Observations on Tinkering in Scientific Education

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Abstract In recent years in arts, technology and science there appears an increasing push to use technology and design in a more personal and autonomous context, integrated with the physical world. Creative platforms are developed that open up personal digital/physical technology to larger groups of novice tinkerers, allowing people to take control of technology and prototype solutions to personal problems and aims. Likewise, education benefits by providing students with tools and platforms to learn by doing and making. However, these advances lead to new challenges for scientific research and education. In this chapter we explore some of the opportunities and challenges and summarize these into key observations. Particular attention is given to tinkering in research-based education, and the opportunities for digital tinkering in emerging worlds.

1 A return to grass-roots technology development

Many of today's technology heroes and aficionados started their careers by what can be considered as tinkering. Bill Gates and Steve Jobs are well-known examples, illustrated by anecdotes of working in garages with small, enthusiastic teams, supposedly working under playful conditions. For many they exemplify what tinkering and grass-roots initiatives could lead to. But also the Wii Remote tinkering projects by Johnny Chung Lee (www.johnnylee.net), shown on Youtube.com, have captured and sparked the imagination of many.

At the level of today's technology consumer, there appears to be an increasing desire to interface our technological power-machines to the real physical world.

And power-machines they are, our personal computers, tablets and smart phones – equipped with highly advanced man-machine interaction technologies, communication possibilities, location-determining hardware, acceleration sensors, and more. However, for all their strengths and possibilities, they do not offer the connectivity to the physical world around us that many dream of. No smart phone is currently on offer that drives itself around the house to play with the cat. No tablet is equipped with motors and sensors that make it suitable to steer a child's soap-box cart. No current iPhone models have a user-accessible digital thermometer to play with. And in a way, this is what we more-and-more expect our technology to do (well, perhaps not exactly this, but similar things) – to connect our computational devices to the physical world.

This desire to connect may have been always present, but there appears to be more of a push towards closing the gaps between human and technology, by leveraging technology in a more personal, private and autonomous manner, under control of the user.

As a result, tinkering with digital/physical computing systems has gained much attention over the last few years. For example the Wiring (www.wiring.org.co) and Arduino (www.arduino.cc) projects offer immensely popular tools for lower-to intermediate-level software and hardware tinkerers (e.g. [1],[2]), spawning thousands of interesting home-grown projects. Similar projects are Raspberry Pi (www.raspberrypi.org), MaKey MaKey (www.makeymakey.com) and, more in the creative coding domains, Processing (www.processing.org) and OpenFrameworks (www.openframeworks.cc).

These initiatives gave rise to low-cost rapid prototyping tools that offer rich, if not full functionality, while hiding complex underlying structures from the developer. The frequent open-source nature of the projects kindles what is, in essence, a community-like support structure, and the ongoing generation of example code and libraries. All this makes it possible for single medium-skilled developers to master complex (physical) digital prototyping tools.

Observation 1. In recent years, physical and digital prototyping was fitted to the scale of the individual. After years of increasing technological complexity in the systems around us, the right combination of technological abstraction and openness has re-empowered individuals to understand, own and prototype solutions to their own problems and aims. This re-enables grass-roots technological development at a greater scale.

We, the authors, are involved in a creative research-based academic program. In this context we incorporate tinkering with (physical-) digital prototyping tools into our own education. From the above observation, our experiences, and from our interest in scientific education, we present further observations on tinkering in scientific education. Small parts of this chapter were published previously [3].

First, however, the next section will briefly review the etymological, conceptual and theoretical roots of tinkering. Section 3 will touch on what can be learned from tinkering. Both sections focus on the *what*-question before we move on to the *where*-question in Section 4. There we discuss the different contexts within which tinkering can take place and focus on two contexts in particular, academic research education and emerging countries. We then argue *how* tinkering success can be optimized by taking psychological aspects into account, and end the chapter with a summary conclusion.

2 What is tinkering, really?

To understand the roots of tinkering, let's first review the word etymologically, beyond the context of this chapter. Merriam-Webster's online dictionary describes a tinkerer as 'a person who in the past traveled to different places and made money by selling or repairing small items'. It becomes more interesting when we get into the additional descriptions and synonyms, which describe a tinkerer as an 'unskillful mender', and tinkering as 'to repair, adjust, or work with something in an unskilled or experimental manner' with synonyms as 'to fiddle, fool, or mess', to 'play, monkey or toy' and finally as 'to handle thoughtlessly, ignorantly, or mischievously'.

In the context of education these roots contain interesting connotations that relate to several key aspects of tinkering. Firstly, it emphasizes the tension between someone who repairs but is to some extent unskillful. In fact, this aspect aligns with applying tinkering as a tool to learn what you do not yet understand, either in an educational context ("I don't yet have the knowledge") or research context (the knowledge does not exist yet). Secondly, it expresses a notion of experimentation, exploration and playfulness. As such, it occurs in a safe environment where it is not a problem if something fails, as we will have nonetheless learned something. Finally, it mentions the notion of fooling, fiddling and messing around – this aligns with the tinkering notion of re-appropriation, using tools or technologies in unintended ways or fashions to induce different views or create tensions

From a learning theory point of view, a key related school of thought is constructionism, as introduced by MIT Media Lab researcher Seymour Papert, which in turn is linked to constructivism [4]. According to this, learning should not be seen as the transmission of knowledge from instructor to student, but as students learning by doing. It proposes an experiential learning approach in real world settings and contexts, balanced by reflection on this experience to reconstruct and update the conceptual understanding of the world. In constructionism specifically this is achieved by literally constructing prototypes and products.

In a creative science context, the concepts of producer, teacher and student may be somewhat blurred. Imagine an interactive art installation that poses research questions or suggests certain theoretical extensions or conjectures. The creator of the installation can be seen as the student and may have certainly learned something by creating the piece. However, if the installation depends heavily on audience participation and interaction, they are in fact producers or co-creators to some extent, and as such will learn from actively engaging with the work.

3 What tinkering can teach you in science education

The adoption of digital/physical tinkering by individuals, as formulated in Observation 1, has had its effect on science and education. Scientists increasingly use publicly available low-cost digital prototyping systems to create measurement tools and other experimental devices (e.g. [5]). To witness, a Google Scholar query for articles containing the word "Arduino" in their title yielded a result of 490 scholarly articles.[1]

Naturally, developments in science and technology resonate in science education (e.g. [6],[7]) and scientific education (e.g. [8],[9]), although not all experiences are always positive. Tinkering is found in curricula worldwide, and students realized a plethora of projects that are disseminated via the web.

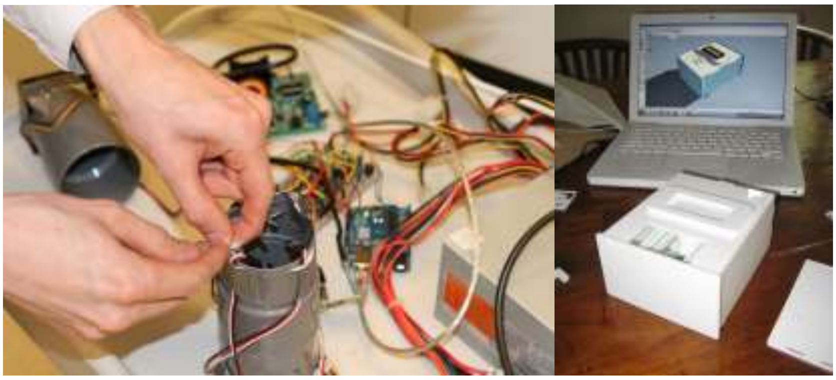

Figure 1. Amplino prototype being tested (left) and mock-up of the imagined final Amplino malaria diagnostic tool (right). Photographs courtesy of Pieter van Boheemen, www.amplino.org.

An example of successful tinkering by academic students that stands out in our opinion is the Amplino project (www.amplino.org), in which students developed a low-cost Arduino-based polymerase chain reaction (PCR) diagnostic tool for malaria. It exemplifies how a current scientific problem (i.c. offering affordable DNA-based malaria diagnosis) can be aided in unexpected ways by student tinkering. Although more examples exists [10], naturally, not all student projects are as

[1] Query result September 2, 2013 from www.scholar.google.com, excluding legal documentation, patents and citations.

successful as the Amplino project. However, they nonetheless have educational value.

Given the technical nature of such projects it is tempting to see this as teaching students certain technical abilities, while allowing them to 'geek out'. However, students also learn about the underlying scientific concepts (education), and occasionally even push the boundaries of scientific knowledge (research). Furthermore, students are trained on a constructionist tinkering approach to problem solving, which is a skill valuable for lifelong learning, also outside educational institutions.

Observation 2. Tinkering projects in education typically strive to teach various technical objectives such as programming skills, understanding of digital hardware, and rapid prototyping skills. However, in addition scientific education may also benefit from the tinkering approach by inducing playful interaction with scientific knowledge, exploration of a problem domain, and solution ownership by students.

4 Tinkering across various learning environments

It is important to realize that tinkering can take place in a variety of learning environments. As an experiential learning approach it is grounded in making learning in educational institutions resemble more the learning that occurs in the real world during one's lifetime. In other words, tinkering can be used as a learning tool all the way from nursery to PhD research. It also applies to environments outside schools and universities. Science museums have adopted tinkering as a means of knowledge creation and transfer. The San Francisco based Exploratorium museum for science, art and human perception extended its vision of playful science education [11] with an in-house Tinkering Studio (www.tinkering.exploratorium.edu). Multinationals are throwing hackathons to encourage corporate tinkering and problem solving, and to improve recruitment [12]. Grass-roots communities form on Meetup.com and other networks around typical tinkering subjects such as creative coding, interactive physical systems and DIY biotechnology.

Observation 3. Tinkering as an educational approach applies across the entire lifecycle of learning, both within and outside traditional learning institutions.

In our case, we are particularly interested in the role of educational tinkering within an academic research-oriented environment. Scientific research is a knowledge-driven activity, geared towards answering questions and generating new knowledge. Although exploration is an important force in science [13], typically scientific research is brought about through rigorous and methodical work, in which the exploratory and playful nature of tinkering has only limited place. The emphasis in science is typically on testing the validity of theories, hypotheses, methods, tools and other scientific end products, as opposed to providing the creative process and tools to discover and generate these. Furthermore, research agenda's may be based on timed delivery of knowledge products, something that does not evidently match the open-ended nature of tinkering. Finally, in research-based education, one may be uncertain how to evaluate the end results of tinkering – should evaluation be based on knowledge discovery, on work methodology, or on aspects of exploration? When to stop tinkering – what is the definition of 'done'?

Unfortunately we cannot offer the reader solutions to these important questions and issues. It is our understanding that these issues must be raised as part of a larger discussion, involving researchers and lecturers from varying disciplines and learning environments. At this moment, we cannot extend our contribution to the discussion beyond observing the need for a discussion.

Observation 4. Aspects of tinkering in research-oriented education require special attention, such as how to combine the open-endedness of tinkering with more fixed research agenda, and how to evaluate tinkering results. Existing insights must be collected and further insight may be developed.

At this point and in resonance with the focus of this book, we would like to address the emerging world as a particular learning environment. Naturally, contrasting emerging countries from their further developed counterparts requires consideration of learning environments along a different dimension than used above – a dimension not spanned by varying types of educational institutions, but by international or interregional differences in economic status and development.

Grass-roots technology development and associated frugal science [10] are relatively independent from economic backing. Although stronger economic embedding makes *any* endeavor easier, if only as an effect of lesser external concerns or more available time, the cost factor of tinkering-based work is less discriminating than that of high-end technological work.

Given this relative independence of funding and the increasing availability of (physical-) digital prototyping tools expressed in Observation 1, grass-roots digital technology development and education are areas in which emerging countries have little disadvantage in comparison to their further developed counterparts, and in comparison to industry and education driven by high-end technology. In particular, youth in emerging markets have growing opportunities to become users and creators of low-cost technology, and to understand, own and prototype solutions to their own problems and dreams.

Observation 5. Low-cost and readily available digital prototyping tools lessen the gap between economically differing nations or regions, with respect to technology development in education and industry. This offers valuable opportunities for the emerging world to strengthen their technological industry, mainly through education.

5 Psychological factors of tinkering success

We have argued in a previous section that tinkering aims to teach students more than technical skills. This implies that, to get the most out of tinkering as a learning tool, non-technical aspects need to be taken into account. Examples of such aspects are the psychological concepts of persuasion, motivation and ability [14]. Essentially, education can be seen as a persuasion problem. To persuade people to actively learn we must ensure that the audience is motivated as well as able to learn. Interestingly, this can be seen both as a precondition for educational tinkering, as well as aspects that tinkering can help realize.

An example of how tinkering could help to overcome lack of motivation for learning would be a science museum targeting children or teenagers. A museum is a less structured learning environment than a school, depending more on the internal motivations of visitors than a traditional school environment does. To this effect, an in house tinkering studio or tinkering installations can increase the motivation as well as focus of visitors, in contrast to more passive, 'instructionist' setups.

To make the point about the importance of ability, let's contrast the above with an academic research context. Apart from differing technical abilities, graduate and doctoral students may have different personality and psychological profiles, which can affect tinkering success in opposing ways.

Take imaginary student A, with a more sensing personality. The student thinks very much in terms of concrete products or pieces, whether more technical or more artistic, and has a clear idea early in the process what needs to be made. A pitfall for this student however, is that tinkering implies one to be able to change direction, when at a conceptual or practical dead end – moreover, sometimes one needs to 'kill their darling' for such change in direction to take effect. A strong practical and perceptual attitude can in fact limit the reflective abilities. Understanding what one aims to achieve conceptually or how what was just discovered impacts one's abstract idea or understanding, is key in a constructionist tinkering approach. Mentoring such a student would be much more focused on stimulating reflection through questioning by instructors or peers and outsiders.

However, the opposite could occur also. Student B can be strong in terms of abstract and theoretical thinking, thereby limiting the ability to become concrete and start creating or changing a product. This could be related to a fear of 'making the wrong choice', either in terms of failing to implement the project aims correctly, or more commonly, the fear of not having chosen the optimal concept to do so. For student B, mentoring strategies could address this by clarifying that it is fine to fail quickly and readjust, as opposed to not trying at all.

Observation 6. For tinkering to be successful as a learning strategy, non-technical psychological factors such as personality, motivation and ability must be taken into account. Different motivational and ability profiles could warrant opposing mentoring strategies.

6 The future of tinkering in scientific education

In this chapter, we explored tinkering as a mode of education from different perspectives. Departing from an etymological view, we moved on to *what* can be learned from tinkering. Focusing next on contexts *where* tinkering can be a valid approach, we mentioned in particular academic research education and emerging worlds. Lastly, we argued *how* tinkering success can be optimized by taking psychological aspects into account. From this informal exploration, we formulated several observations regarding the topic at hand.

To draw extensive conclusions from our exploration would do injustice to its informal nature. Moreover, summarizing the observations appears fruitless, as we trust them to concisely speak for themselves. However, our explorations do lead us to some general comments regarding the future of tinkering in scientific education.

Firstly, it is our position that the value of tinkering has proven itself in scientific education, although this value remains to be quantified. Moreover, there is no reason to assume that this addition of value will diminish over time. Tinkering will remain a productive learning tool for new generations, even though we must not shy away from evolving its scientific results into more rigorous and methodical scientific studies.

Secondly, the observed need for further insight into aspects of tinkering in research-oriented education will not magically disappear. To this end, efforts must be made and extended over the different knowledge domains involved.

Finally, we acknowledged the benefit of digital tinkering for the emerging world. To maximally exploit this potential benefit, we must not accept it for *status quo*, but more actively involve emerging regions in our tinkering developments. In particular we must recognize when groups and individuals from emerging regions have reached beyond tinkering and jointly take up the challenges that they encounter.

May the forces of tinkering be with you.

References

1. Thompson, Clive: Build It. Share It. Profit. Can Open Source Hardware Work? Wired Magazine 16.11 (2008)
2. Banzi, Massimo: Getting Started with Arduino. Make:Books & O'Reilly Media (2008)
3. Lamers, M.H., Verbeek, F.J., van der Putten, P.: Tinkering in Scientific Education. In: Reidsma, D., Katayose, H., Nijholt, A. (eds), Advances in Computer Entertainment, LNCS 8253, Springer (2013) 568–571
4. Papert, S., Harel, I.: Situated Constructionism. In: Papert, S., Harel, I. (eds), Constructionism. Ablex Publishing Corporation (1991)
5. D'Ausilio, Allessandro: Arduino: A Low-cost Multipurpose Lab Equipment. Behavior Research Methods 44(2) (2012) 305-313

6. Dougherty, Dale: Learning by Making: American Kids Should be Building Rockets and Robots, Not Taking Standardized Tests. Slate / Future Tense Article (June 4, 2012) [online resource]
7. Gerstein, Jackie: The Flipped Classroom: The Full Picture for Tinkering and Maker Education. Post on User Generated Education Blog (June 16, 2012) [online resource]
8. Brock, J.D., Bruce, R.F., Reiser, S.L.: Using Arduino for Introductory Programming Courses. Journal of Computing Sciences in Colleges 25(2) (2009) 129–130
9. Jamieson, Peter: Arduino for Teaching Embedded Systems. Are Computer Scientists and Engineering Educators Missing the Boat? Proc FECS (2010) 289-294
10. Reardon, Sara: Frugal Science Gets DIY Diagnostics to World's Poorest. New Scientist 219, issue 2933 (September 7, 2013) 20–21
11. Oppenheimer, Frank: The Exploratorium: A Playful Museum Combines Perception and Art in Science Education. American Journal of Physics 40(7) (1972) 978–983
12. Overfelt, Maggie: Corporations Adopt the Hackathon. Workforce Article (September 12, 2012) [online resource]
13. Doherty, Peter C.: The Beginner's Guide to Winning the Nobel Prize: Advice for Young Scientists. Columbia University Press (2008)
14. Petty, R.E., and Cacioppo, J.T.: The Elaboration Likelihood Model of Persuasion. Advances in Experimental Social Psychology 19 (1986) 124–206