and design based research). This intrinsic motivation will be one of the authors research topics within this design based research study.

In our opinion the question if such a complex topic can be given to lower secondary level students depends strongly **on the expectations the teachers have**. Moreover, gathering some understanding about the complexity and the exact points which make the problem that difficult would be a big success.

Some comments on introductory lessons and first experiences

In this subsection we describe our idea for and some results from the introductory phase of the course, i.e. the first seven weeks[11]. In the course we have 19 students, 12 girls and 7 boys, who chose STEM as their elective course for the next three years. Although they are highly gifted, this does not imply that everybody is very good in all of the three subjects – but as mentioned before we do not expect this heterogeneity to be a problem at all. Besides working on the problem itself one important goal of the first weeks was to obtain a deeper insight into the social and mathematical or computer science abilities of the class. Vice versa, the students should have a chance to acclimatise in the teaching style of active learning, which was not much used in the years before.

We do not present details on the biology part here since the authors are teaching mathematics/computer science and at least for the introductory phase there is no need for a close ties between the subject. Of course, there is an exchange of information between all teachers on a regular basis. All we want to mention concerning the first biology lessons is that the main goal was to gather some basic knowledge on the anatomy of birds and the way they are able to produce sounds. Later on, it will be very interesting to investigate the role of the singing of the birds and why they are able to sing various and sometimes rather complex songs: Is it a matter of genetic inheritance or of learning from their parents – or maybe a mixture of both?

Concerning the mathematics/computer science part we first have to note that despite having only three subjects in the course we knew that also a lot of physics would be involved right from the beginning.

In fact, in the first lessons the students investigated the physics question: *What is sound?* We therefore decided to replace computer science by physics for the first

[11] Remember that we have three hours of lessons per week (one each in mathematics, computer science and biology).

weeks. Our first lesson started with the four diagrams shown in Figure 1 and the question of their meaning. The diagram was made by the freeware program Audacity.

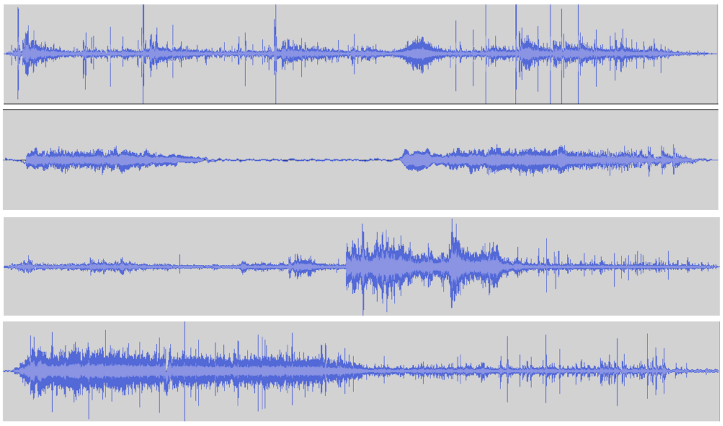

Figure 1: What's that? (Audio tracks visualized with *Audacity (Freeware)*)

The students had an intuitive interpretation and although there are no axis labels they all related these diagrams to sounds. They even gave some qualitative interpretations of the kind of sound they expected behind each graph. This is quite astonishing since of course by labelling and scaling it is possible to assign very different meanings. It would also be interesting if the quasi-symmetry with respect to a horizontal axis (which corresponds to a zero amplitude of the signal in this case) was an implicit factor for the interpretations of the students.

During the first lessons we did a lot of physical experiments to learn more about the nature of sound and the main teaching concept was *learning circles*. A lot of time[12] was spent on working in groups as well as on preparation and presentation of the results. For example, after the first series of experiments the students were asked to prepare a documentary video for each of the experiments. They first had to write their own scripts, then do the corresponding recordings and finally prepare an audio commentary that was mixed together with the video.

The next step was to obtain common definitions for the physical notions of a *tone*, a *complex tonal sound*, a *sound* and a *bang*. To assist the students during this discussion we introduced the oscilloscope as a measuring device[13] and performed some experiments to get more clarity about the characteristics of the different types of sound.

[12] In a classical physics course the teacher would probably have spent at most half of the time to achieve the same goals.

[13] An iPad with the app *Oscilloscope* was used. The feature to connect the tablet to a beamer was extensively used.

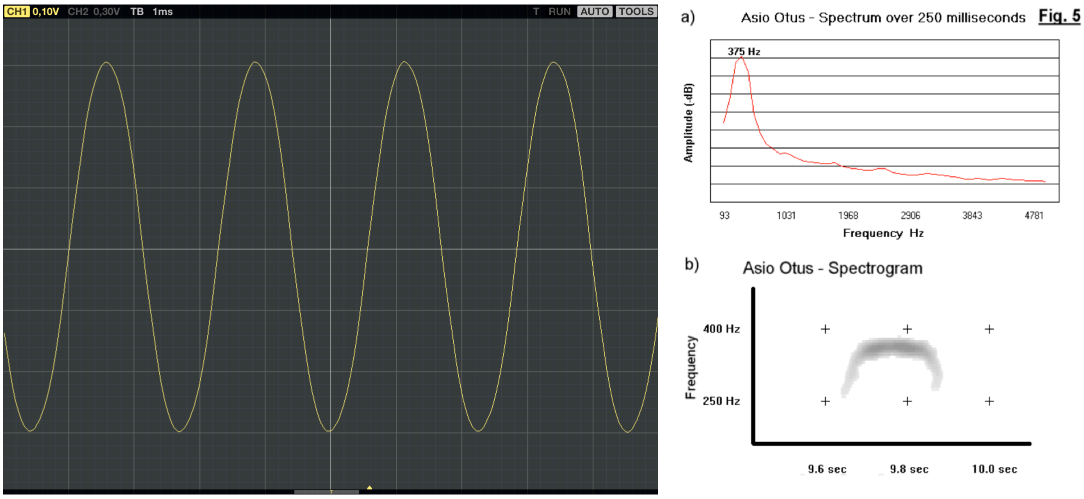

Figure 2: Sounds on the oscilloscope (left) (iPad app *Oscilloscope*) , Example for a sonogram, from http://www.birdsongs.it (right)

Since during their research the students found the terms of amplitude, frequency and wave length we used screenshots of the oscilloscope (where the iPad app *Oscilloscope* was used) (c.f. Figure 2 (left)) for a tone they have actually heard before and asked them for an analysis, guided by some questions like *Where are the zero-passings/minima/maxima of the graph?* They created value tables for each of the features and plotted the corresponding graphs. Of course, this can be done for different tones and the next goal we agreed about is to derive a mathematical characterization for what seems to be the basis for all the graphs we have seen so far.

After that, computer science will enter the game since we have to process and analyse data of sound recordings. One main goal for the first year of our course (concerning mathematics/computer science & physics) is the ability to produce and read so called *sonagrams* or *spectograms*, i.e. frequency-time-plots, that display more information than a simple waveform (amplitude-time-plot). An example can be seen in Figure 2 (right).

TEACHING CONCEPTS AND DESIGN BASED RESEARCH

One important point in our teaching concept is to look carefully at the questions the students are posing and trying to answer them completely and uniquely (cf. Singer, 1999). If necessary, we are going to add experiments or mini-lessons to achieve this goal. Educational methods taking this knowledge of learning into account are about 100 years old and go back to Pestalozzi, who already stated that an effective learning is learning with head, heart and hand. By Vygotsky's theory (Vygotsky 1978), it is crucial to choose the lessons according to the individual zone of proximal development of the students in order to obtain a sustainable knowledge and to improve already existing skills individually. Of course it is not necessary that the teacher poses problems and questions, also the students their selves can ask for problems they are interested in. In our opinion this will even augment the motivation for learning techniques to solve the problems.

Furthermore in our opinion it is important, that at the end of the project we have an end-product. As in a typical order in an industrial company, there should be a product the students have to construct. This is the main goal, which can of course be manipulated during the period. Towards this, the students claim smaller problems to solve, according to their interest and the needs to the final product. With this setting we try to give the structural impulse mentioned above.

The main idea of this project is to use the so-called Design-Based Research model, see e.g. (Collective, T. D. - B. R., 2003), to improve the techniques during the process. We plan first to practice the above-mentioned strategy to the group of students to adapt the methods according to their educational success.

RESEARCH TOPICS

During the project we want to evaluate the following measurements:

- Motivation (how does the method of teaching motivate the Sustainability of knowledge
- Self-Efficiency, as in (Jerusalem & Schwarzer, 1999)
- Sustainability of knowledge

Furthermore we want to investigate the usage of tablet computers in STEM and the dependence on the above topics.

NOTES

1. In German, the common analogue for STEM (Science, Technology, Engineering, Mathematics) is MINT which stands for Mathematik (Mathematics), Informatik (Computer Science), Naturwissenschaften (Natural Science), Technologie (Technology). In our opinion the definition of MINT is too restrictive since it does not involve other sciences than biology, chemistry and physics – the ones that are taught as separate subjects in the German educational system. Since the notion of MINT has become a standard we don't want to change it but instead we suggest the implicit extension of the 'N' within the German acronym MINT to include other disciplines like geo sciences, social sciences and economic sciences. Moreover, STEM explicitly incorporates the engineering disciplines in addition to technology whereas in MINT they are included in the term technology. On the other hand, the emphasized role of computer science in MINT reflects the importance of this field for typical topics associated with STEM/MINT – and this is missing in STEM…

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