Addressing modern technology: a systems approach

Lars Björklund

Att arbeta med modern teknik i Grundskolans Teknikämne
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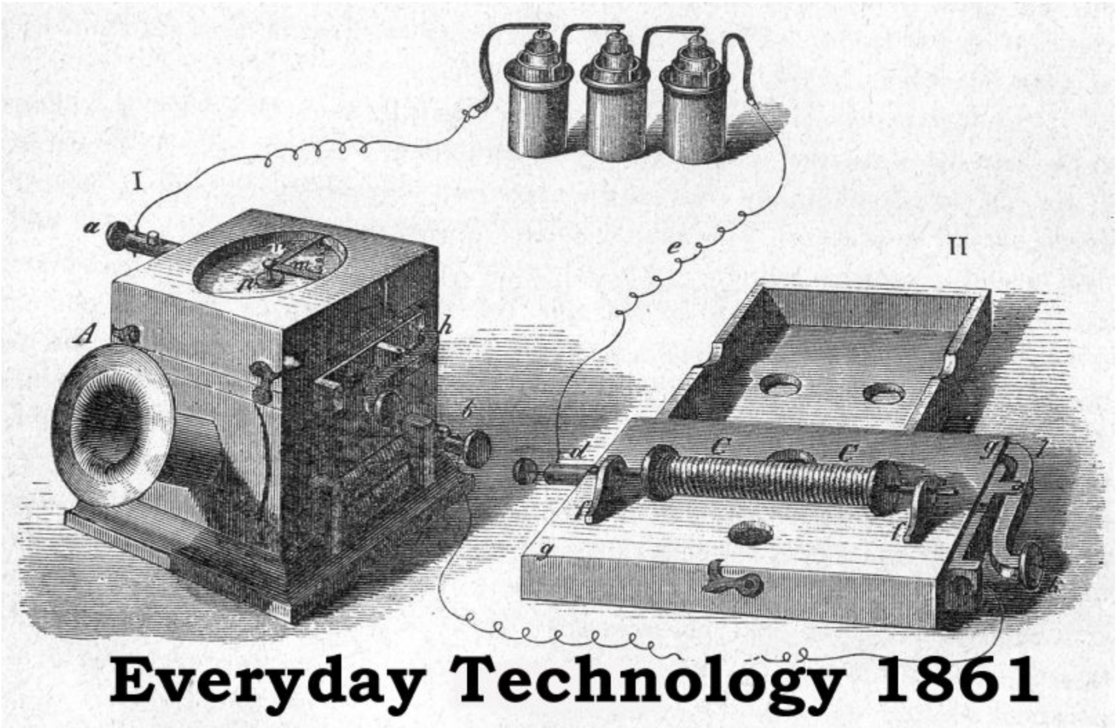

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A way to augment relevance to Science education and to achieve greater attention from students, is to address the everyday life experience by young people of technology. This is not an easy task; the technology of today is very often complicated. Mobile cell phones, MP3-players, computer controlled toys are hard to explain and to understand. The scientific method of Physics is to reduce and find general laws and models of the smallest parts in nature. To be able to address and to understand modern technology one needs to use the methods of technology, i.e. of engineering design. One must use two, for science education uncommon, perspectives on knowledge and understanding of artefacts. These are function vs. structure and a systems approach.

Function and structure

There are two different ways in which a technological artefact can be described: its structural physical properties and its function. At Delft University of Technology in the Netherlands a group of researchers are engaged in a project on ”The Dual Nature of Technological Artefacts”. Peter Kroes (2002, p. 294) writes:

> ”Technical artefacts are objects with a technical function and with a physical structure consciously designed, produced and used by humans to realise its function. But as a mere physical object, it is not a technical artefact. Without its function, the object loses its status as a technical artefact. This means that technical artefacts cannot be described exhaustively within the physical conceptualisation, since it has no place for its functional features.”

The idea of functional knowledge is not new. In 1809 Jean Hachette and others at the Ecole Polytechnique tried to classify mechanical devices by function and produced synoptic charts of elementary mechanisms, which enjoyed wide popularity for over 100 years (Ferguson, 1992). Even earlier, around the year of 1700, the Swedish engineer Christopher Polhem established a “Laboratorium Mechanicum” to promote the study of machines that might aid the economic development of Sweden. Polhem devised a series of models, “The mechanical alphabet”, as necessary for a “mechanicus” to know of and keep in mind as he designed complex machines. Polhem saw the five powers of Hero of Alexandria - the lever, the wedge, the screw, the pulley and the winch as the vowels. “Not a word can be written that does not contain a vowel”, he averred; “neither can any machine limb be put in motion without being dependant on one of these”. The students had to manufacture their own models in wood and were able to understand and design complex machinery. The Polhem alphabet survived him and it was used in the first technological educational institutes in Sweden until the 1840’s.

Early in the nineteenth century, Robert Fulton of steamboat fame, took up the idea of a mechanical alphabet. Brooke (1981) quotes him: ”The mechanic should sit down among levers, screws, wedges, wheels etc. like a poet among the letters of the alphabet, considering them as the exhibition of his thoughts, in which a new arrangement transmits a new idea to the world.”

The emphasis on design and problem solving has put focus on functions now more than ever. Hirtz (2002) describes a functional language designed to enhance and expand the frontiers of research in design repositories, product architecture, design synthesis, and general product modelling. ”In engineering design, all products and artefacts have some intended reason behind their existence: the product or artefact function. Functional modelling provides an abstract, yet direct, method for understanding and representing an overall product or artefact function.”

When researchers have tried to describe the design process, they talk about a problem state, a search space and a final goal state. Middleton (2002) emphasizes that to define the problem state is part of the problem. He presents a modified model with a problem zone and a satisfying zone. In both descriptions, the first part of the problem is about functional properties, the second of structural properties of the artefact. The task of defining the first and finding the latter is the core of design work. There are some findings showing that experts are more able to describe problems in functional terms. They also seem to reason backwards, trying to link and adapt “old” problems to the task in question. They try to find a problem similar to the one at hand, to be able to use their experience of linked function-structures knowledge to extract a solution. Novices are more straightforward and seek immediate solutions to the problem, by the method of “trial and error” (cf. Lars Lindströms chapter in this book).

A systems approach

Technological developments very often address ”individual technologies” or components (Laudan, 1984). Examples of this kind of artefacts are the steam engine, the propeller and the transistor. Together they are used to build technological complexes or systems. A complex has a long lifespan; the embedded components will evolve and may be changed without a change in the overall systems function. Edvard Constance (1984) describes the hierarchic structure of a system and Richard Kimbell (1997) use the term *hierarchy of tasks* which has - at one extreme - a very open and ill-defined context and – at the other – a highly specified task. A systems approach is in this context used as an analysing tool to understand the constructed world. By selecting an appropriate level of detail, even very complex systems are understandable.

In design work, it is of utmost importance to choose the appropriate system level. The cognitive restriction of the human brain makes it impossible to handle details that are too complex. This limitation has been circumvented by designers through a clever organisation of knowledge and design tasks on different system levels. It has made the design of the large technological systems of today feasible. Very much like an architect, the engineer will move between different levels of detail during the process of design. In large projects, tasks can be divided and distributed to different individuals or teams working on different system levels.

These two aspects of knowledge about complicated systems are related: a) When you move to a higher system level, knowledge of functions becomes more important; b) The knowledge is transformed from structural detail to more extensive functional properties.

An example from another educational field may clarify these two aspects further. When you learn a foreign language, for example Russian, you have to recognise the new letters, how to pronounce them and how to draw them. You will have to learn words, how to spell them and how to pronounce them. The grammar makes you apprehend the rules of the language and how words are connected and modified in different ways. This structural knowledge is not enough to make you a good writer or speaker; you need to grasp the meaning, the function of the language components and how the meaning is changed with the context. This is achieved by experience, i.e. by listening, talking, reading and writing. Every language teacher acknowledges these two aspects of learning and recognizes the systems aspect. Interpretation becomes different depending on the level. On the top level the text must be seen into a larger context, ways of speaking, cultural tradition etc. At the bottom level meaning is nearly incomprehensible as the individual letters or even the words convey very little information. The whole is more than the sum of its parts!

Implications for education

An educational subject such as Electronics will also benefit from the use of the system/function approach. Electronics is very often treated as part of science curricula, usually in the Physics curriculum. The structural part is about atoms, electrons, charges, electrical fields, current, conductors, isolators, resistors, capacitors, transistors, amplifiers, integrated circuits etc. The opinion formed by students and teachers is that Electronics is very complex and not easily comprehended. The “magnificent” idea of making and using integrated circuits, IC’s, is completely misunderstood. Textbooks and teachers often try to explain the inner structure of the chip instead of concentrating on the functional properties of this super component, which is constructed to enable design on a higher system level.

Electronics in Technology education

In the Swedish National Curriculum (Lpo94, 1994) there is a rather new subject or discipline, *Teknik*, which is using a systems/functional approach. *Teknik* is a very broad subject including concepts and principles from the social sciences, the natural sciences, the visual arts, design craft and other subject areas. Contents are not specified but address several important aspects of modern technology.

Function	**Materials**	**Energy**	**Information**
Transform		Elec.Flash	Rh-sensor
Store		Backup	RAM
Transport		CCD	CF-memory
Control		Filter	Timer

Fig. 1 Function of the Capacitor according to Lpo94

One of the aspects to consider in teaching *Teknik* is: ”*What technology does.* Technological problems and solutions can be categorised in different ways. The following fundamental functions can be identified: transforming, storing, transporting and controlling.” (Fig. 1)
If you add three different areas of action: Materials, Energy and Information, the resulting matrix will organize knowledge of almost any kind of artefacts. The teacher makes a choice of suitable technology according to local interest and resources. The area of Electronics is

very well suited to this kind of structure. A common component as the Capacitor *stores* electrical energy. It *controls* AC-current and can be used as a filter. It will be used for timing purposes and as a *transforming* sensor capable of detecting humidity, acceleration, etc. Its storage property can be used in a digital memory *transporting* music in a MP3-player. The functional properties of a Capacitor can be discovered and learnt in hands-on practice without complicated theories. On this systems level there is only one more electronic component, the resistor. Termistors, transistors, diodes can all be considered as variants of the basic resistor. In principle, therefore, it is possible to use electronics as a basis for addressing all modern everyday technology. Lessons of this type have been developed and tested by the present author in classes of 15-16 year-old students; preliminary results have been very encouraging. Since the knowledge apprehended was directly linked to a utilitarian use, meaningfulness and motivation was high.

Artefacts and Black boxes

The idea of the Black box is used in both Science and Technology education, very often to address something too complicated to handle thoroughly. When it comes to open up or to understand the Black box, scientists and technologists use different approaches. The scientist's analytic way is to try to reduce the Black box to its elementary parts in order to study these in detail and understand the interactions that exists between them (de Rosnay, 1997). By modifying one variable at a time, the scientists try to infer general laws that will enable them to predict the properties of systems under very different conditions. The scale is getting smaller and smaller, from molecules via atoms to subatomic levels. It is tempting to believe that if we know the innermost parts and the most fundamental laws, everything else can be deducted. Many scientists, especially biologists, do reject this myth however. They realize that the great complexity of real systems and the strong interactions of it's diverse elements makes addition of properties difficult; 1+1 is not always 2.

A physicist uses the Black box model in a special way. Phenomena, like gravitation, are explained by a mathematical model. This use of a mathematical Black box has been debated and criticized ever since Newton published *The Principia* (Gingras 2001). Michael Faraday wrote to Maxwell: "Mathematics cannot of itself introduce the knowledge of any new principle ". Maxwell insisted that for him: "natural philosophy is and ought to be mathematics, that is, the science in which laws relating to quantity are treated according to the principles of accurate reasoning". Mathematization contributed to the formation of an autonomous scientific field. As Mathematics is a language and foreign one, young learners very often are unappreciative for the abstract world of Physics.

In Technology the normal way of understanding the Black box is to investigate its interactions with the environment, how it is influenced by and what it is “doing” with, its surroundings. The Systems box, well known from technology education in many countries, uses the following description of a Black box: one or several inputs of data, an internal process or function and an output.

The dual use of artefacts

Technological artefacts are usually designed for a transformation of some part of the Nature, a tool for changing the world for some utilitarian use. This type of action could be termed “pragmatic” (Verillon 2000). Most technology curricula deal with these kinds of artefacts. The artefact embodies knowledge and may help an unskilled person to manage complicated tasks. The walking stick, the shovel, the calendar, the car and the computer are good examples. The development of the American manufacturing system was a way of dealing with inexperienced, temporary workforce, immigrants just waiting for a westbound train.

An artefact can be used as a mediating tool to help us investigate and understand the world. By converting aspects of the world not immediately accessible to us, it will enable us to detect, register, measure and make meaning to different kinds of phenomena. Gravity, electric fields and light are typical examples of what could be investigated and measured with the proper instrument. However, an instrument is a twofold entity comprising the artefact and the operator. To obtain the proper handling, the appropriation of an instrument, the user has to learn how the artefact interacts both with its object and with the user himself. This can be a time-consuming process. The digital instruments of today are very different from the tools of the pioneers of electricity. Alexandro Volta (1800) used his own body and no mediating artefacts when he described the effects of his newly invented battery:

> “A person who now puts one hand into this water, and with a piece of metal held in the other hand touches the summit of the column, will experience shocks and pricking pain as high as the wrist of the hand plunged in the water, and even sometimes as high as the elbow.
>
> It has been ascertained by repeated trials, that these effects are stronger in proportion to the greater distance of the metallic pairs, which are made to communicate... with a column of about sixty pairs of plates, shocks have been felt a high as the shoulder…

> The sensible effects... do not, it seems, consist merely in shocks, contractions, or spasms in the muscles or limbs; but, besides affecting the sense of touch, they are also capable of exciting an imitation in the organs of taste, sight and even hearing.”

Some parts of the Science curriculum, like Mechanics, could be investigated without artificial instruments, since students benefit from a long experience with their own bodies and its interaction with gravity. Some teachers relate to this experience with good results. However, even the understanding of Newton’s laws could gain from the use of an appropriate artefact, as Jonte Bernard (1998) has shown, utilising computer-based instruments in lab work.

My hypothesis is that to be really effective and useful, the measuring artefact must be well known and the user familiar with its interaction with the phenomena in question. If we want to measure electric current, the artefact must be “mentally” connected to the concept of electricity. A lamp bulb or an electric motor may be appropriate tools for a teenager, but a digital voltmeter certainly is not.

Accurate measurement is one cornerstone of science, but is not considered a science of its own. Nevertheless, it is the most important part of technology, the foundation of regulation and control. Georg Stiernhielm, a Swedish poet and engineer, declared in 1648: ”No One can deny that she (the art of Measuring) is the most outstanding, most worthy and most indispensable of all Arts known to Man.” (”Så kan ingen förneka att hon [mättekniken] är den värdigste, ypperste och högnödigste av alla konster som en dödelig människa i världen lära må och bör.”) Most of the scientific discoveries of today are caused by better measurement technologies; in this respect science can be understood as applied technology.

The concept of measuring is very well suited for practical work and has also been tested on the same group of young students mentioned earlier in this paper. The final part of this paper will give detailed information on the experiment and present some results from observations and assessments of knowledge and attitudes of the students.

Method of investigation

The object of study was two classes in the Swedish compulsory school, ”Grundskolan”. The students were 15 and 16 years old and in their final, 9th, year. The school subject was “Teknik”, the Swedish version of Technology Education. The original purpose of the project was to change girls’ negative attitudes towards technology, electricity and electronics in particular. Several international studies, interviews and inquiries show that girls tend to have a very low interest in these boy-dominated subjects. The literature proposes some remedies to the gender problem and together with a female teacher, I tried out several of them in a development project: gender separated classes, female teacher, context-rich problems, work in groups, diaries, oral examinations etc. The project was considered a success by students and the school staff and has been repeated several times with other classes. One of the “girls only” groups of 19 students was observed during 15 hours. Lab work was video-taped, interviews recorded and written inquiries were made. Diaries/logs were collected and analysed. Part of that data material is used in this paper to tell the story of what took place in this particular group of students.

In this study, Electric and Electronic components were handled as technological artefacts, Black boxes, with an emphasis on functional aspects. Education was inquiry-based with a lot of practical work in small groups of 3 or 4 girls. The objectives of learning were:

?? How do these artefacts interact with the surroundings?

?? How can these artefacts be used to solve a problem?

Measuring devices

We needed an instrument that could detect small currents and their direction. We decided to use a light emitting diode (LED) instead of an ordinary lamp bulb. Since it is a diode it has to be connected in the right way and it will detect current only in one direction. The high sensitivity of a LED facilitates the detection of small currents. To strengthen the relation between the students and the artefact, i.e. the LED-probe, the students designed and manufactured it by themselves, soldered the LED, the current limiting resistor, the wires and the connecting clips. A student’s own documentation is showed in Fig. 2.

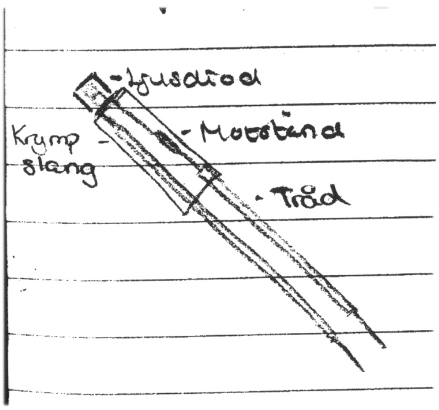


Fig.2 LED-probe

The second measuring device, the Motor, was equipped with a large and easily visible red propeller and indicated both the intensity and the direction of an electric current. The two devices were considered Black boxes with a function of measuring intensity and direction of electric current.

In the students' diaries, several entries indicate that they understood and used the LED-probe, the lamp, and the motor as indicators of electric current:

> ”When you heat the legs of the thermistor, which is a resistor, it will open up for more current and the lamp will glow stronger”
>
> ”The propeller did spin. It was fun! There was some smoke, we got too strong current.”
>
> “I've soldered the wires so they will conduct current… We will test the connections with a lamp. If the lamp glows everything is correct.”
>
> ”When you heat the thermistor, the resistance will be smaller and more electrons will pass and the lamp will glow stronger.”
>
> We connected a switch diode, which is rectifying. Then we had to connect the LED-probe in a correct way to make it light up.”

The third measuring artefact is procedural or intellectual; when you want to measure something, you must compare it with a standard. The task is to find a state, a position, of equilibrium between two entities, one known and one unknown. We therefore needed to find a method to compare two electric voltages. We asked the students to investigate how the intensity of a current related to potential differences. This is a very difficult area in the conception of electricity. Hans Niederer (1996, p. 16) studied the conception of pressure as an analogue to voltage and concluded:

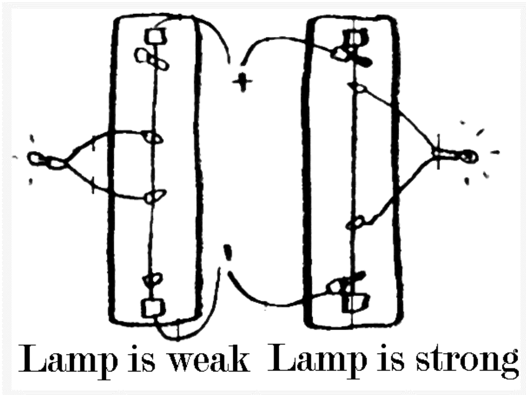
> “The following ideas get *no resonance* in students' thinking:
> - Pressure balance: two high pressures result in no movement.
> - Pressure difference.
> - Pressure in all directions; pressure in the backwards direction hinders movement…
>
> These ideas are so crucial to understand voltage with the analogy of pressure and pressure difference. Only if students think of pressure going in all directions they can understand the importance of pressure of difference being responsible for the movement and current of electrons. Only by balancing pressures they can understand, that high pressure on both sides of a resistor means that no current is running.”

The LED-probe and the motor were at this stage habitual mediating tools that indicated intensity and direction of the electric current. The object of investigation, the artefact, was a resistance wire made of NiCr, suspended between two connecting posts on a rather long, 75 cm, wooden pole or batten. The wire, forming a kind of open potentiometer was connected to a 10V DC power source. The “Electric Pole” should preferably be standing vertically, making an embodiment of “high and low” voltage easier. The teacher used a metaphor of a waterfall and some notion about high and low pressure to introduce this new Black box. Explanations using this kind of model appear in the diaries of a small number of students.

The task for the student was to investigate the electrical properties of the artefact and to find out how current would change according to the placement of the two connecting clips along the wire. The following questions were asked:

- ?? How would you connect the probe to achieve the brightest light?
- ?? How should the connecting clips be placed to minimize light?
- ?? If you move both clips up or down the wire, with the same distance, what will happen?

A majority of the students were able to find maximum and minimum values for the detected current and they explained how to find them, in their diaries, in text and in pictures as in Fig. 3



> “The lamp is glowing strong when the difference in voltage is large. The light from the LED will be of the utmost brightness when the connecting wires are as far from each other as possible… It has to be a difference in voltage to make the lamp glow”

Some students used the term “pressure” instead of voltage as these excerpts from the diaries sho:

> ”You keep the legs of the lamp far apart from each other, this will make the pressure difference larger. The voltage will also be larger.”

> “When the lamp goes out there is no difference in voltage.”

Fig. 3 Intensity of light as a function of potential difference

It is of utmost importance to know that it is the relative positions, not the absolute ”altitude”, that matters. This example suggests that the student has grasped the idea:

> “When you move the lamp back and forth with the same distance between the contact clips, it will glow with identical strength. If you change this distance, the intensity of light will change”

In the following transcript of a video clip, two students, “2” and “3” seems to have a working understanding; the third, “1”, is still revising her theories:

F: What will happen if you move the lower contact along with the upper?
3: It will be approximately the same pressure
1: .. approximately the same (not confident)
There it is such pressure, I don’t know.
3. The pressure will stay the same!
1: ..It.. will… stay…. the same pressure, in spite of them being far away
It will be higher pressure? (seeking eye contact with student 3)
F: So, the distance between them is important?
1: Well, I, I think so (uncomfortable), if my theory is correct (wags her head)
F: What will happen with the motor if you change the connectors (pole reversing)
2: If I take this (lower clip) and move it to that place, but then it will be lower, cause
1: Both of them are up high.
2: No, but it is a smaller gap (watching the motor)
3: It will be lower, I can feel it and the vibrations!
2: But it is because of the smaller gap, if I move the lower clip it will be higher

Girls number 2 and 3 seem to have understood the concept. Number 1 is seeking advice. This is something that is typical of girls only groups, “a willingness to ask for help and just as importantly a willingness to provide that help”. (Underwood et al., 2000)

An interesting fact of this class was that not one girl did notice that the propeller sometimes changed the direction of spin. A follow up test with a Peltier-element showed that no girl, nor boy noticed that one side of this component became cold while consuming electrical energy. Electrical energy could be transformed into heat but not chill. This indicates that we observe using our experience of what might happen.

One of the girls asked the teacher if she and her mates were allowed to raise the voltage that supplied the resistance wire. Permission was granted, the wire became hot, glowing hot, started to shine with a white light and was burned out in a few seconds. The class was hilarious and every girl wanted to “make” a wire glow, wires were destroyed en masse, wooden poles burned and the students learned something very important. In almost all diaries this event was highlighted:

> ”When we connected it, all the wires became long and yellow, then we burned it.” ”..and we also played, burned wires and pencils. It was great fun cause we were allowed to play with the electric current.” ” The most enjoyable moment was when we ”blew up” the wire.. we were playing with electricity!”

In the class with boys only, every group burned their wires, without asking for permission.

To measure, the electrical pair of scales

The students now were able to detect differences in potential/voltage. They were now invited to work together with an adjacent group. The “Electrical Poles” were connected to the same DC-source, giving them a common ground (Fig 4). The first group attached one of the connectors to the LED-probe somewhere on their pole and the second group tried to figure out where, on what altitude this was done. Almost all students knew or found the answer of how to succeed:

> “When the lamp goes out there’s no difference in voltage!”
>
> “You’ve found your mates position when the lamp goes out”

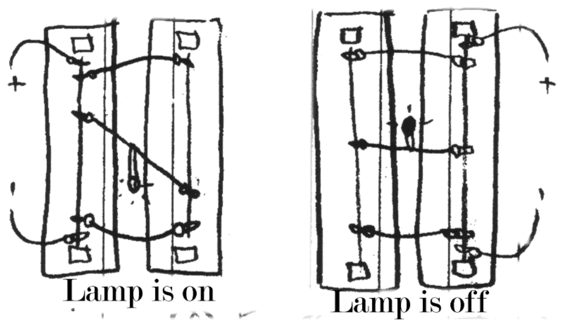


Fig. 4. Unbalanced and balanced Electrical Pole

The instrument consisting of two potentiometers and a null detector is well known under the name of The Wheatstone’s Bridge. Charles Wheatstone presented this “Rheostat” to the Royal Society in London in 1838.

The concept of comparison is fundamental to all types of measurement technology, even the soundcards of modern computers uses the same principle and compares the signal from the microphone with an internal variable reference.

Calibration of the voltmeter

The next step for the students was to calibrate their “Electric Pole” with electrical sources of known voltages*:*

> ”I have made a voltmeter [Fig. 5] and played with a solar cell, we used different batteries to calibrate the Electric Pole. I had great fun doing this. The solar cell produced 2.5 Volts in direct sunshine and 2 Volts in the shade.”

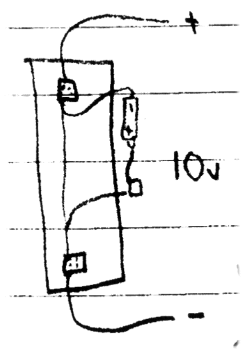


Fig. 5 Voltmeter

Some other students used sensors as thermistors and photo resistors to build voltage dividers that could be measured with the Electrical Pole. The calibrated tape could be substituted for new ones marked in Centigrade and Candela. The null detector could be improved by using a more sensitive motor. The null is very easily detected when the motor slows down and suddenly changes direction of spin. An amplifier made the null detection even more sensitive, very small error would show up and the error signal could be used to control a fan or some other form of actuator in a feedback control system.

Discussion

Most of the activities during this project could have been done in a Physics class, but the emphasis on technological concepts and functional properties seemed to have created a positive atmosphere where most students took the opportunity to experiment and play.

Playing with electricity was initially considered very dangerous and prohibited; girls seem to be very observant on rules of engagement in laboratory work. This is a correct attitude towards safety-regulations, but will deprive them of much experience and knowledge boys take for granted. As teachers we should have this in mind when we design practical projects and laboratory tasks. The event with the propeller and the burning wire are typical examples.

The idea of separating boys from girls was assessed by some girls in one of the interviews:

> 1: I think it has been more fun; well maybe not fun, but usually the boys are doing everything, we just stand there watching, as always!
> 2: They don't think we can manage …they just want us to watch!
> 1: Yeah
> 3: Yes, now we took an active part, we were allowed to do much more.

Attitudes to "Teknik" were very positive, every girl used words as fun, enjoying, nice, amusing in their diaries. In one of the interviews a girl expressed her feelings:

> "In the beginning I believed it would be boring, it's boy's stuff, but we started and when I was allowed to experiment and play it became great fun, I'd say this is important for us."

Another girl expressed her positive attitude to the subject of "Teknik" in this way:

> "In Math and Science there is only one correct answer, one way to do things, but in Teknik there are several ways of doing things and you are allowed to make mistakes.

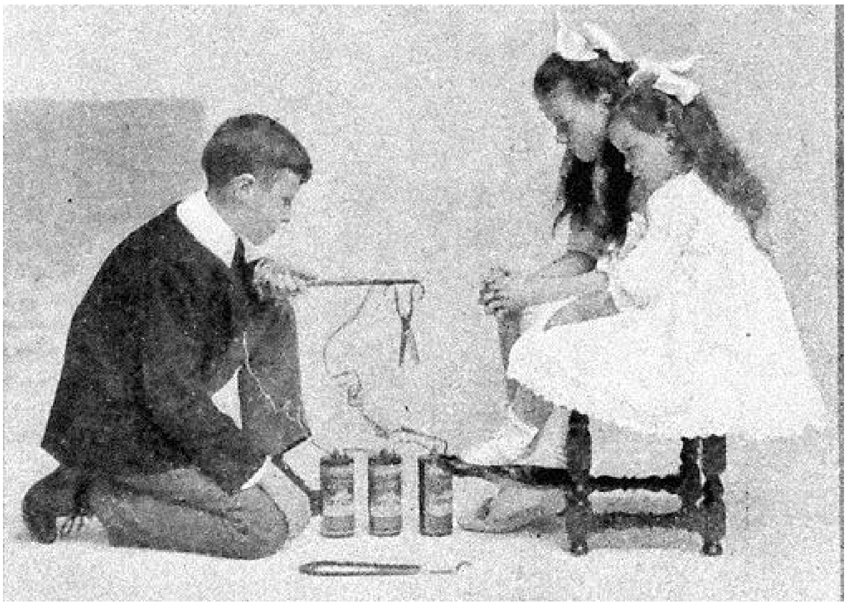


Fig 6. Illustration from ”Science for boys and girls” (Gibson 1923)

The Electronic Alphabet, what is next

The idea of a Functional Alphabet is not new in history and seems to have a strong importance for design abilities. Our idea of concentrating learning efforts on the functional properties of resistors and capacitors was successful in one sense. The students were able to analyse everyday technology and recognize possible electronic letters; the large capacitor in the camera flash, the photo resistor in the computer mouse, the potentiometer in the volume control etc. However the level of detail was to small to enable them to design and construct electronic apparatus on their own.

I am now planning a longer study on design and creativity with a material on a higher systemic level, the “Event boxes”. I will follow and observe a class of learners together with their teacher in a kind of action research. The students will be working on a large constructional project where differences in approach and method are probable. The teacher will be trying to assess product and process abilities according to the benchmarks and standards of the curriculum. What the project will help me to understand, can be framed in terms of the following research questions:

?? How do young learners use structural and functional knowledge?

?? How is the concept of systems level experienced?
?? Is the ability to use these two aspects of artefactual knowledge something that can be taught and assessed?
?? How can this ability be described by product and/or process criteria?
?? Is it possible to describe progressive stages in this ability?

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