The Adventure of Computer Science

Understanding the Impact of Informatics on General Education and Designing the Living Environment

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Abstract. In the 20th century, a paradigm shift started regarding the acquisition of knowledge. Our living environment is more and more determined by engineering-driven construction. This paper explains how the tangible living environment of pupils and the models of explanation used in general school education drift further and further apart. Introducing computer science as a nationwide mandatory subject in schools offers a chance to take this paradigm shift into account. In this context, didactic approaches like CS Unplugged or "Abenteuer Informatik" (the adventure of computer science, a German project) can help to implement school education that is really general.

Keywords: Abenteuer Informatik · CS Unplugged
Acquisition of knowledge · Peirce · General education
Models of explanation · Construction · Design
Mandatory subject computer science

1 Of Peirce and the Natural Sciences

In human history preceding the age of the Enlightenment, one had an exact idea of how new knowledge can be gathered: above all, there was study. This primarily meant the study of scientific (and religious) literature. The main ways to yield new knowledge were *deduction* – implying special knowledge from general knowledge – and *induction* – achieving general knowledge from special cases. Since all implications had to be strictly related to some knowledge that was already present, introducing new ideas required detours.

Thus, also natural scientists were not yet recognized as such. Galileo Galilei, who formulated principles of scientific research by experiments and observation already at the beginning of the 17th century, was far ahead of his time. Even a century later, Isaac Newton was recognized as a philosopher, not as a scientist. The living environment in those times was shaped by faith. Design was largely related to art and architecture, much less to profane things of every-day life.

In the 19th century, the Industrial Revolution created a new point of view on the living environment: Steam engines provided independence from rivers as

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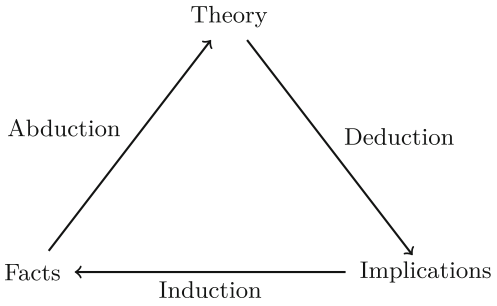


Fig. 1. The Peirce cycle of abduction, deduction, and induction

a means for driving the mills, and chemical fertilizer revolutionized agriculture and, very concretely, reduced starvation. Understanding the working principles of nature now was an important foundation of society. “Discovering” new physical or chemical connections was increasingly viewed as reasonable.

Taking this development into account, around 1900, Charles Sanders Peirce introduced the notion of *abduction*. This can be seen as a formal model for generating hypotheses from new ideas that are inspired by observations. From such a hypothesis, one can then use deduction to derive possible consequences, and can scientifically verify or falsify these in experiments using the principle of induction. The relations between abduction, deduction, and induction can be visualized in a cycle diagram as shown in Fig. 1, which goes back to the work of Peirce [11]. Hence, abduction is no revolutionary idea, but the mere acknowledgment of a scientific principle that was in practice used by mankind “all along” to acquire new knowledge about the surrounding nature. Following this acknowledgment, natural sciences were also introduced into the educational system. At universities, faculties of natural sciences were established and partitioned into single disciplines. For instance, during the 19th century, chemistry emancipated itself from medicine and became a separate discipline at many places.

Due to the needs of the industrialization, also the school system could no longer avoid the respective lessons in natural sciences, but these were much under-represented with 2 out of 20 lessons in the high-school (“Gymnasium”) curriculum of the 19th and beginning 20th century. However, there existed some special schools (“Realschulen” and, to some extent, “Realgymnasien”) that put much more weight onto these subjects. The transition to specialized subjects within the natural sciences at high school happened, depending on the region, only a hundred years after the differentiation at university level. But the proportion with respect to the complete curriculum did not rise significantly, with a percentage of, e.g., 12.5% in Hesse in 2018.

Abduction, as the possibility to build hypotheses about already present material or immaterial artefacts in an explanatory, deducing way, is already included in the school curriculum, although probably not under this name.

Fig. 2. Fictitious headline

Until the end of the last century, this scientific, explanatory approach was at large consistent with the living environment of the pupils. Although the environment was more and more influenced by human-made artefacts, the laws of nature were also valid for those. Euler's implication of Newton's second law "force equals mass times acceleration" is also valid for a car, for which one has to estimate whether it is possible to cross the street in front of it unharmed.

2 The Living Environment in the 21st Century

Due to the increasing virtualization, the shift of human communication to social networks, and the all-time-everywhere reachability, the living environment is increasingly dominated by human-made artefacts that do not necessarily follow the laws of nature.

Of course, such artefacts can in the first place be viewed and analyzed in the traditional way. Besides a manganese nodule found close to a volcano, or a water sample from a local source, also a desktop computer can be (disassembled and) analyzed. The cycle of abduction, deduction, and induction also works for this, and the pupils "learn" to understand their living environment. However, a very relevant element is missing, which constitutes the key to a full-fledged participation in a modern living environment: the ability to participate in actively designing it.

We want to illustrate this with a striking example: The fictitious headline from Fig. 2 is no "fake news", but is based on a study by Ugander et al. from May 2011 [12], which analyzed 721 million people with 69 billion friendship relations

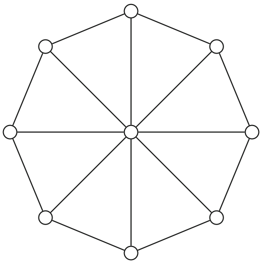


Fig. 3. Friendship graph

– an order of magnitude that is extremely remarkable for an empiric study. A basic hypothesis of this study was that most people have less friends than their friends do.

Included in this study were all Facebook users which were signed in for at least four weeks and had at least one friend relation there. The results indeed showed that about 84% of the "study participants" had less friends than the average of their friends.

An important question that remains, however, is how relevant this result actually is. As computer scientists, we know the intellectual tool of modeling for analyzing and solving problems. If we use this tool on a "normal" example with, say, 9 friends, we arrive at a graph like the one shown in Fig. 3. Here, vertices represent people and edges represent friendship relations. A very sociable person is present in the center and has a large number of friends. Surrounding this person, there are several cliques of people that know only two more friends besides her or him.

In this example, we have one person with eight friends and three friends of friends on average, and eight persons with three friends, but 4.67 friends of friends on average. This means that "provably" eight out of nine people (thus, even almost 89%) have less friends than the average of their friends. On the one hand, this example supports the findings of the study, but on the other hand, it is easy to see that people with many friends contribute more to the friends-of-friends statistics than those with less friends. This insight makes the result of the Facebook study much less surprising.

The same result was indeed also obtained 20 years before the study of Ugander et al. by Feld [3], who calls this the "friendship paradox". More precisely, he proved the following result: If there exist, in a group of people with friendship relations, at least two people having a different number of friends, then there is always a majority of people in the group that have less friends than their friends on average.

Here, we can take two different points of view: One is the view from the outside, where we can analyze the situation with the Peirce cycle. On the other hand, the artefact to be analyzed is a social network, and thus something

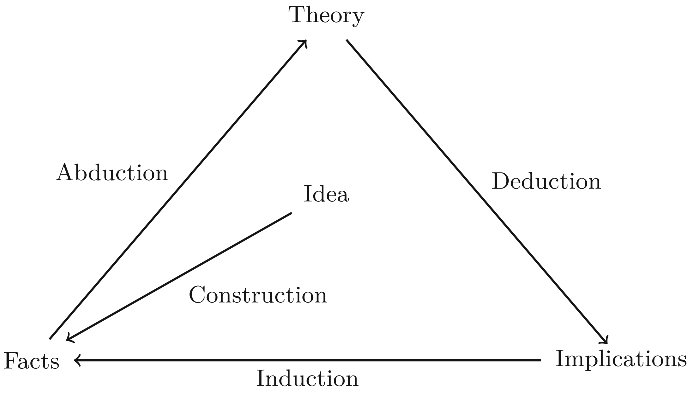


Fig. 4. The Peirce model with construction

human-made. Hence, it seems to be much more direct and reasonable, and in particular much less tedious, to incorporate this design into the study.

3 Taking Peirce to the 21st Century

This human-made design in our living environment does not only become visible in social networks: car-sharing apps rough up the transport market, Industry 4.0 promises cooperation on a completely new level, insurance companies can use "big data" for much more individualized offers, and deep learning comes up with results that by now really remind us of artificial intelligence.

At universities, the masterminds of such designs can mostly be found in engineering and computer science. These are scientific fields that often have emancipated themselves from natural sciences and mathematics in the middle of the 20th century. The knowledge generated by them can in fact be analyzed using the Peirce cycle, but not the generating process itself. They are more than hypotheses: Our living environment is permanently enriched and extended by human-made design. Hence, Fig. 4 shows the proposal to add the principle of *construction* to Peirce's model.

Construction creates new facts which then – as already shown in an example – can be analyzed using abduction, deduction, and induction.

Construction is not new to the school system! It can be found in classical subjects such as art or literature. Nobody would expect pupils to analyze a painting by Picasso before having tried out a pencil or a brush themselves. An interpretation of Goethe's work is done only after gaining own experience with writing simple essays. But in the area of artefacts, which have an immense impact on our living environment, one usually immediately starts with the analysis: media-pedagogic articles eloquently explain, with the use of quantitative empirical research, the implications of social networks. The contribution to "big data" edited by the "Bundeszentrale für politische Bildung" (federal central office for political education), which is an important source for teaching materials for many schools in Germany, is comprised of six articles written by journalists, lawyers, sociologists, politologists, and physicians, who view and analyze this "phenomenon" from the outside.

How can and must school carry out its mission of general education with respect to this? For sure by acknowledging that construction is an element that massively, and possibly soon in a vital way, shapes our living environment. Today's pupils are no longer only asked to passively analyze the respective artefacts or – in an also passive way – to operate the resulting systems. Today's pupils will design the artefacts and systems of a future living environment! General education means that, on the one hand, all should have the chance to participate in this design – actively by constructing themselves – or also passively by participating in decisions regarding the possible application of newly constructed systems, based on their deeper insight into the basic working principles and models of the systems. On the other hand, general education means to preserve cultural coherence, thus very explicitly not to create a society of "nerds" who are able to design systems and a society of the "others" who view the products of these nerds like natural phenomena. This legitimates mathematics as mandatory subject for the whole school period, but also a special subject addressing the constructive approach – like computer science.

Also the remaining tasks of general school education as described by Heymann [8] – preparation for life, practicing communication and cooperation, orientation towards the world, critical thinking, development of the willingness to take up responsibility, and strengthening self-esteem – suggest to take construction at school seriously [5].

4 Structural Chances of Teacher Education

Models of knowledge acquisition are central competencies in all school subjects, just as, e.g., considering tasks of general education or scientific working techniques. Hence, within the scope of a quality enhancement program for teacher education, Technische Universität Darmstadt has established a network for didactics students, where the respective competencies are developed in an interdisciplinary way, among others within an integrated lecture about "central ideas and tools".

After short inputs in the form of a classical lecture, project teams consisting of four or five students from different disciplines independently develop teaching sequences under a very broad common theme that varies from year to year. For instance, the theme of the first course in the summer term of 2017 was the "intelligent refrigerator", which was aimed at stimulating thoughts about sustainability, functioning principles, and communication abilities of home devices from the point of view of the living environment of the pupils. The theme in the forthcoming summer term 2018 will be "To pixel or not to pixel", following a presentation by the mathematician Sir Michael Francis Atiyah, who talked about discrete and continuous models of our world at TU Darmstadt in 2017 [1].

The main task of the students is, given this common theme, to set particularly central ideas and tools into the context of school and to connect them to the living environment of the pupils. The course of action follows research-centered learning according to Huber [9]. The best results are presented at an (internal) peer-reviewed conference [6].

Consequently, the goal is not the unilateral focus of teachers on construction and engineering-like thinking, but an integration of this new viewpoint on knowledge acquisition, as we discussed it here, into the previous context, also providing the chance to strengthen the connections and cooperation between different scientific disciplines.

The student feedback for the first course was consistently positive, apart from some comments on initial organizational difficulties; the self-estimated increase of competencies was high.

5 Implications for the Content of the Curriculum

Finally, we want to illustrate with an example, what implications the extended view on construction can have on teaching contents, and in particular on learning goals.

Today, the binary system for the representation of numbers is without doubt firmly connected to computers and informatics; thus, it is contained in almost all curricula. It can be easily explained using binary cards or a combination of binary clock and binary cards [7], and there exists a multitude of activities concerning binary numbers; see also [2].

But how do we motivate in class why we deal with this number system that might appear cumbersome at first glance? The explanations commonly used can be mapped to the following two approaches.

> In computer systems, signals have to be transmitted, and this signal transmission is more secure having two states, as the distance between signal and noise becomes larger.

Yes, this might be true. Nevertheless, modern data transmission protocols work with significantly more states to enhance efficiency, e.g., with 256 states in the case of VDSL. This explanatory model is thus not convincing.

> Zuse had relays at his disposal, and these have two switching states.

Although, strictly speaking, Konrad Zuse did not use relays for his Z1, but home-made logical units constructed from small metal plates, the first completely functional models indeed used relays. Nevertheless, Zuse would have had also the rotary selectors from telephone engineering at his disposal – a kind of relay with 10 switching states. Thus, also this explanation does not work.

To find a reasonable explanation, we follow a historic-genetic approach [13] and reconstruct a traditional algorithm from ancient Egypt, which is also known as "Ethiopian multiplication" or "Russian rural multiplication". Already in those

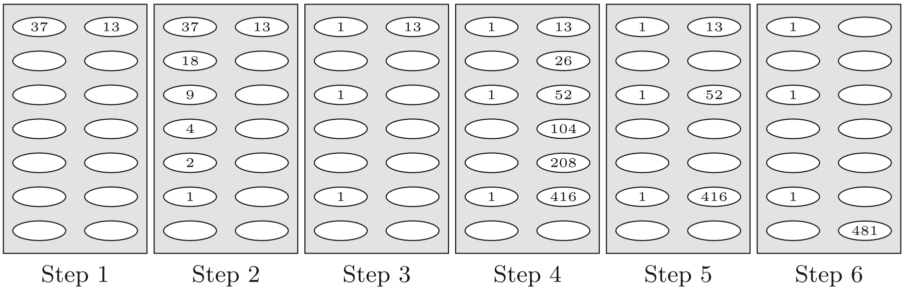


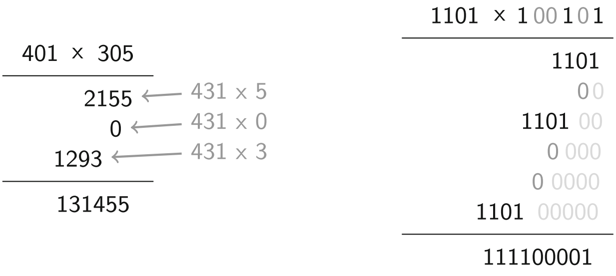
Fig. 5. Egyptian multiplication with the multiplicands 37 and 13

times, a trustworthy method was needed for, e.g., determining the total price of 37 amphorae at 13 dinar each, without buyer or seller being able to calculate.

The calculation was carried out with the help of hollows in the sand and small stones, which we represent here by their numbers per hollow. The calculation now strictly follows the rules of the following algorithm.

1. Fill the two uppermost hollows with the multiplicands.
2. In the left column, do the following: Into every still empty hollow, put half of the content (rounded down) of the preceding hollow.
3. In the left column, do the following: Remove pairs of stones from each hollow as long as possible.
4. In the right column, do the following: Into every still empty hollow, put double of the content of the preceding hollow.
5. In the right column, do the following: Empty every hollow that is neighboring to an empty hollow from the left column.
6. In the right column, do the following: Count all remaining stones.

Figure 5 shows an example with the multiplicands 37 and 13. The Egyptian multiplication is a method which transforms a rather complicated operation



(a) decimal **(b)** binary

Fig. 6. Written multiplication

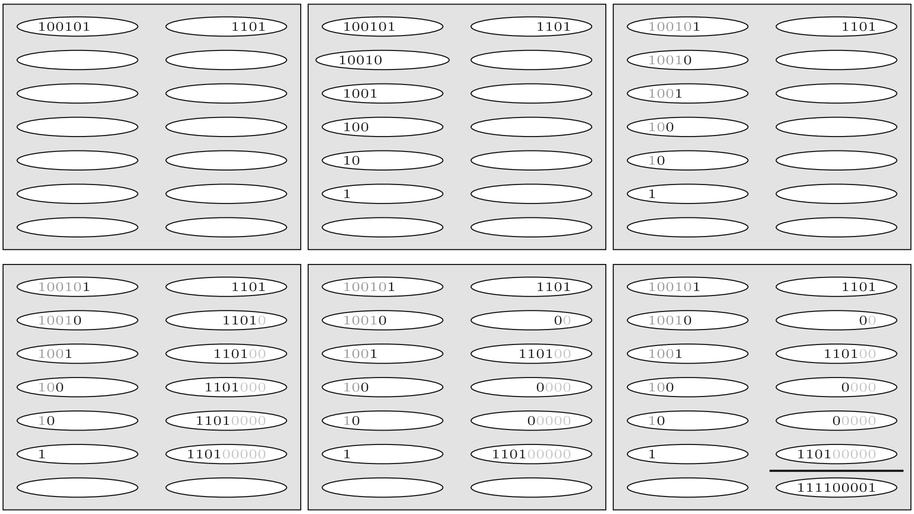


Fig. 7. Egyptian multiplication with binary representation

– multiplying two arbitrarily large numbers – to a never-changing sequence of simple actions. These actions are "halving", "doubling", and "adding". This kind of transformation is called *structured partitioning*, and it constitutes the basic idea of an algorithm and is thus a fundamental idea within computer science.

To find out what this has to do with the binary number system, we take another detour and look at the written multiplication as taught in primary school. An example of multiplying 431 and 305 is shown in Fig. 6a. Also here, we transform something complicated into simpler calculations – in this case into the basic multiplication table and written additions for adding the intermediate results. Now we look at exactly the same method applied to numbers written in binary. The result for the numbers 1101 and 100101 is shown in Fig. 6b. For better readability, the intermediate results are not only indented, but also the correct number of zeros is appended.

Already at this point, the pupils should recognize that the written multiplication in binary was rather easy. The principle becomes even more obvious if we now show the connection to the Egyptian multiplication, namely that both methods are in principle identical. The Egyptian multiplication with the binary representation of the numbers 37 and 13 is shown in Fig. 7. A more detailed teaching instruction can be found in [4,7].

In principle, the ancient Egyptians multiplied in the same way as every computer does it nowadays – based on binary number representations. In this context, it is irrelevant whether the ancient Egyptian mathematicians were conscious about this representation. It is more important that the motivation for this was the same then as it is now: it is amazingly simple! It is based on the "very small" multiplication table for binary numbers as shown in Fig. 8. How much easier would primary school have been for us if we had have to learn only this...

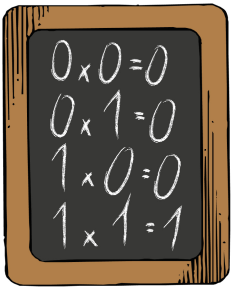


Fig. 8. Multiplication table for binary numbers

Thus, our whole computer technology is not based on complexity, but on the opposite: on simplicity. Together with structured partitioning, this principle can be used to solve a vast majority of all problems effectively. Specific artefacts of our age – like the popularity and importance of the binary number system – can be analyzed using induction and deduction. Since these are completely intellectual creations, not even explainable by physiognomy (like the decimal system is by humans having ten fingers), they can only be explained by competencies in construction. Taking part in designing our living environment is only possible with constructive competencies.

In the above sketch, no construction happens, though – it is just reproduced. But using the derived competence of structured partition, many more principles can be rediscovered and newly derived, e.g., binary search or sorting algorithms, but also principles outside computer science such as modular construction.

6 Conclusion

Informatics is part of general education. This claim has been established and proven in many articles in the past, e.g., in [14]. The paradigm shift of the living environment discussed here, and the resulting necessity to accept construction as an important element of knowledge acquisition and to teach it in school implies a stronger version of the claim:

General school education is not possible today without a mandatory subject with appropriate time slots for all pupils that focuses on the – very relevant with respect to the living environment – principle of construction! The only established school subject that is able to provide this is computer science.

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