# When Engineering becomes Children's playground

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## INTRODUCTION

In our modern society we have become dependent on a large number of technical systems. Even simple everyday tasks involve the use of quite sophisticated machines such as computers, the internet, cell phones, programmable home appliances, cars and many more. If we get ill, we are accustomed to treatment by physicians equipped with a plethora of ingenious devices to monitor and cure our diseases. Over the years, all these devices have become ever more performing while at the same time more user friendly. This evolution is of course due to a large extent to the work of engineers, technicians and scientists. So it is fair to say that these people shape the world we live in, cater for our basic needs, and provide comfort and joy of living. What more could one wish for when looking for a meaningful job? Yet it is a sad reality that too few youngsters look to science and technology (S&T) as a viable option to study and to find a job.[3]

Recent scientific research has provided insight into this matter. The ROSE study compared children (age 15) from 41 different countries as to how they perceive the Relevance Of Science and Technology. Although almost all children agree that S&T is important for society, only a small fraction considers studying S&T or getting a job in these fields. Paradoxically, the interest in S&T correlates inversely with the degree of technological development of the country: in developing countries children are eager to learn about S&T and to obtain jobs in these fields while in the developed countries it is the opposite. Why do capable youngsters fail to see the relevance of S&T and the possibilities for themselves to contribute to a better society through a job in S&T?

The answer to these questions involves different factors. First, a crucial role is played by the teachers. Not all teachers are themselves passionate about science and technology and succeed in motivating their pupils to overcome the hurdle of “S&T is difficult”. Also, few teachers ever talk about today’s or tomorrow’s technological developments in their class. They teach what their curriculum prescribes, which is by nature lagging far behind the ongoing technological innovation process. Hence, very few teachers, or parents for that matter, can explain and illustrate the role of engineers and scientist in our society. If we want more youngsters to consider engineering as a future for themselves, *the role of engineers in society has to be clarified*, exemplified, illustrated, or simply put in the right perspective, This is a task for teachers, but they need assistance from experts in the field: the engineers themselves.

Enticing youngsters for S&T is not the only reason to pay more attention to engineering in education. Almost all human activity, professional or leisure time, requires some form of manipulating technology. To do this safely and efficiently requires a certain level of *technological literacy*. But there is more. In our democratic society, many a political decision involves a thorough knowledge of technology. Questions about transport, logistics, energy supply, the use of natural resources, sustainability, … cannot be dealt with on the basis of emotions and opinions alone. Grasping the problems and assessing the options has become a responsibility of the politicians and the citizen alike. Engineers do this all the time. It is their job to tackle problems and to invent and implement solutions that strike a balance between all the specifications that need to be met. Engineers have developed strategies and methodologies to tackle complex problems with a high chance of success. This *“engineering way” of tackling problems is very valuable*, also outside the engineering domain. It is our conviction that teaching the “engineering way” of solving problems to young children will be tremendously beneficial for their later live, irrespectively of their profession.

In Flanders (Belgium) engineering is not part of the curriculum, neither in primary nor in secondary education. Much attention is paid to the fundamentals: language and math. Technology education is only being introduced at the age of 12 to 14. But the topics come nowhere near the specific nature of engineering. Every debate about engineering in education is blocked by arguments that “no time should be spent on engineering before language and maths have been sufficiently mastered”. The authors adopt a different stance: working on technical problems “the engineering way” involves the learning of language, the acquisition of mathematical concepts and the development of social skills. Moreover, this learning process happens very naturally, almost as a side-effect of the strive to solve a technical problem. Thus motivation is high because the relevance is immediate. *Hence our central thesis: learning to think and act like an engineer develops the core competences of problem solving, language mastering, mathematical insight and social skills*. We also believe that learning the “engineering way” provides the best insight in what engineers do. Which is an essential component of a well founded study and carreer choice.

In this paper we describe a didactical method and the accompanying hardware we have developed to teach engineering to pupils at the age of 13. The material was developed in a joint project between RVO-society and the microelectronics and sensors (MICAS) division of the Electro-technical department of the Katholieke Universiteit Leuven [1]. The RVO-society is a non-profit educational organisation founded by Imec, Belgium, in the honour of the late prof. Roger Van Overstraeten (RVO), founder of Imec [2]. The paper is structured as follows. First, we describe the prerequisites we think must be met to teach engineering to young children. Second, we describe the material we have developed for this purpose. Third we give an evaluation of the material. Finally the paper is concluded and future work is described.

## 1 PREREQUISITES FOR TEACHING ENGINEERING TO CHILDREN.

Engineers solve technically challenging problems. Hence, to teach engineering we need technical problems to challenge our target group of 13 year old pupils. We focus on *technical design problems*. A technical design problem is a problem that requires the creation of a technical system that meets certain specifications. Creating a technical system also presupposes that some technology (components, utencils, …) is available. For example, a wooden kitchen table should meet specifications of dimension, colour, strength and so on. To build such a table one needs wood and all kinds of woodworking techniques. To be useful, the design problems we need should be executable in class, safe, preferably not too expensive, but above all interesting and stimulating for the target group.

Many methods for technology education take the “building-up” approach. The teacher introduces different components and materials and explains how they work. Utencils are demonstrated and the pupils have to learn step by step how to operate them. Only after these steps have been tediously mastered, some more creative tasks are assigned. One such method has been used in Flanders for 20 years to teach digital logic. Pupils have to learn 3 logic gates, 3 input devices and 3 output devices. All these devices are neetly presented in a black box. The explanation how they work is provided in the form of truth tables and a very abstract input-processing-output metaphor. This “building-up” approach has had only limited success. In retrospect we can see why. This building-up approach assumes that pupils can be interested in the basic technology of logic gates and switches as such. This assumption does not hold because thirteen year old boys or girls with an genuine interest in logic gates are rare. These youngsters are interested in computers, social media, … all kinds of things which are built from logic gates. But you can perfectly use them without knowing a thing about the logic gates inside. So why bother? Especially because learning about logic gates is not easy nor fun for most youngsters!

Instead of the building-up approach we have investigated the *use of digital design problems as the start of the learning process*. To capture the attention of the pupils we choose as a design problem: the automation of a Lego train. We want our Lego train to be “intelligent”, perform a set of actions automatically and avoid catastrophes. This type of problem can be formulated in plain language and is easily understood by our target group. Moreover, almost all children know the world of Lego trains and are easily lured into thinking about the problems we pose. Despite the playful nature of these problems, they are highly relevant because real trains have to perform in very similar, although more complex, ways. The basic components we provide: a number of simple logic gates, sensors and actuators, are also reminiscent of the technology used in the real world. Hence the problem context is highly relevant and illustrative for the real world and the work of engineers.

One last prerequisite for succesfull teaching of engineering to young children (and to older students as well), is that it should be hands-on and less ex cathedra lecturing. Learning-by-constructing is by far more stimulating and rewarding than listening or analysis on paper. And constructing a technical system is teamwork. There are many ways to implement teamwork. We have adopted the cooperative learning method (explained later). There is vast body of scientific literature that cooperative learning is very effective when teaching children about science and technology, see e.g [4] and the references therein for more information.

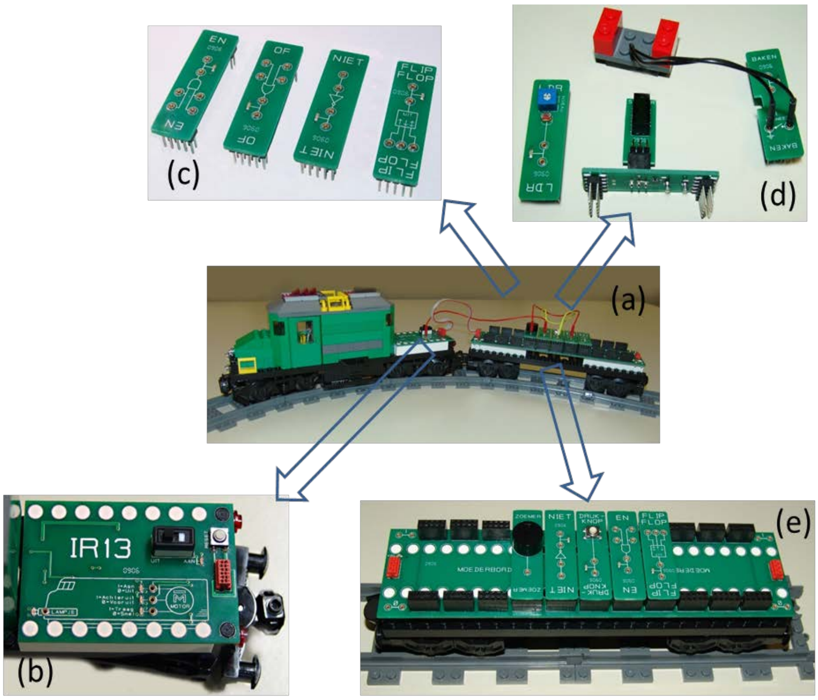


*Fig. 1:* Pictures of the modified Lego train. (a) Overview, (b) controlling the motor. (c) Logical functions. (d) sensors. (e) Motherboard on a wagon

# 2 IR13: 13 YEAR OLD ENGINEERS (M/F) BUILD AN INTELLIGENT LEGO TRAIN

## 2.1 Technical setup

Project IR13 is built around a Lego train, see

Fig. *1*, that has been extended with several electronic modules. The extensions come in three classes: Actuators (e.g. the motor), Control elements (classical logical functions) and Sensors.

The design problems we present to the children challenge them to create some automated behaviour of the train. We start from simple problems, e.g. “make the train run continuously after a short push on a push button”. While solving these simple problems the children discover the different electronic modules. We also teach them  the basics of the solution methodology in a learn-by-doing approach. One of the first methodological elements they learn, is the use of symbols to create a schematic diagram. A 13-year-old’s version of a gate level schematic diagram is shown in Fig. 2.

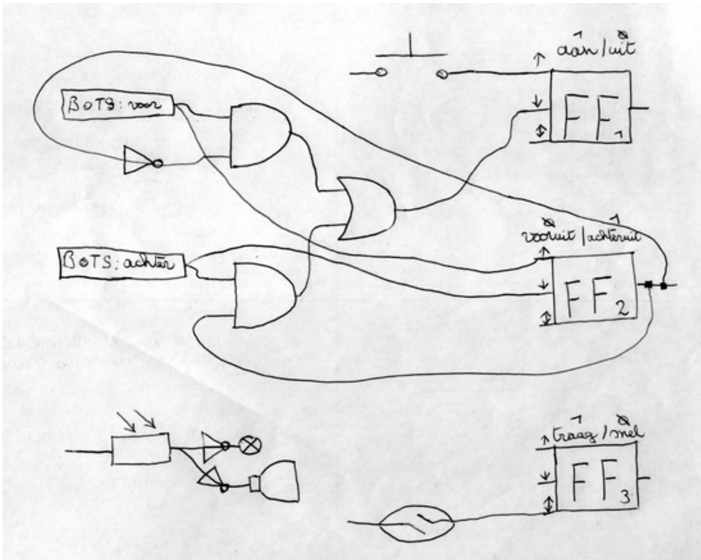


*Fig. 2:* Schematic diagram created by a 13 year old (The annotations on the drawing are in Dutch)

While working their way through a set of problems, our young engineers are also introduced to the concept of a design flow. The flow we propose is:

- Description of the problem in natural language. This description refers to the real world situation, (train, obstacles, behavior) in easy to understand and familiar language.
- Drawing of a schematic diagram with paper and pencil, as shown  in Fig. 2 Building this diagram amounts to a change in representation, from natural language to the formal system of symbols.
- Simulation of the circuit on a computer. A dedicated IR13 simulator was developed for this.
- Testing of the circuit in a prototype environment. We provide the children with a train emulator board that is connected to their circuit instead of the real locomotive. This board contains the same connections and visual elements as the locomotive but all actuators (motor, lights, …) are replaced by LEDS, see
- Fig. 3.
- Final test of the circuit with the real train. This final test may only be performed with an already verified design. All errors must have been detected and corrected with the help of the emulator board before the final

test on the train. Even with a verified design things may go wrong, for example a sensor may “miss” an obstacle because of the specific real world situation. This is an important lesson to learn!


Fig. 3: picture of the IR13 emulator board. The train control part looks the same as on the real train with LEDs emulating the train behavior.

### 2.2 Cooperative learning of engineering

It is clear that this flow contains the basic elements of a standard design flow like systematic design, early verification and so on. It allows the children to familiarize themselves with these design steps and their usefulness. It is important to note that the lecturing time is reduced to a strict minimum. The children are given the hardware and the manual. They start on their own and involve the teacher when required. This is one of the main reasons why the children are very much involved and motivated. The time they have to listen is very short compared to the time they can do.

In a typical classroom for 20 to 25 children only one Lego® track and locomotive must be present. Five setups with emulator boards are used in parallel. In this way 5 groups of 4 to 5 children teamup to solve the challenge. Each team tests its own solution on the simulator and/or the emulator board. When it finally works the “cherry on the pie” is the final test on the Lego Train. Note that more than one solution may exist (and usually does exist). Hence the freedom of each team to create its own solution. No need to copy, and no worries that other groups appear to work differently.

To stimulate cooperative learning we use the CLIM method. [5] CLIM stands for Cooperative Learning in a Multicultural Environment. CLIM assigns a specific role to each team member in such a way that they need each other to achieve the goal. The roles we use are: organizer, researcher, material responsible, and reporter. Each of these roles addresses a different aspect of the engineering teamwork. The different roles are rotated amongst the different team members. In that way all pupils develop the different skills. Furthermore, as cooperative learning prescribes, the pupils will learn that diversity of a team is an asset. [6].

### 2.3 Critical success factors

Apart from the prerequisites a few more aspects were crucial in the success of this project. First this project was developed in a common effort of secondary school teachers and engineers. This is essential because both, knowledge about teaching and knowledge about engineering, are equally important to come to didactical material that is used in classrooms. “Material” does not only mean the train hardware as described above. It also comprises of workbooks for the pupils, manuals for the teachers and training sessions for the teachers. As a matter of fact, we require teachers to take a training session to use our material properly, before we make the actual train available to them.

A second critical factor was the production of a complete prototype in a relatively short time, followed by an extensive period of field trials. The prototype train was given to pilot schools. This allowed us to test the robustness of the hardware in the hands of pupils. Additionally it was possible to evaluate classroom quality of the texts and manuals. These tests allowed us to co-develop the train hardware and the textbooks and training material. The early field trials require a lot of effort in supporting teachers in the pilot schools. When problems occured they had to be fixed fast, i.e. in hours or maybe a day, if the field trial was to continue. Problems with new material were of course inevitable.

A third critical factor is the look and feel of the modules. Of course all electronics should be designed according to common electronic practice but one should refrain from some typical engineering efficiency. For instance: it is not appropriate to put more than one function on a single module. This might be space and cost efficient but is confusing for the children. Also it is not wise to put more terminals on the modules than needed. Just the inputs and outputs is fine. Adding things like a permanent logical “0” or “1” only generates confusion.

### 2.4 Evaluation of the material

Evaluation of the material is difficult because there are no benchmarks for engineering education for young children. However based on feedback from teachers and pupils qualitative conclusions can be drawn.

In Flanders some “information technology” is taught in the first two years of secondary school. In this course children learn about elementary logic gates without too much context. No logic problems of a practical size are tackled. We asked the teachers that have used the old material and started using our new IR13 material to compare both methods. Almost all teachers stated that the level of enthusiasm of their pupils is much higher than it was before. The fact that *they can start from a technical problem, relevant in their own context, leads to a much higher motivation of the pupils*. A lot of teachers also notice a significant improvement in the understanding of key technical concepts. For example the pupils working with IR13 understand that sensors “observe the environment” and produce signals based on what they observe. With the old method most pupils could give sensors a name but they had more difficulties understanding the role of a sensor in a system. The only negative criticism came from teachers describing the material as “quite complex” or the design method as “too chaotic to use in regular teaching”. This criticism expresses a certain fear for “loosing control” on the part of the teacher. Hence the need for training and demonstrations.

When pupils are asked about their opinion they usually refer to the project in terms like: “playing with the train is fun” or “it’s amazing what you can make the train do with these little modules”. They clearly enjoy the learning experience, which in turn leads to a better understanding. When questioned about problem solving and system behavior, pupils show a much deeper understanding of technical problems and of the solutions they designed themselves. The pupils also acknowledge the usefullness of the diagrams to construct and debug a circuit. Before, drawing schematics was often referred to as ‘stuff the teacher requires us to do.’

A engineering professional pointed out that we do not always use the standard symbols for the components. Indeed we use simplified symbols for flip flops or sensors. If children use their own versions of the symbol we advise teachers to allow that. We feel it is important to first let pupils understand the use of symbols as the formal expression of a given behaviour rather than focussing on correct use of the conventional symbol. The drawback is that the pupils sometimes have difficulties in interpreting each other diagrams. When this problem occurs, it is the ideal moment to introduce uniform symbols in the cooperative classroom. At that moment, the need for uniformity in the symbols is something they will have experienced themselves. However the case for uniform logical symbols from the beginning can be made. It is a choice to be made by every teacher individually.

The results obtained so far are very promising. We are confident that starting from a design problem and gradually learn through construction and in a cooperative team provides a “close to reality” experience about the way engineers work. We have plans to extend our material for age groups 14-16 and 16-18. Interested parties can contact us.

## 3 CONCLUSION.

We show that it is possible to start engineering education with 13 year old pupils. The key enabler is the adaption of real life technical design problems and technology to a scale that can be tackled by these pupils. We have developped and validated didactical material to allow teams of pupils to build quite complex electronic circuits in “an engineering way”. We observed a rich learning experience blending engineering, language acquisition, social skills and more. We now plan to extend our work to older pupils.

## 4 ACKNOWLEDGMENTS.

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