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TINKERING AS METHOD IN ACADEMIC TEACHING

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ABSTRACT
In this work we argue that tinkering can be a vehicle to gain knowledge and skills profitable for working in engineering, design and science. We analyse how to implement tinkering in an academic context and illustrate our findings with examples from our environment. In academic environments tinkering often has the reputation of playing around without plan, with unclear outcome. We argue that, when implemented and executed well, due to its practical and iterative nature, its high applicability and hands-on nature it can be a valuable contribution to design and engineering and other academic disciplines.

Keywords: Tinkering, Engineering Rationale, Engineering and Design Education.

1 INTRODUCTION

“Technological fruit fall from scientific trees” [1], is a common academic perspective on engineering and design, meaning that the straightforward application of scientific theory leads to technological applications. In other words, the “normative curriculum still embodies the idea that practical competence becomes professional when its instrumental problem solving is grounded in systematic, preferably scientific knowledge” [10]. In engineering a different kind of knowledge is necessary than science provides; this was discussed in the sixties of the last century [13] and supported by a number of prominent authors [14,9,2]. Still the academic nature of elements of our curriculum that aim at practical success of technological applications is often questioned.

Technological knowledge is different from scientific theory. The quality criteria of science are truth, universality, theoretic consistence, coherence, simplicity and empirical adequacy. The quality criteria of technology lie in the practical success of a technical solution, applicability, reliability, effectiveness and efficiency [1]. It is obvious that it is a different kind of methods and knowledge that leads to results satisfying the quality criteria of technology from these of science.

In many places universities have recognized the shortcoming of engineering curricula and introduced new content to educate a different kind of engineer, such as Problem Based Learning[1] or project centred approaches[2]. Here, we argue that tinkering is another useful contribution to engineering and design curricula, satisfying additional goals. As a definition of tinkering we take the one of [8]: “The tinkering approach is characterized by a playful, experimental, iterative style of engagement, in which makers are continually reassessing their goals, exploring new paths, and imagining new possibilities.”

We also argue that not only engineering and design can profit from tinkering, but also science education. There, the focus is often restricted to reproduction of current scientific theory. Development of new scientific theory, including observation, reflection, formulation of new hypotheses and their proof, identification of problems and their framing is little addressed. It is assumed that a student can only begin with these after mastering the current state of the art in science.

It is already acknowledged that tinkering plays an important role in STEM (science, technology, engineering and mathematics) education of young children [7,8]. Many successful experiments have been performed and toolkits developed to stimulate children to tinker, both for motivational and instructional use. In this paper we would like to investigate which elements and form of tinkering are

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[1] E.g. at Aalborg University: http://www.en.aau.dk/about-aau/aalborg-model-problem-based-learning/

[2] e.g. at the University of Twente: https://www.utwente.nl/tom/en/whatistem/

suitable to be systematically included in academic teaching, based on our own experiments and experience.

In section 2 we will discuss what activities and skills relevant for science and engineering can be supported trained by tinkering. Section 3 deals with the question on how to set up tinkering, i.e. what the ingredients to make tinkering happen. The considerations there are illustrated by examples in section 4. Section 5 contains discussion and conclusion.

2 THE CONTRIBUTION OF TINKERING IN ACADEMIC TEACHING

In addition to the definition of tinkering in the previous section, we want to emphasize the following characterizing aspects of tinkering: *initially, tinkering is a seemingly undirected process; it is driven by curiosity and playfulness; problems and challenges are self defined; iteration of prototyping, observing, reflecting, definition a new challenge; failing.* A number of activities and skills can be identified that can be considered relevant in academic teaching which can be supported by tinkering, such as its contribution to the following:

Raising questions is one of the driving factors of science. It is a key to new insights, to formulation of hypotheses and theory forming. In contrast to that important role, raising questions is not part of science curricula. In the process of tinkering raising questions is a starting point of each iteration of an experiment. The questions raised in early stages might be simple, such as "How does this part work?" or "What could I use this part for?' It is reasonable to start a personal development of raising questions on a small scale, with simple questions. With the maturity of the student and the quality of the toolboxes (see section 3), the complexity of the questions will also increase. Important is to develop a habit of raising questions. In this aspect, we share motivations of problem-based learning.

Reflection requires first observation, and then interpretation of the observed. It is an activity that precedes the above, raising questions, and also forming of hypotheses and theories. In the process of tinkering reflection is the step that opens each new round of experimenting: the students have to get into an active role concerning seeing and interpretation. Even if the cycles in the beginning may be small, it is precisely the type of reflection that is relevant in any design process, where the design process is understood as an exploration of the design space. Reflection in tinkering can be seen as an exercise in reflection-in-action [9] on a small scale.

Hands on knowledge is the means to make things work. It can be gained only by doing, and very often by making many faults. Tinkering is without doubt one efficient and effective source for getting hands on experience and knowledge. Here are at least three interdependent dimensions included: first, there are practical aspects of engineering knowledge such as operation principles of devices or components, material knowledge, knowledge on composition, integration, construction principles [1], or debugging experience. Second, there is what Schön calls *Knowing-in-Action* [9], "knowing that is tacit, implicit in our patterns of action and in our feel for the stuff we are dealing". It is knowledge that is internalized, sometimes by an aware process of understanding, often "unaware of having learned to do these things, we simply find ourselves doing them". Third, depending on the toolbox, actions take place in the physical world, physical manipulation is required that also has the effect of activating the right hemisphere of the brain and stimulating interaction between logic and intuitive thinking, a vision propagated by constructionist thinking [16]

Seemingly undirected process. One of the points of critique of the tinkering process, is that it is seemingly undirected, playful and into the blue. This contradicts the dominant perspective of science that new insights or inventions are made in a logical, straightforward process, where new results are derived from existing theory, the engineering rationale [10]. However, history shows that the most relevant inventions of engineering were not made in this straight derivation process. And also for science it is argued that finding of new theories requires the non-directedness of tinkering [4]. There are at least two possible aspects of the "non-directedness": first, much of the engineering process goes unconsciously [1,9]. This may cover all kind of intuition and implicit knowledge about design and engineering processes. Second, new results achieved often carry a seed of randomness, as in the famous example of the discovery of penicillin. In tinkering, undirected exploration is also only one part. Resnick et al. [8] state: "Others worry that tinkering is too unstructured to lead to success. That critique confuses tinkering with random exploration. The bottom-up process of tinkering starts with exploration that might seem rather random, but it does not end there. True tinkerers know how they turn their initial explorations bottom into a focused activity up".

Problem framing. "In real world practice, problems do not present themselves to the practitioners as givens. They must be constructed from the materials of problematic situations which are puzzling, troubling, and uncertain." [10]. Relevant in this discussion are for us that framing a problem is a kind of work a practitioner has to do, and, that uncertainty is a key element here. Uncertainty also refers to the previous aspect of undirected processes – here we argue that coping with uncertainty in the light of problem framing is a skill that is trained by tinkering.

Increase of personal toolbox. The set of building blocks available to a designer is personal, and it is subject to a life-long growing process. It shapes the kind of product ideas a designer comes up with. Tinkering is one way to expand the personal toolbox, by playful exploration of building blocks, trying out their working principles and application possibilities.

Use technology for new applications. There is a continuous demand from academia and society to identify new applications for either existing or new technology. We argue that tinkering precisely trains and repeats this process (if the toolbox is technology). Only, "new" may mean "new for the student", and not "new for the world". On the long term, however, when the experience space of the student has increased then "new for the designer" will coincide with "new for the world".

Making design decisions. Design decisions are often taken on the basis of incomplete knowledge. The factors that determine the decisions are mainly personal experience, personality (e.g. daring vs. cautious), and the personal toolbox. Tinkering is a process where (small) design decisions have to be taken relatively often (e.g. compared to a project course, where typically a whole group decides on the design and bigger fragments of the time go to problem framing and realization). In this sense we claim that tinkering as a training field for design decisions on "small" scale, helpful as an experience basis when "bigger" scale design decisions have to be taken.

Similarly, In [7] engineering practices were examined and related to tinkering practices. The list includes: defining problems; developing and using models; planning and carrying out investigations; analyzing and interpreting data; designing solutions; engaging in arguments from evidence and obtaining, evaluating, and communicating information. There are a number of activities and their descriptions, which are related such as bricolage [5], making (of makers) etc. We see many these descriptions and aspects thereof in line with our findings, some at a different level of abstraction.

3 THE SETUP OF TINKERING

We consider tinkering more as a mind-set and attitude than a method used in a single workshop. It needs a number of iterations in tinkering experiences, which vary and expand during the period of the study program, and include different domains and courses. We identify a "playground" or setup below that has to be set for each tinkering activity, all these ingredients together define a method. We mainly present the description of the playground here, examples will be discussed in the next section.

Playground: Tinkering takes place both in a physical and 'mental' space. Not every common classroom is sufficiently equipped for the process. Creative environments such as design labs, maker spaces etc. include aspects stimulating the tinkering mindset and process which readily available materials and tools, flexibility in setup, drawing canvasses, etc. See also *make space* [17] Typically tinkering as process takes place in 'sessions', bounded in time and place. A session is usually hosted by a skilled facilitator with a certain mastery of the toolbox or as expert on a presented 'seed'.

Toolbox: One of the goals of tinkering is to explore the material of a toolbox and integrate it in the "personal toolbox" of the designer. We have "typical" tinkering toolboxes with an Arduino toolkit, but we also consider elements of programming languages a toolbox, collections of algorithms another, etc. The content of toolboxes can be material, ranging from cardboard, pipe cleaners, glue etc., or electronics of different levels, to immaterial components as for programming, or philosophical concepts to tinker with. Making a toolset smaller stimulates students to explore the potential of the components in more depth. The art is to provide a setting of low threshold and high ceiling.

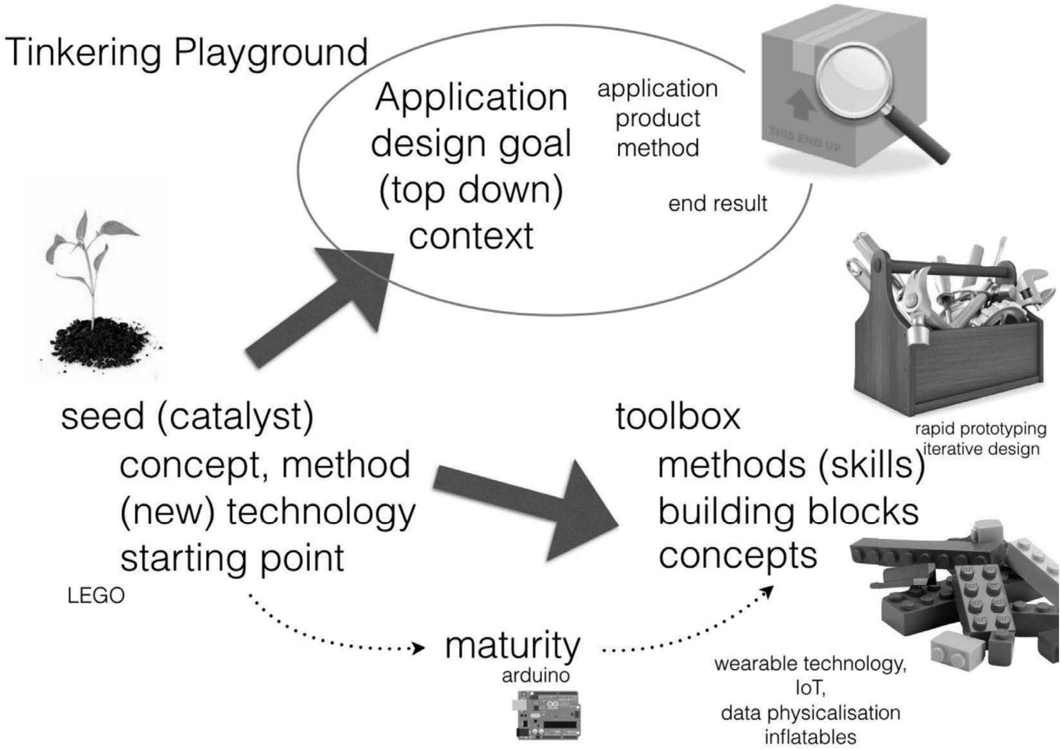

Figure 1. Tinkering playground setup

Seed: A seed has to work as a motivating factor or starting point. A typical seed can be a new type of technology or building block that can be used in bottom-up tinkering: "here is something new and interesting, what can we do with it?" We identified different levels of seeds to be given according to the maturity of the students. Different approaches to deal with a seed are possible: In the Tinkering Studio [7] the role of the seed seems to be taken by facilitators, who individually coach participants. Also (open) problems and re-runs or reproduction of existing examples (e.g. in [15]) of other sessions can be used as starting point or 'seed' for a tinkering session.

Maturity: Seed technology has not an endless shelf life. We observe that many building blocks start out as seed technology (many examples of Arduino tinkering workshops can be found) and eventually end up in the student's toolbox as 'regular' skills or components. This means that the hunt for fresh seeds is a continuous process, for both the facilitators and as skill for (experienced) tinkerers.

Goal: although the end goal is not necessarily in view (tinkering aims at serendipity, the unsought find) by tinkering solutions for problems can be found. Different problems, goals (and formulation of assignments) therefore exist. *Teacher's problem:* Assignments as seeds would be of the form that a defined goal has to be reached, but the way to get there is not defined, e.g., make a thermostat from the elements in the toolbox. Within a given assignment the space may be open enough that students can at least define their individual sub-problems. *Open teacher's problem*: Assignments here typically define a class of possible instances, such as "make an interactive installation addressing {some set of requirements on users}". It should be possible to identify different problems in this assignment (such as an installation for learning, or an installation for entertainment). *Framing of not well formulated problems*: This is typically the kind of problems presented by users or clients. Effort has to be put in the process of extracting or inventing a solvable problem satisfying the client. *Define own problem*: For very trained tinkerers a new element in the toolbox alone might already be stimulating enough, but it also might be the case that they implicitly refer to earlier tinkering activities and challenges. In the end, we want students to define their own challenges, identify and phrase their own problems.

Feedback: As for all design education feedback is essential when tinkering, especially for beginners. Here the main kind of feedback is helping to see new opportunities, stimulating to get into and to remain in the process. We have to hold ourselves back not to debug setups for the students and thus spoiling their learning moments. Making faults is a crucial source of learning in tinkering.

Group context: We observed that group dynamics can have very stimulating effect on the tinkering process. Mechanisms of competition play a role ("I want a better solution than he has.", or, "There are already so many with this solution, I want a different one."), as well as cross-stimulation ("This is a cool solution – how could I use something similar in my project."). In the Tinkering Studio this aspect is described under solidarity [7].

4 EXAMPLES

In this section we provide a number of examples of tinkering tryouts in our teaching environment, some repeated for a number of years. For theses examples we only look at the quality of the results achieved by the students and the elements of the setup. Other academic skills as, e.g., raising questions are not investigated here. Also, the courses we give cannot be tinkering alone – e.g. we have to be sure that a student gains at least some experience with the elements of a toolbox.

Programming 1 & 3: In both courses the toolbox was Processing [11,12], in the first the building blocks were elements of a programming language, in the second it was algorithms, one abstraction level higher. In the first course, the seed assignment was using a self chosen picture of art and animate its elements. In the second, students had to combine several algorithms treated in a coherent application. The major part of the course was given in a classically, lectures and tutorials with focus on practical support and feedback. Half of the results were mediocre, half of the results (very) successful. Obvious was that the students with successful results were driven by enthusiasm to make their self-chosen concept work. Theses concepts included game elements, pure aesthetic animations, pure quantity, or story telling, all outside the scope of programming. Surprising was also the range from simple building blocks, but beautifully arranged to complex and sophisticated combinations.

Programming and Physical Computing: Toolbox here were an Arduino toolkit and programming elements [12]. The seed was to make a musical instrument. Also here, there was a number of standard solutions (cap-sense pianos, light-sensor instruments), but also a number of excellent and original examples. Notable was the effect of group dynamics showing that students influenced each other not just by the technology used, but also in the search for unusual concepts. Students who did their assignment outside the group had significantly weaker results, confirming of the influence of the group context.

Wearables on Wednesdays: An extra curricular activity, with the intention to use knowledge students have from Physical Computing for "fun" applications. In a first attempt, a number of attractive materials were provided. Interested students came, did not know what to do, looked up far too complicated projects on the internet that did not match with the materials available, did not make anything and did not come back. Here, obviously, the proper seed was missing, the "attractiveness" of the material alone was not sufficient for the students. In another attempt with a small group of advanced students with tinkering experience chose to make a flower that opens and closes when a person approaches or leaves. It was decided to use an iris-mechanism, and in very short time a first prototype of an iris was downloaded, laser cut, tested, the mechanism completely re-designed, laser cut and equipped with motor, distance sensor and Arduino. Notably in this group was the attitude that the "toolbox is the whole world", the fast realization of different prototypes, and the strong cooperation, building on each others ideas, and the own choice of the seed.

Interactive Inflatables: In June 2014 a tinkering workshop was scheduled for students in their graduation phase aimed at designing "interactive inflatables". The seed technology was proposed by Kristin Neidlinger, and was mainly the 'idea' combined with some transferable skills in making inflatable garments by fusing textiles. Since the technology needed for inflation was lacking, the number of successful designs was limited. In a second workshop at TEI2015 [18] as additional building blocks a number of pumps and valves were brought. Still the level of maturity required too much tinkering effort in getting the tech to work rather than tinkering in concept- or design space. One of the outcomes of the TEI workshop was a simple building block, a cup with a tiny fan (dubbed the inflatacup[3]). A third workshop at MU in Eindhoven (feb 2016) used this inflatacup as 'seed' together with the concept of interactive inflatables. In terms of working concepts it was much more successful than the previous attempts.

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[3] http://makezine.com/projects/inflatable-wearables/

5 DISCUSSION AND CONCLUSION

With the starting point that technological knowledge requires an education different from classical science (alone), we argue that tinkering supports a number of skills relevant in engineering practice and design, but is also relevant for academic and scientific work. Based on our experiments and experience in tinkering (elements in) academic courses, we tried to analyse the ingredients that form a tinkering setting. For us, it is useful to have these ingredients in an explicit form, as it helps us to (re)design our courses, and we hope they form a contribution to tinkering in an academic setting [6].

The main questions for evaluation are: To what extent did students learn tinkering during this study? And, do the students at the end of their study have the skills discussed above? Since tinkering is not the only element in the study program distinguishing it from classical curricula, it seems difficult to separate the effect of tinkering from the overall results. Students also do a lot of project work, have design courses etc. and some students might be more practically oriented than others. What we see however is that at the end the students of our program can cope comparably well will poorly defined problems, come up with creative solutions, know to realize them, and can justify their design decisions. Many students become natural ‘tinkerers’, all seem to recognize tinkering as tool or part of the design process in its own right.

REFERENCES

[1] Boon, M., *How science is applied in technology*. International studies in the philosophy of science, 20(1):27–47, March 2006.

[2] Ferguson, E. S., *Engineering and the Mind’s Eye.* MIT Press, 1994.

[3] Jacobsson, M., *Tinkering with Interactive Materials* : Studies, Concepts and Prototypes. PhD thesis, KTH, Media Technology and Interaction Design, MID, 2013. QC 20131203.

[4] Kantorovich, A., *Scientific Discovery: Logic and Tinkering*. State University of New York, 1993.

[5] Louridas, P., *Design as bricolage: anthropology meets design thinking*. Design Studies, Vol. 20, No. 6. (1999), pp. 517-535.

[6] Lamers, H. M., Putten, P. and Verbeek, J. F., *Observations on Tinkering in Scientific Education*, in: Entertaining the Whole World, pages 137–145. Springer London, London, 2014.

[7] Petrich, M., Wilkinson, K. and Bevan, B., *It looks like fun, but are they learning?* In: Design, Make, Play: Growing the Next Generation of STEM Innovators. Taylor & Francis, 2013.

[8] Resnick, M. and Rosenbaum, E., *Designing for Tinkerability*, in: Design, Make, Play: Growing the Next Generation of STEM Innovators. Taylor & Francis, 2013.

[9] Schön, D. A., *The reflective practitioner*. Basic Books, 1983.

[10] Schön, D. A., *Educating the Reflective Practitioner: Toward a New Design for Teaching and Learning in the Professions*. Higher Education Series. Wiley, 1987.

[11] Shiffman, D., *The Nature of Code*. D. Shiffman, 2012.

[12] Shiffman, D., *Learning Processing : a beginner’s guide to programming images, animation, and interaction.* The Morgan Kaufmann series in computer graphics. Morgan Kaufmann/Elsevier, Amsterdam, Boston, 2008.

[13] Simon, H. A., *The Sciences of the Artificial*. MIT Press, Cambridge, 1981.

[14] Vincenti, W. G., *What Engineers Know and How They Know It.* The John Hopkins University Press, 1990.

[15] Wilkinson, K. and Petrich, M., *The Art of Tinkering*. Exploratorium, Weldonowen, 2013.

[16] Papert, S. and Harel, I., Situating Constructionism. Constructionism, Ablex Publishing Corporation: 193-206, 1991.

[17] Doorley, S. and Witthoft, S., *Make space: How to set the stage for creative collaboration*. John Wiley & Sons, 2011.

[18] Neidlinger, K. and Dertien, E., TEI 2015 Studio *Interactive Inflatables: Amplifying Human Behaviours*. Tangible and Embedded Interaction, 2015.