Shareables: Systems for Rapid Prototyping of IoT Devices to Broaden Participation in Engineering Design

by

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Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

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ABSTRACT

The thesis outlines the development of a design activity and toolkit for connected devices, which provide opportunities for social impact through technical creativity. Statistically, girls place higher value on social impact than their male counterparts, while they see less how engineering can have relevant social impact. These two factors contribute to girls tend to losing interest in STEM, often during middle school, so a mindset change is desirable to achieve a motivational and thus educational effect. Creative, innovative engineering activities with perceived social impact may motivate middle and high school girls and build their confidence in their ability to impact people's lives with technology they create. This work tests this hypothesis using different forms of a design activity that enables students to collaboratively build personal and wearable smart devices. Examples of creations based upon this design toolkit include connected medical bracelets, physical activity monitoring and other devices.

Design requirements for intrinsically motivating and engaging experiences are derived from literature and practical examples in psychology, behavior and education research. A creative experience is based on these frameworks and is prototyped to test engagement, attraction, mindset change and other parameters with adolescent girls. This offers new working methods for the human-centered design process around complex systems design. Building on focus group experiments and experience testing, a hardware toolkit is developed, which combines modular sensing devices with a wirelessly connected cloud-based programming application. Sensors include accelerometers, temperature and pulse sensors. A multi-instance implementation of IBM's Node-Red interface is adapted and customized to form the basis of an interactive, audio-graphical program and application editor.

The realization of this toolkit allowed for conducting experimental workshops and for quantifying an increase in participants' self-efficacy and interest in design and engineering as a result of the intervention. A fundamental change in many girls' mindset was observed in multiple experiments with the prototype systems, regarding both creative self-efficacy and engineering perception. Girls who initially thought of themselves as "not creative" were able to contribute viable, innovative ideas when they were introduced to the toolkit concept. Once equipped with adequate tools, ideas could form and come to surface.

An important finding from experimental workshops was was that even girls with extensive prior STEM or coding experience showed a significant increase in their self-efficacy in using technology for social impact. The opportunity to impact a range of personally relevant areas adds purpose and meaning to existing skills. In the same experiments, interest in an engineering career also increased to a significant degree. In a separate analysis, the effect of instruction style on self-efficacy and motivation is investigated. It is shown that it is critical to encourage participants to reflect on the social impact of their creation in order to convey a relevant real-world experience ("I enjoyed it because I made something useful").

Based on workshop findings, detailed feature requirements specific to the toolkit are identified and implemented over multiple iterative design stages.

A web platform that allows students to share, collaborate on and interact with each other's projects is developed to provide means for long-term engagement beyond the experimental workshop settings.

This work contributes research methodology for quantifying the success of motivational interventions. Observed sensitivities and input gathered by participants inform design principles for similar educational experiences.

Thesis Supervisor: David R. Wallace
Title: Professor of Mechanical Engineering

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This doctoral thesis has been examined by a committee of the Department of Mechanical Engineering and the Department of Comparative Media Studies and Writing as follows:

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Chapter 1

Introduction

In the light of recent breakthroughs, both technological and societal, this work could not be more timely. A brief overview will provide context for understanding the setting in which this work was created.

1.1 Background

My high school education at a technology-focused school provided me with great exposure to engineering. But throughout my teenage years, I had little opportunity to experience my skills as *socially impactful.* Certainly, my teachers gave me positive feedback on skills I gained and tasks I completed, but nothing I created was truly useful to anyone in a way I could appreciate. I felt I knew what engineering is and which tasks are involved; and I perceived myself as sufficiently skilled to become an engineer, but I did not perceive engineering as *relevant* to my life or that of anyone around me.

Planning my career during that time, like so many others, I knew I wanted to work with people and impact the world around me. I consequently picked a business major in college. But a year into my college degree, during an internship, I had a key experience that changed everything. During a summer job at a German precision parts factory, I programmed the control system of an inspection machine (using tools I had been taught to use in high school). This machine dramatically improved my co-workers' jobs and earned the respect of all supervising engineers. This experience entirely changed the way I saw engineering. From one day to the next, there was a purpose to engineering. Suddenly, the little fears I had, that it might be dominated by guys or that industry might be requiring different skills than those in which I had proven myself in school, were no longer important. As quickly as I realized this, I pivoted in my career path and started over in college – this time majoring in mechanical engineering.

It is the recognition how critical this experience of social impact was and the desire to package it in a way that is accessible to middle or high school students, that was my driving force in this dissertation.

1.2 Problems Addressed

1.2.1 The need for real-world impact to engage girls in STEM

It is the year 2017. Inequalities in our society are still deeply unsettling. While the socio-economical divide is rooted in the mechanisms of capitalism, which has in turn enabled our economy's sustained overall prosperity, another divide seems to be purely cultural and resist the groundbreaking shift in women's role in society: technical fields have been and are still predominantly male. To help solve these educational challenges, the US government has allocated $3 billion of the 2017 budget to support STEM education [1], but still, computer science classes and STEM after-school activities remain dominated by boys.

US national statistics show that many girls' see their grades in math and science fall behind boys' between grades 6 and 8 [2]. This can be seen as a symptom of a deeper problem. And it has been known that this happens at the time in life, when girls' self-perception changes significantly and, consequently, their interest in science and engineering drops compared to boys [2], [3]. A recent study in the Chicago area found that in middle school, only 27% of girls consider a career in tech, and this number drops to 18% in high school – compared to 47% of boys [4], [5]. Once they fall behind, girls statistically underperform in STEM subjects until they reach college, where they overwhelmingly choose non-STEM majors [6].

By contrast, girls are interested in real-world impact, often with a social connection, and technology becomes more interesting with "purpose" [7]. For example, if a female student chooses a certain career path, the aspects she takes into account tend to be associated with people or broader humanistic concerns [8]. Similarly, if technology is introduced as a means to an end, e.g. communication or tool for creative work, girls may be as likely to adapt it as boys [9].

It is argued that girls' motivation and excitement for engineering activities can be triggered if certain requirements are satisfied, using technology thus far underutilized in the education space.

1.2.2 The Need for Broader Participation in the Innovative Process

As engineering has been a male-dominated occupation [10]–[12], history offers plenty of examples of products that were built for male users and underserved other groups of the population.

The first ever car airbag system protected tall, heavy passengers, while women and children were at a severe risk [13]. And not just the lack of female engineers is to blame. While airbags became compulsory in the nineties, it was not until almost 20 years later that they were properly tested with female statue dummies. Only in 2008, the US Department of Transportation updated their standards to use female dummies on the passenger seat in crash tests starting with model year 2010, taking into account mixed perspectives from automotive companies [14]. Among the considered comments, GM presented evidence that women occupied the passenger seat frequently and got injured worse in accidents. Car front safety ratings generally decreased as a result to the legislative change [15]. Moreover, studies determined a 20-40% chance of serious injury or death for a woman using a design that tested fine for men [13]. And by the time this legislation was passed, many women and children had died in airbag-related accidents, often at very low speeds, when the airbag deployment might not have been necessary. A study at the University of Virginia found seatbelts put women at a 47 to 71 percent higher risk of getting seriously injured in an accident than men in a comparable accident. The reason for this discrepancy: Not only are women smaller, placing their chin where an airbag might hit them, but also their necks are less muscular, potentially leading to spinal trauma and brain injuries as a result of sudden deployment of an airbag [16]. Asked by ABC News why car makers did not take the female physiology into account when testing vehicles, Dr. David Lawrence, director of the Center for Injury Prevention Policy & Practice at San Diego State University, replied: "Manufacturers and designers used to be all men. It didn't occur to them they should be designing for people unlike themselves" [16]. This attitude certainly runs contrary to any human centered design philosophy.

And still today, seat belts are often uncomfortable to pregnant women [17], and may, in rare cases, lead to the loss of the unborn child in case of an accident [18]. As a result, pregnant women in the United States often choose not to wear a seatbelt, putting themselves and thus their unborn child at greater risk [17]. This highlights just how important empathy is in the design process.

Another example is early speech recognition, which had problems recognizing higher-pitched voices and accents, and still does, for example in the automotive space [19]. In some cases, contrary to any human design philosophy, engineers may not see the problem in the system, but rather in the user. ATX Group's VP of voice recognition was quoted saying: "Many issues with women's voices could be fixed if female drivers were willing to sit through lengthy training …" to essentially learn to speak like a man [20]. In an anecdotal story, a friend experienced that it helped to imitate a German accent with his BMW 5 series from the early 2000s, since the brand new infotainment system had trouble with his American English. While all sorts of English accents are available for computer-generated text-to-speech voice output [21], the recognition of spoken words in those accents has been a struggle [22].

Breakthrough innovation is often designed for the majority user, while minorities' needs remain unaddressed. In many cases, a product's main design target is the majority user, but the design is improved as soon as minority users' or extreme users' opinions are taken into consideration. For example, users in the developing world have been found to identify otherwise unidentified needs of users in the developed world, thus acting as lead users [23]. And it has also been shown that a more diverse design team improves overall problem solving skills, i.e. diversity trumps ability [24], [25].

In many cases, however, individual needs are exclusive to a small market, which may not justify an investment, such as specialized sports or hobbies. If we want to serve those minorities, we have to reduce the investment that is required to develop new technology.

To open up the engineering space and invite diverse groups to participate and contribute to innovation, a new set of technologies and components can be employed. These have become widely available and accessible and they are the basis for a range of novel products with varying utility, which are suitable for versatile applications.

1.3 Enabling Technologies

A number of developments have taken place in the past years that have made certain technologies more accessible than ever before. Micro-processing devices, sensors and computers have never been so available, so connected, so compact, and so affordable.

1.3.1 Ubiquitous Connected Technology

Some of us remember a time when phones and computers were the only way to reach people far away. And a few may even remember a time when a phone had to be plugged into the wall to work.

We have come a long way from then. We have seen the development of cell phones, which now have more computing power than early rockets that brought men to the moon. We developed Bluetooth, a wireless protocol, and connected hands-free speakers to cell phones and keyboards to computers. Today, our home thermostat connects to the internet through our home Wi-Fi and it can be connected with a mobile app. The same is true for our home security systems, bathroom fixtures, kitchen appliances, and home entertainment system. The adaptation of wireless technologies has increased dramatically and over the past years, a new term has emerged to capture this development: The Internet of Things (IoT). It captures that many of the newly added, connected devices are simple, low-cost, ubiquitous items, far below the computing power of what was previously though to justify the investment of internet connectivity. More and more connected devices can be seen in every aspect of life. A growth prediction is shown in Figure 1.1.

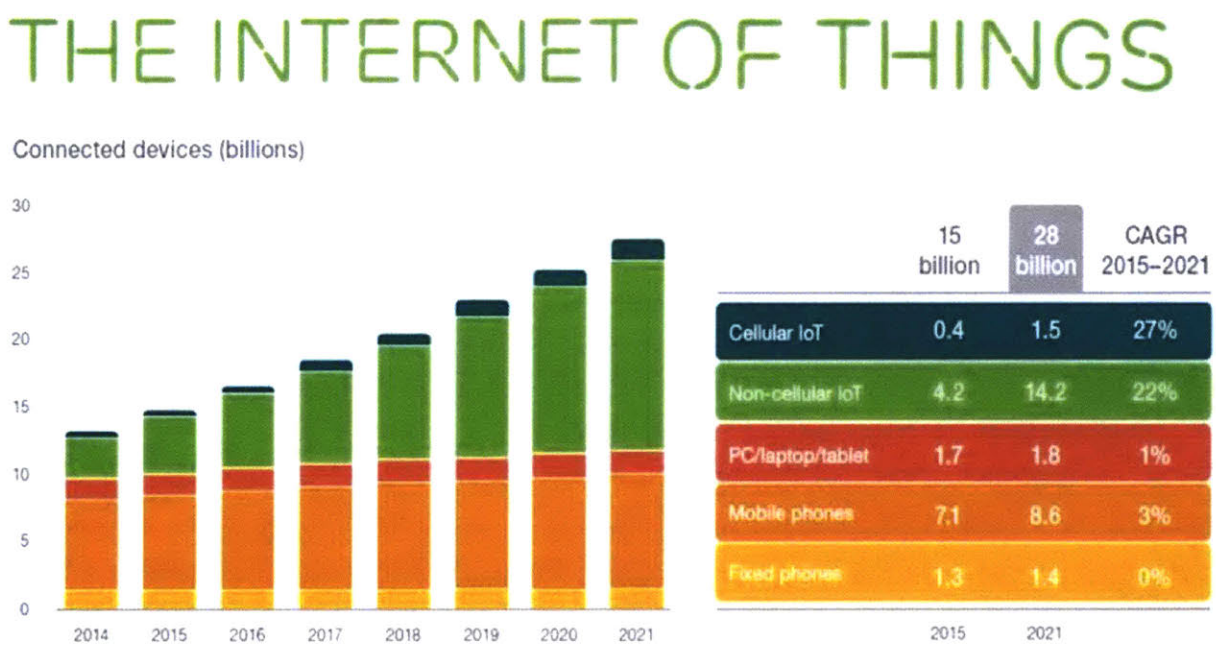


FIGURE 1.1: The number of connected devices is expected to reach 28 billion by 2021 [26].More than half will be IoT devices, including wearable devices, connected household devices and connected vehicles.

According to Janusz Bryzek, former VP at Fairchild Semiconductor, the following factors have fueled the growing interconnectivity of digital devices [27]:

- The most recent IPv6 protocol enables an almost unlimited number of devices connected in a network
- Major network providers have decided to provide additional layers (Fog layer, Swarm layer) to networks
- Market opportunities on the order of ≈ $10 trillion, such as industrial internet, make investments into connected infrastructure worthwhile

This allows for an ever-more interconnected world. New products are designed for all areas of life, industry and the bigger economy (see Figure 1.2). As component prices shrink, more and more applications become worthwhile for innovators and developers.

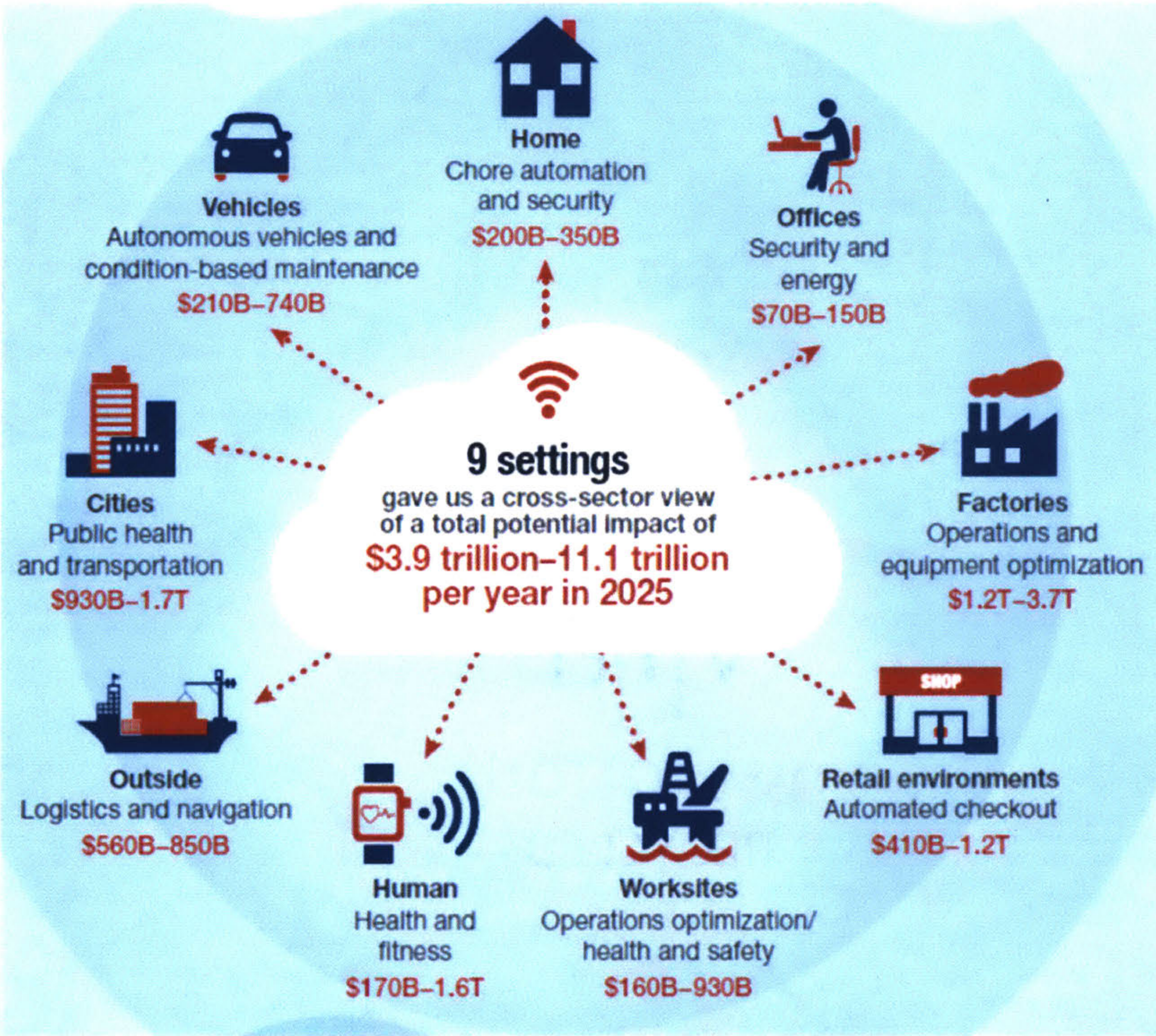


FIGURE 1.2: Forecast market potential of various areas, in which Internet of Things applications may be used to solve problems [28].

To list just a few developments of the past, the figures illustrate applications in the home (Figure 1.3) and the retail environment (Figure 1.4).

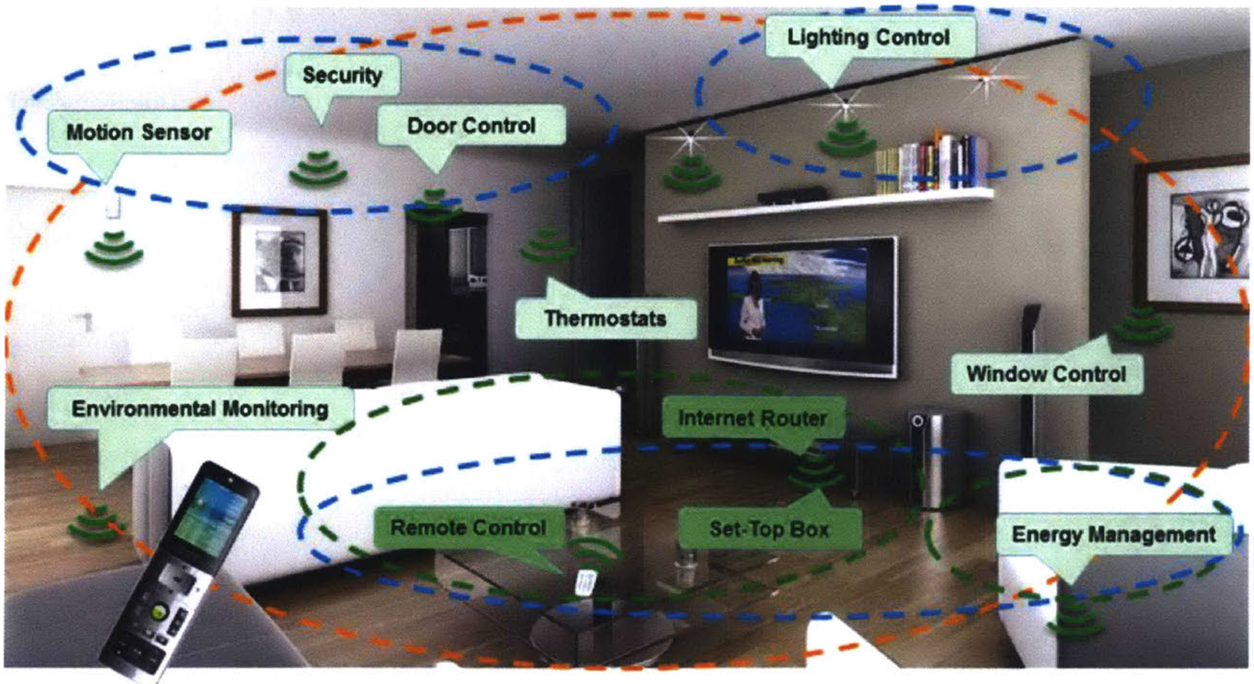


FIGURE 1.3: Connected devices throughout the home [29].

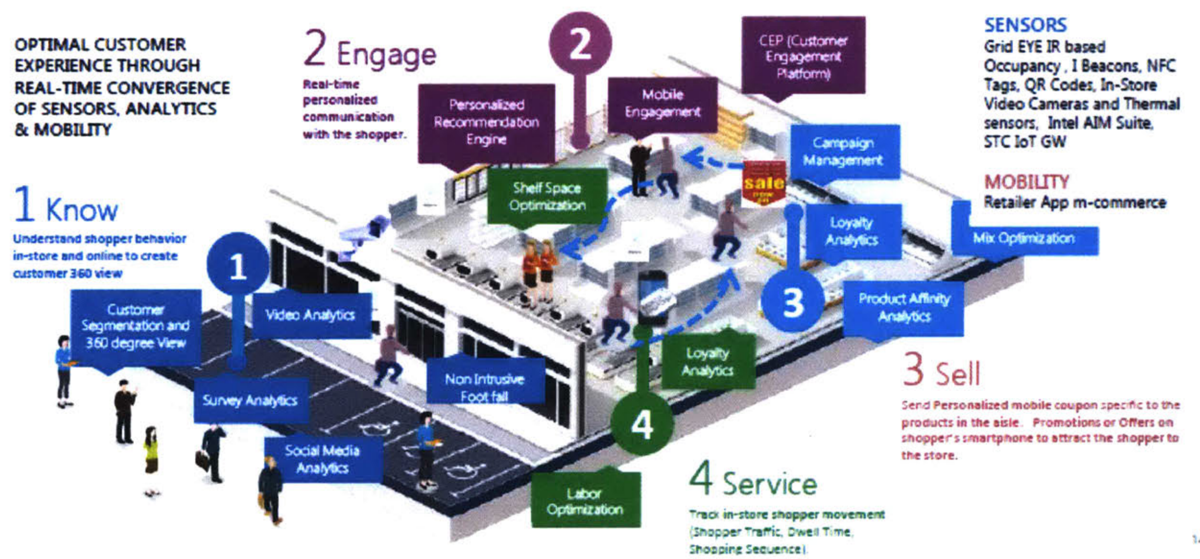


FIGURE 1.4: Connected "smart retail" environment [30].

1.3.2 Ubiquitous Sensors

What makes the growing interconnectedness so useful is the growing availability of sensors. With advancing technology, prices of components have been falling (Figure 1.5), while the reliability and ease-of-use of sensors has improved. Whereas heart rate monitors and blood oximeters used to be pricy medical devices in the past, they are now part of every-day devices, to which we all have access. Thermometers are now digital and connect with the cloud[1]. Hobbyists can acquire sensor breakout boards and download open-source driver libraries for their microcontroller project. Thousands of sensors are available today and they differ widely in cost, size, precision, bandwidth, robustness, integrated processing ability, and cross-platform flexibility.

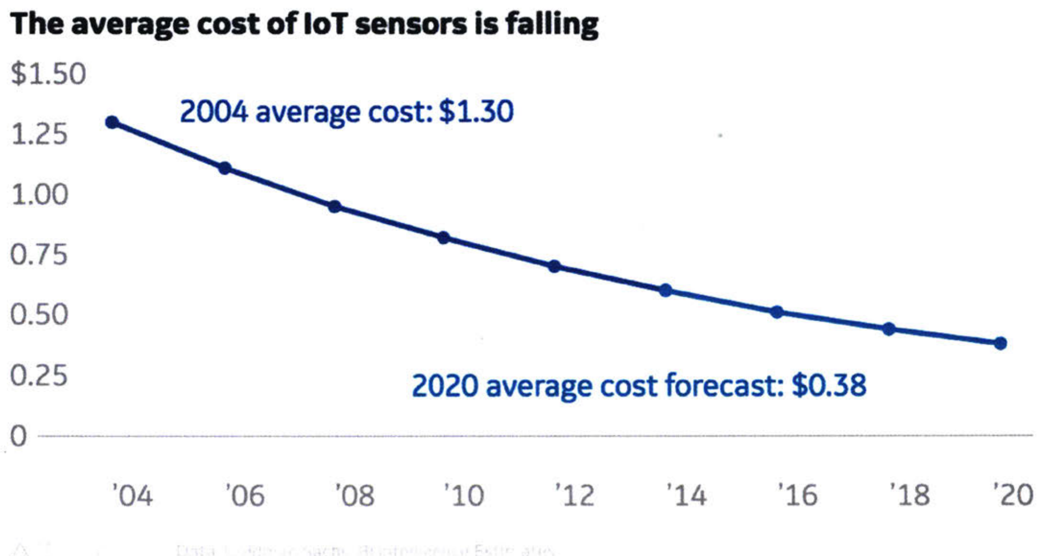


FIGURE 1.5: The falling cost of sensors [31]. Data: Goldmann Sachs, BI Intelligence Estimates.

Common sensors include microphones, acceleration sensors, light sensors and various optical sensors, hall effect sensors ("compass"), thermometers, humidity and water sensors, force and pressure sensors, oxygen sensors, various chemical detection sensors, electrical current sensors, air flow meters,

[1] The "cloud" generally refers to an internet-connected remote server that is used to collect or process data.

gyroscopes, proximity sensors (optical, acoustical etc.), tachometers, and GPS sensors. A great number of sensors are designed for specialized industrial and scientific applications.

1.3.3 Wearables and Other Smart Devices

Among the many applications of wireless, connected sensors, there is one that is particularly noteworthy, which is body-worn sensors. So-called wearable devices, or wearables for short, open up the arena for a plethora of health-related as well as personal products. Even sub-medical-grade sensors can help detect serious conditions if they track the wearers' every heartbeat over days, weeks, months, even years. The advances are enabled not only by an increasing availability of sensors and low-cost, ultra-compact wirelessly connected embedded systems, but also by the low power requirements of many of such systems today, as well as compact batteries with high energy density that can power such devices for an extended period of time. In summary, it is easier than ever before to shrink an environmentally aware, self-contained computing device in size and deploy it where gathering data is immensely interesting and useful.

As a result, the number of wearable devices in the United States in predicted to grow, as shown in attached Figure 1.6.

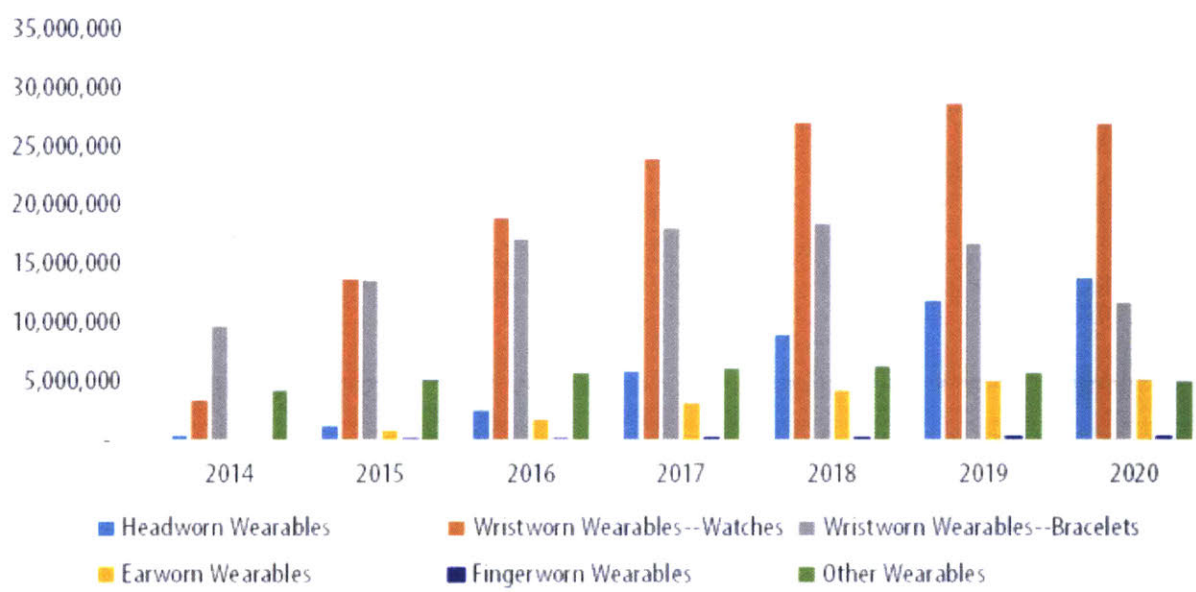


FIGURE 1.6: Forecast of the US wearable electronics market [32].

It can be seen in the figure than wristworn devices are expected to contribute the majority to the number of wearable devices, even for the foreseeable future. This is in part due to social acceptance of wristworn devices, which often resemble a watch, a fairly common accessory.

While smartwatches and activity trackers have been the most well-known types of wearable electronic devices, there are a great number of applications in other areas, for example in industry.

Some examples are shown in Figure 1.7 and Figure 1.8.

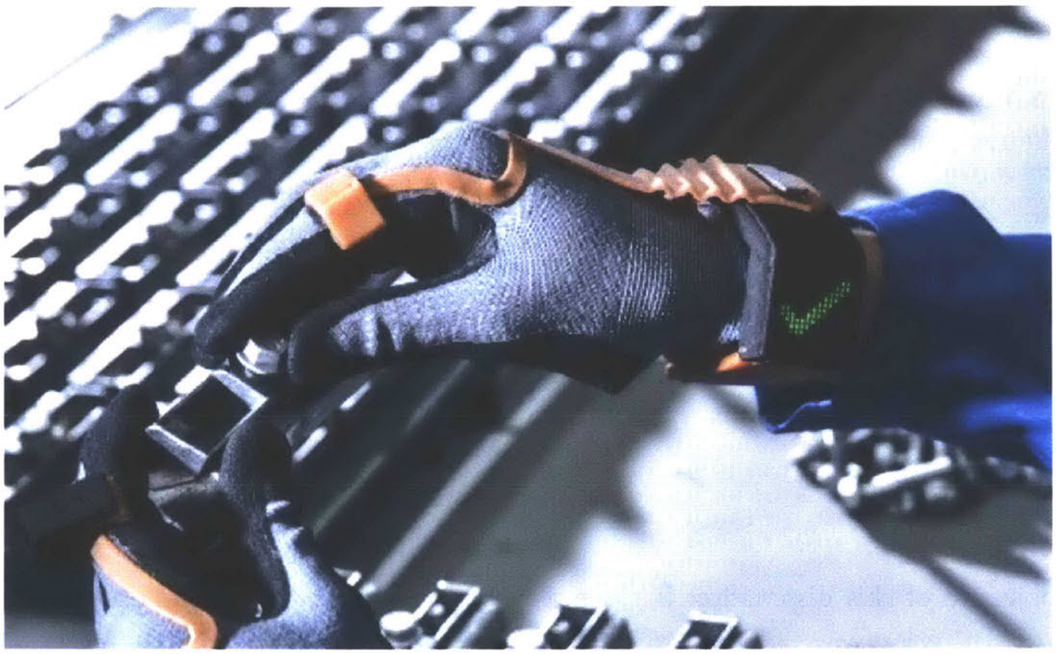


FIGURE 1.7: ProGlove, a wearable for industrial use [33]. It combines an RFID sensor and various other sensors for workflow control.

FIGURE 1.8: Smartwatches can be configured to alert workers in various work environments. (Use case by Bittium, Finland [34]).

But also applications in healthcare and personal hobbies have allowed designers to contribute smart devices for tracking, communicating, benchmarking, motivating (via "gamification"), and many other uses. The variety of designs and the breadth of possible applications make this an especially interesting space for broadening participation in the design process.

1.4 Outline

The objective of this dissertation is to employ a systematic approach to creating educational experiences in design and engineering for a specific user group; and the technical implementation and experimental evaluation of such a solution.

Chapter 2 will give an overview of behavioral and motivational considerations and present other literature addressing other creative learning experiences. Chapter 3 documents the qualitative investigation of user needs, introduces a concept for an educational device system, and presents two very different studies used to refine this concept. Chapter 4 details the implementation of the conceptual education device system as a customizable wireless sensing device system and suitable curriculum. Chapter 5 provides qualitative and quantitative results obtained in a number of experiments based on these educational tools and methods presented in Chapter 4. Chapter 6 discusses the findings of Chapter 5 and derives generalizable results. Chapter 7 puts these findings into a wider context and explores possible future avenues for deployment. Chapter 8 summarizes contributions of this work to the education field, to design and engineering, and to broaden participation in innovation.

Chapter 2

Psychological Frameworks

A brief overview about girls' standing in STEM education was given in the preceding chapter. In the following, different educational aspects are considered that will inform the creation of a novel solution in this space.

2.1 The Psychology of Motivation

Learning is not merely the convection of content, but it also entails a shift in mindset. Learning is only possible with engagement, motivation, and an open mind. Motivation is deeply linked with one's desire to learn and one's ability to learn [35], [36]. Motivational dimensions like contextualization and autonomy dramatically increase students' engagement, content retention, amount of learning per time, and levels of aspiration. Motivation is part of learning; and given that STEM resources have been available equally for boys and girls for some time, while participation still differs, an unintentional imbalance in appealing to learners' motivations may be the main barrier to equality in STEM education.

The following literature review will provide a brief overview of findings in behavioral, social and educational psychology, particularly to what makes activities engaging and motivating; and of related findings specific to girls' perspectives on STEM education.

2.1.1 A Short Introduction to Intrinsic Motivation

What makes people want to engage in a particular activity? Generally, psychology distinguishes two different categories: Intrinsic motivation and extrinsic motivation. Extrinsic motivation encompasses things we may not truly want, but that others make us do: For example, when we get paid or when we may get punished. Intrinsic motivation, however, is the motivation of "free will", when we genuinely enjoy an activity.

2.1.1.1 Factors Enabling Intrinsic Motivation

Researchers have extracted a set of attributes that make a particular activity intrinsically motivating. Lepper and Henderlong [37] find that important factors are: challenge, curiosity, control, and context.

- *Challenge*, or rather "optimum level of challenge", means a task can not be too easy or too hard. That usually means the challenge level should increase as someone becomes more skilled and more confident.
- *Curiosity* describes that someone should be able to learn new things and be able to go in different directions.
- *Control* means that people always want to feel in control of what they're doing, both free to choose and feel capable of.
- *Context* requires that an activity be relevant. This includes alignment with cultural, parental, peer, school and community attitudes.

Ryan and Deci [38] find three innate psychological needs: competence, relatedness, and autonomy. These make an activity "self-determined", which increases intrinsic motivation.

- *Relatedness*, similar to *context*, is based on relationships and culture.
- *Autonomy* means someone is free to choose and to direct their activity, similar to *control*.
- *Competence* describes that one feels competent to achieve a task. *Perceived competence* is also known as self-efficacy [39].

Summarizing the terms used in literature: To make an activity intrinsically motivating, students have to (1) feel in control and free to choose their own way to achieve different tasks, (2) see the activity as relevant to their socio-cultural value system, and (3) be confident that they have the competency that is required to achieve the different tasks.

2.1.1.2 Perceived Competency: Self-Efficacy

Self-efficacy describes and individual's beliefs about their skills and abilities necessary to execute a specific task or solve a specific problem in a given context [40]–[42]. This perceived competency determines students' activity choices, how much effort students will put into a task before giving up, and how easily students get frustrated [42]. It thus predicts students' future behavior and career choices [43], [44], making self-efficacy a very important parameter.

Self-efficacy beliefs are influenced by past performance, teacher feedback, and observing others [42]. By its nature, self-efficacy is always subjective and context-specific.

2.1.2 Why Girls Leave STEM

It has been shown that girls' grades in math and science fall behind boys' between grades 6 and 8 [2], a time in life when girls' self-perception changes significantly and, consequently, their interest in science and engineering drops compared to boys' [3]. Studies have shown that show self-efficacy diverges between boys and girls at this time and that, among other factors, to build up self-efficacy at the same rate, girls require more encouragement than boys [45]. Once middle school girls fall behind, girls statistically underperform in STEM subjects until they reach college, where they tend to choose non-STEM majors [6], [46].

Engineering challenges sometimes appear intimidating or irrelevant to many girls [47]. By contrast, "social" and "medical" areas are more important to girls at that time [48].

Social media like Instagram, Snapchat and other apps are very popular among the teen demographic, especially among girls [49]. As these mostly graphical apps require users to manipulate a number of elements to compose any work they share, it may be argued that they trigger girls' creativity. As can be concluded from girls' tendency to move away from technical subjects, most established approaches to engineering and STEM education may not meet their needs.

2.1.2.1 Perceived Cultural Expectation

Meece and Courtney [50] find that individuals who feel strongly about gender identity value achievement higher for activities they perceive as appropriate for their gender. Math and science in particular are perceived as male domains [51]. To let all girls partake in the opportunities presented by STEM, these fields must be presented in a way supported by their gender value system. Female stereotypes typically encourage girls to "be communal (e.g., socially skilled and helpful)" and "gravitate toward activities that emphasize interpersonal relationships." [52] Furthermore, at an age when boys still play, girls are more concerned with social relevance, partly manifested in aesthetics [53]. A survey conducted by Girl Scouts of the USA of boys and girls at ages 8 to 17 indicates girls are more likely than boys to aspire towards altruistic goals, like helping others, helping animals and the environment, making the world a better place, and being nice to others [54]. Social context and purposefulness an especially strong motivator for girls [55], [56].

2.1.2.2 Fixed Mindset and Growth Mindset

Dweck [39] attributes teenage girls' statistical underperformance in STEM fields to their greater fear of failure, which comes about by how they are treated as children. Simply put, boys tend to be praised for their efforts, for trying and taking risks, while girls tend to be praised for outcomes or state of being (implying an absolute measure). Dweck [39] finds that girls disproportionately grow up with a fixed mindset, i.e. they are more afraid to fail than boys and they blame a fixed set of skills if they do (versus seeing failure as a growth opportunity, which Dweck calls a growth mindset). Notably smart and intelligent girls that behave well as children tend to be praised for being "smart", an absolute label they might loose if they said or did something that may not deserve it. As a result, they let boys get their hands dirty and let boys have all the fun and learning opportunities. Dweck finds this especially limits their performance in math and sciences: "in junior high school, these girls traditionally have begun to fall behind their male counterparts in achievement, especially in math and science achievement" [39].

2.1.2.3 Competition versus Teamwork and Collaboration

Collaborative experiences in math and engineering projects have been shown to increase girls' confidence, interest, and aspirations in the same fields [52], [57]. The correlations between individual and peer interest in STEM and increased interest in collaborative environments that impact girls were notably absent in teenage boys [57], [58]. Halpern [59] and Wang [57] also find that "girls appear to respond more positively to math instruction if it is taught in a cooperative or individualized manner, rather than a competitive manner, and from an applied/person centered perspective, rather than from a theoretical/abstract perspective" [57]. Lavy and Sand [60] present similar conclusions. Moreover, girls are more likely to take advanced science and math classes in high school if their female friends have performed well in the same classes [52].

2.1.2.4 Key Factor: Perceived Social Impact

In fact, purposefulness has been shown to be a critical factor for making engineering attractive to girls. Margolis, Fisher and Miller find girls are not interested in learning about computers if they don't see a personal application, whereas boys are curious to learn how they work [7]. While relatedness is a motivator for both boys and girls [38], [61], this relatedness requires social context for girls, while for boys an engineering context is often sufficient. Medical or social applications are especially interesting to girls [48]. In a comprehensive study with over 3000 individuals, the National Academy of Engineering (NAE) determined that while it is more important to girls that a potential career path "can have a positive impact on people's lives", it is also less obvious to girls than it is to boys that engineering "can have a positive impact on people's lives" [62]. The findings are shown in Figure 2.1. Together, these two factors contribute to girls losing interest in engineering. Thus it is critical to present engineering as relevant, socially rewarded, and meaningful.

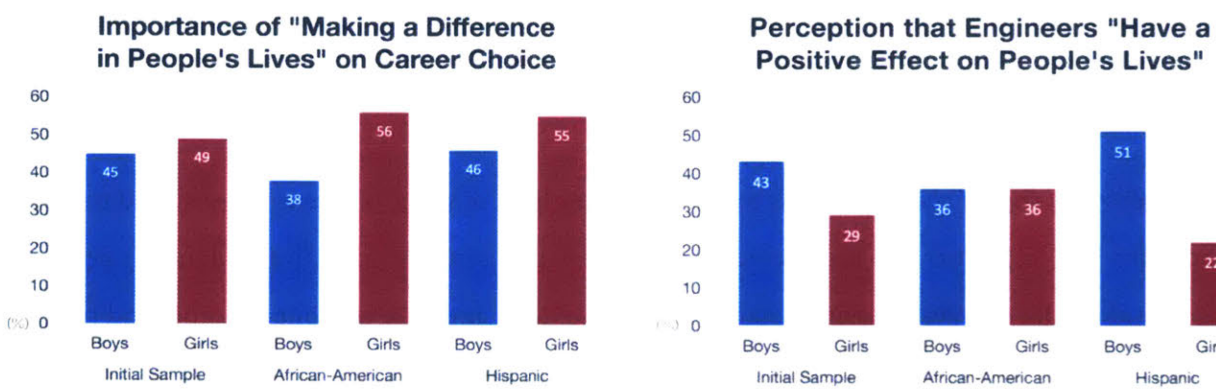


FIGURE 2.1: Teen girls' desire for social impact vs. their perspective on engineering. This was shown to be the most important factor for girls when compared to boys among: availability, difference, challenge, salary, recognition, and prestige. Data from [62].

Social impact is not just important to girls, but to many young individuals in general. Also from a generational perspective, Generation Z, those born between the late nineties to the early 2010s (exact definitions differ), places at least as great a value on social impact as Millennials [63], [64], also known as Gen Y (mid-1980 to late nineties), a generation that was much more socially driven than Generation X (mid-1960 to mid-1980s). At the same time, identity tends to be less constructed by gender among many individuals of Gen Z, who grew up more open to fluid gender identities than many of their parents [63]. Therefore, it is paramount to present STEM careers as socially impactful.

2.1.3 What Makes an Activity Engaging

Fredricks, Blumenfeld and Paris identify three requirements for sustained engagement in education: relatedness, autonomy, and competence.

Relatedness is based on relationships and culture. It builds on students' need for feelings of belonging, i.e. feeling valued, included, and encouraged.

Autonomy describes students' freedom to make their decisions and do things for personal reasons as opposed to external control.

Competence is based on a sense of control and capacity, meaning students know which actions will make them successful.

Csikszentmihalyi [65] defines requirements for creating a "flow experience": direction, immediate feedback, and an optimum level of perceived challenge.

Direction or structure gives people a sense of progress, i.e. it is clear what to do to succeed and to make progress.

Immediate feedback provides a closed loop, so it is always clear what is happening and progress is visible.

The *perceived level of challenge* needs to grow with the level of skills, between too easy and too hard.

Schaffer [66] rephrases the requirements for flow experiences as: high (but balanced) perceived challenges and skills, always knowing what to do, how to do it, and how well one is doing, and freedom from distractions. Schaffer also cautions from overusing extrinsic motivators (e.g. in gamification) and instead advises to "engineer intrinsic motivation" and get users into a flow [66, p. 9].

To provide an intrinsically motivating learning experience, it was shown that it is important to give learners the freedom to take ownership of the learning process, to adapt their learning to individual contexts, and to provide variable levels of challenge. The following educational approach addresses these requirements outstandingly well.

2.2 Constructionism: Education Through Creative Freedom

A number of STEM learning experiences can be described as "constructionist" learning activities. The term *constructionism* was coined by Seymour Papert, who used it to describe experiential learning through the creation of meaningful products by using a designed set of materials to achieve an educational goal in the learner [67]. Constructionism is thus a form of "learning through creating" and sometimes presented as a process comprising the four steps: making, personalization, sharing, and reflection [68]. It is based on both Jean Piaget's and Lev Vygotsky's ideas about constructivism, a form of learning where knowledge is not merely transferred but achieved through individual experience and discovery [69]–[72]. Sherry Turkle has contributed to the idea of constructionism with her concept of evocative objects, meaning physical objects that are endowed with meaning through the creative process [73].

Papert states that "traditional education codifies what it thinks citizens need to know and sets out to feed children this 'fish'," whereas letting children program and build objects for themselves, they are empowered to "catch the fish" for themselves [74, p. 139]. By tinkering on their own terms, learners can explore what is important to them, and learn engineering principles behind objects and functionalities they are particularly interested in. This, in turn, encourages ownership of one's learning and a further quest for gaining knowledge on one's own.

Sherry Turkle adds a tangible-object-based approach to the constructionism Papert discusses. Constructionism generally results in ownership of objects meaningful to the constructor. However, Turkle believes that focusing on the tangibility of objects specifically creates a special world of reflection, wherein these possessions become "goods-to-think-with." Her work on meaningful objects is reflected in the framework for ownership, integration and sharing - and thus for identification and meaningfulness - that was envisioned in this dissertation [73]. Turkle emphasizes the usefulness of material objects in this playfulness with creating ideas that are emotionally and personally meaningful. The work presented in this thesis is intended to do just that: give users the opportunity to personalize and create new, creative functions through a tangible platform.

Resnick and Rosenbaum [75] have developed guidelines for "tinkerability" in construction kits, acknowledging Papert's [74] and Turkle's [73] principles around constructionism, which will be discussed in more detail in the following chapter. Central characteristics are the user: is never left in the dark; can start playing without prior training, and; can explore various applications. They give examples for such kits, but do not qualify a desired or expected learning effect. Although not explicitly stated by the authors, fulfilling their design requirements provides a flow experience with continuous user engagement [65], individual relevancy [76] and relatedness, creating an internally motivating activity [38].

2.3 Prior Art: Modular Technology in Education

With national support for STEM education [1], [77], [78], a number of learning experiences have been developed. Some of these studies have targeted girls or focused on collaborative STEM learning. Interestingly, the following projects were largely developed by researchers affiliated with the MIT Media Lab. These projects are worth mentioning as they illustrate the novelty and innovation of the presented approach.

Scratch is an online platform meant to make coding a fun and social experience for kids. Users can register for free and create animated movies or games online, which can be viewed or played by other Scratch users and the public. In contrast to Scratch, the similar platform ScratchEd can be played on iOS devices, but the developers of Scratch are currently working on a mobile version of Scratch to allow kids to use Scratch on tablets and other devices.

The creators of Scratch attribute its success to four pillars: Projects, Passion, Peers and Play [79].

The "projects" pillar refers to the iterative nature of Scratch and the "creative learning spiral" of imagination, creation, play, sharing and reflection. No matter how brief their creation is; the implementation of Scratch allows them to share it with the community. Any interaction with the platform creates a result that is in some way functional, making it very satisfying to use.

The "passion" pillar refers to the range of genres that kids can interact with through Scratch. Similar to Brophy's relevancy idea, kids are able to tell stories about anything of importance to them.

The "peers" pillar is reflected in the community that defines Scratch and the ability to share and discuss creations on the website. In fact, kids often say that what they like most about Scratch is the community.

The "play" pillar refers to the experimental and exploratory nature of Scratch. Kids are encouraged to tinker and experiment and remix projects. Also, they can check a "draft" checkbox when they publish their project, to tell others that it is work in progress. (Anticipating the product framework developed in this dissertation; similar features are now possible in the online community presented in chapter 7.3. Moreover, value is added by allowing online users to add "collaborators" and thus make online project publishing a team experience.)

Little Bits (www.littlebits.cc) offers a range of electronics toolkits with magnetic connectors, which encompass various signal-processing elements. An online community allows users to share projects and not just share the results, but also the creation process, a strategy that Little Bits found very useful for ensuring hardware projects are communicated well. Kits start at $99 and are themed for music and other applications. Although the kits were shown to generally lower barriers to entry into electronics experimentation [80], motivational dimensions have not been examined and detailed user demographics are not available.

MaKey MaKey (www.makeymakey.com) is a board that is recognized as a keyboard by computers, which allows users to access it within Scratch projects. Many games that use the MaKey MaKey are shared on the Scratch platform. The kit facilitates exploring conductivity properties of various materials, so its simplicity and accessibility make it interesting to use even for a very young audience [81].

Circuit stickers (www.chibitronics.com) are another approach to combine electronics with familiar materials and thus lower barriers to entry, while providing a broad range of possible applications [82].

Jewelbots (www.jewelbots.com) is a reprogrammable bracelet that was created in 2014 to raise girls' interest in programming [83]. Limited research is available exploring its educational results. The device does not have sensors but can be programmed to light up and vibrate to notify the user about online events. The limit of sensors will likely limit its applications, so especially older girls may find it difficult to design something that appears "purposeful" to them with Jewelbots.

The LilyPad Arduino is focused on e-textiles [84]. Connecting electronics with fashion, it creates a similar learning experience. It entails sewing with conductive yarn and does not provide a simplified programming interface. It may very suitable for a more advanced audience with an interest in fashion and technology, e.g. girls who enjoy creating or decorating fashion and may already have initial familiarity with electrical engineering.

Furthermore, a number of workshops have used the materials previously presented or other materials to teach youth or specifically girls about engineering. For example, "Learn to Teach, Teach to Learn" and "Science Club for Girls" run workshops on a regular basis. Some workshops may be centered around creating wearables. For instance, Lincoln Labs hosted a number of "Make Your Own Wearables" workshops for high school girls [85], [86]. Materials were made available on MIT Open Course Ware to reach a broader audience [87]. The structure of the workshop and the participation of inspiring role models make it particularly suitable for girls. The goal of this dissertation is to develop a product that can be used as part of such workshops, or independently, by individuals or informal groups, who may not otherwise be reached.

Complementing these existing solutions with the findings from literature about girls' social motivations and dispositions discussed earlier, a new concept is developed from the discussed frameworks in the following.

Chapter 3

Designing a New Experience

As a first step, a new creative experience was to be designed and prototyped, taking into account findings from interviews and focus groups and making a first prediction about the potential outcomes of a technical implementation. The hypothetical creative experience was then the basis for a technical implementation in the form of a toolkit, which in turn allowed conducting detailed studies.

3.1 Goal

What is needed is a learning experience that makes engineering problems engaging and relatable to middle and high school girls; an experience that builds self-efficacy and an intrinsic motivation to be creative and "invent" innovative products.

To achieve this, an experience has to serve teen girls' social needs and allow them to have social impact in a way they can relate to.

Literature suggests the following areas are of interest to girls:

- Medical [48]
- Social [48] and helping people [88]
- Art [89]

Furthermore, data on young people's career aspirations can be used to gauge how teen girls wish to impact the world around them. According to a study that asked 1,028 American teenagers, 11% of 13- to 17-year-old girls said they wanted to become a teacher, 9% a lawyer, 8% a doctor, 6% a nurse, 5% a designer [90]. The study data are visualized in Figure 3.1.

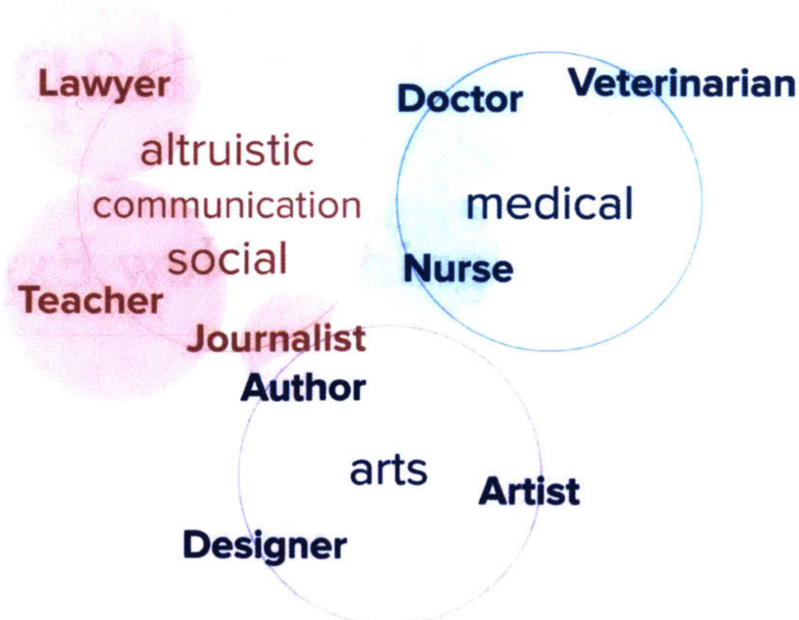


FIGURE 3.1: Teen girls' career aspirations. These are overwhelmingly areas in which teen girls feel like they can help people. Data: [90].

To serve all areas of interest, a constructionist activity has to span all 3 areas: social, medical, and artistic applications. This can be achieved through a product design activity for artistic, health-related, and social real-life uses. A connected device can be especially useful for social cases if it enhances communication, e.g. a connected device. Medical applications may also serve sports, including team sports, and various personal health purposes.

A solution is derived to bridge these areas and thus complement other STEM experiences as shown in Figure 3.2.

The approach to be taken needs to give learners agency and ownership, so the learning experience should be in accordance with constructionist principles, and it should serve girls' need for collaboration [52], [57].

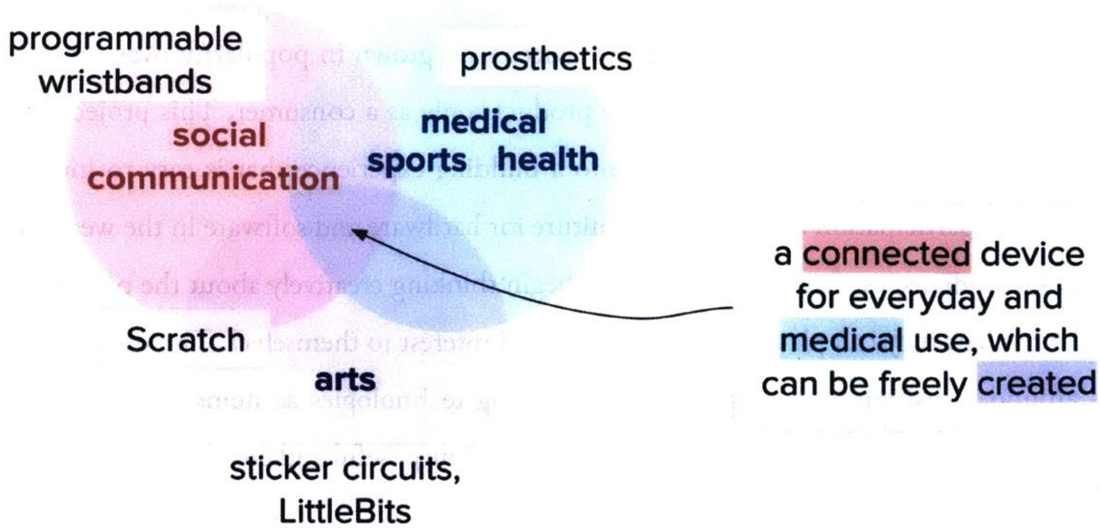


FIGURE 3.2: Solution space: between medical, social, and artistic applications. To unite these areas, a connected, customizable, wearable electronic device is envisioned.

Thus, the aim was to build a platform that empowers non-engineers, and specifically teen girls, to create their own smart devices, such as wearable devices. Research studies were then conducted to find out whether the activity of building custom wearable devices can successfully make technical creativity "socially relevant" to teen girls. It could thus be investigated how girls' social motivation relates to their motivational needs for STEM education.

Hypothesis:
A smart device toolkit empowering students to have social impact with design and engineering can increase socially-motivated girls' self-efficacy and interest in solving technical challenges.

The focus of this research was girls in middle school, ages 11-14 and up, the very age that girls have traditionally tended to turn away from building, inventing, and STEM in general [2]. To cater to preteen and teen girls in particular, this work addresses the identity struggle at that age, as they enter adolescence and find a new sense of self. The platform of modular smart devices is one that allows for expression of personal identity, interpersonal connectivity, social relevance, and aesthetics, many of which become important to a majority of girls this age.

The end product would ideally encourage young individuals to participate in self-directed projects in STEM-related fields and empower students to tinker with the system outside of school to come up with their own ideas in scientific or engineering fields. While wearable devices in the form of fitness trackers, health monitors, e-textiles, and other devices have grown in popularity over the past half a decade, the average person interacts with these products only as a consumer. This project intends to change the culture around wearable devices into a building experience that is easy to interact with, thereby allowing participation in a read-write culture for hardware and software in the wearable space. This is key for students, especially young girls, to begin thinking creatively about the products around them and what part they can play in developing tools of interest to themselves. The presented product revolves around transitioning young girls from viewing technologies as items to buy pre-made to thinking about them as an accessible space. Engineering is purposeful and enables to creative solutions to real problems. The goal of the toolkit developed in this dissertation is to empower girls to write their own stories with (wearable) devices, rather than depending on others to define what they are able to do. While any type of creation builds this ideology to some extent, a coding-based platform extends the level of creativity drastically, as even a basic toolkit can perform a variety of functions.

3.2 Needs Extraction from Initial Interviews

In product design manner, preliminary interviews and focus groups were conducted to extract user needs. The first part of the feedback interviews mentioned later was also considered in this task. Friends helped with one round of focus groups and two undergraduate students helped with another. To analyze the results, interesting quotes were copied to post-it notes and sorted on a whiteboard, until a number of needs could be summarized from them. 10 needs were found (unweighted), which can be categorized with motivational criteria from motivation research literature (for examples and quotes please see Figure 3.3):

- Individuality
- Freedom to tinker
- Familiarity
- Security
- Meaningfulness / relevance / purpose
- Fun, aesthetics
- Belonging / connection

- Status / signaling
- Reward

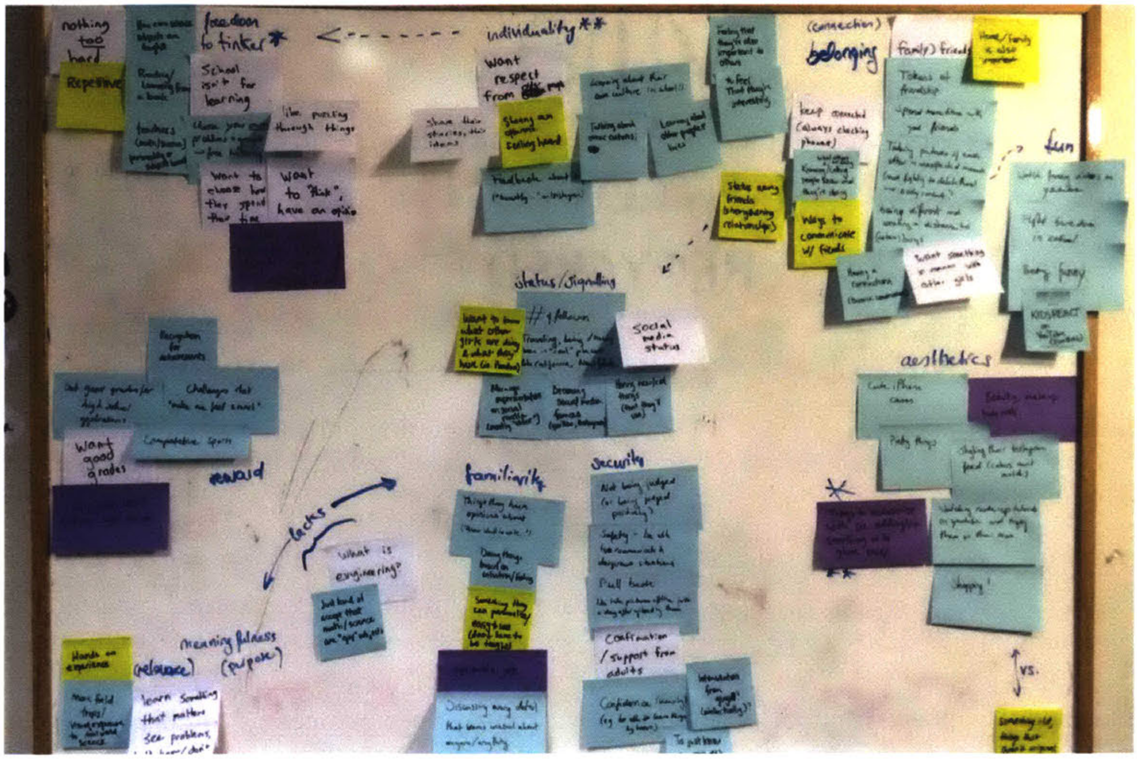


FIGURE 3.3: A whiteboard and post-it notes were used to sort through girls needs extracted from preliminary interviews. (Full-resolution photo in Appendix B.)

These needs were not ranked since the data pool was not large enough to permit for such analytical tasks. However, the observed needs correlate with motivational aspects described in literature. Ryan and Deci's motifs of autonomy, competence, and relatedness [38] are very much reflected here, as are Lepper and Henderlong's context, challenge, control, and curiosity [37]. But it can be argued that Habgood and Ainsworth's [91] division into intrinsic (fantasy, challenge, flow, control, curiosity) and interpersonal motivations (competition, cooperation, recognition) represents the different social needs with greater precision.

The needs extracted from focus groups were thus matched with motivational aspects described in different works of literature. The observed needs and their references from the body of motivation literature are listed in Table 3.1.

TABLE 3.1: Motivational dimensions observed in focus groups.

Observed need	*Corresponding motivational factor in literature*
Individuality	Autonomy [38]
Freedom to tinker	Autonomy [38], optimal level of challenge [65], curiosity [91]
Familiarity	(Perceived) competence [38]
Security	(Perceived) competence [38]
Meaningfulness / relevance / purpose	Relevance, relatedness [38]
Fun, aesthetics	Fantasy [91], relatedness (when social) and context [37], or autonomy [38]
Belonging / connection	Interpersonal recognition or cooperation [91]
Status / signaling	Interpersonal recognition, cooperation, or competition [91]
Reward	Interpersonal recognition [91] or external motivator

Whereas Dasgupta & Stout [52] mention that girls may be demotivated by competition, especially in math tasks [57], it may be argued that competition applies more subtly and on different areas (e.g achieving Instagram popularity), according to what one of the interviewees said. Also, girls self-efficacy may be lower in certain subjects [39] and they may be more intimidated by failure (Ibid). As Csikszentmihalyi identified, perceived challenge must be at an optimum level relative to perceived skill to create a flow experience [65]. Hence, competition may be hurt more than it helps in those areas, for example STEM subjects [50], [52].

It can be seen that some of the identified motivational factors are not served by the experiences the girls described from science class and other school-related activities; see Figure 3.4.

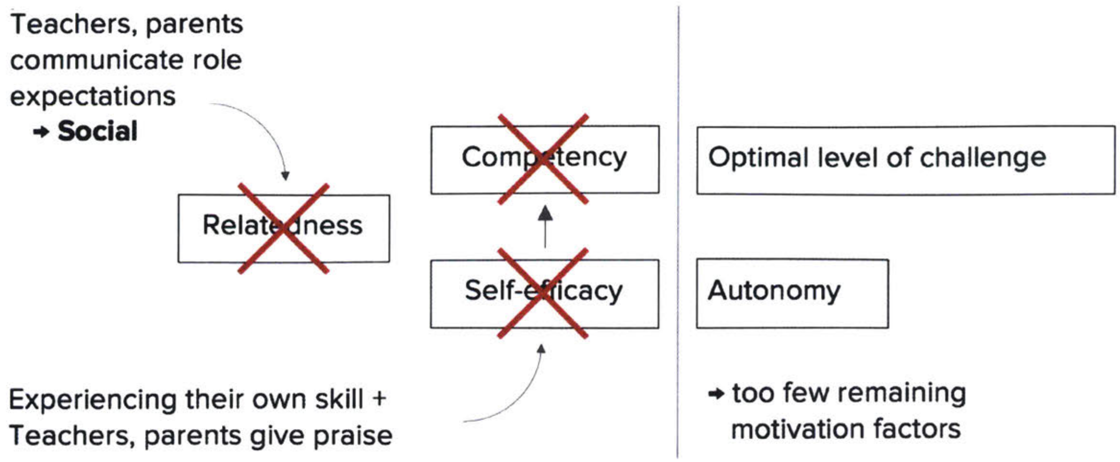


FIGURE 3.4: A simplified view of underserved motivational dimensions for many girls in STEM.

As mentioned in the previous chapter, Resnick and Rosenbaum [75] have also derived guidelines for designing construction kits for "tinkerability," acknowledging Papert's and Turkle's principles around constructionism that were covered in the Psychological Framework section. Their elements are immediate feedback, fluid experimentation, and open exploration. The element of immediate feedback is to make sure that the user is never left in the dark and always knows what is happening. The element of fluid experimentation lets users start playing without prior training or reading of rules. Although not explicitly stated by Resnick and Rosenbaum, the elements of fluid experimentation and immediate feedback are important aspects to create a flow experience with continuous user engagement [65]. The open exploration element lets users integrate whatever materials they are familiar with and apply the experience to any area of interest to them. Although Resnick and Rosenbaum do not support their claims in this way, it may be argued that Brophy's [76] idea of relevancy is what makes their open exploration element so important. Also, relatedness is needed for creating an internally motivating activity [38].

These principles also match this work's findings from interviews and focus groups and match the initial goals for the toolkit.

3.3 Concept: A Learning Experience for Engineering

The proposed solution toolkit and design experience has been developed with the emerging needs of teenage girls in mind, as laid out in the literature. It brings together the experimental and intuitive nature of constructionism with the social purposefulness of product design, specifically smart device design.

Based on prior art, the requirements for embraced for the proposed design toolkit were (see Table 3.2):

TABLE 3.2: High-level educational and functional requirements for the proposed design toolkit.

- potential for creating range of different solutions with social impact, e.g. including medical devices
- supporting creative freedom and ownership (agency)
- low barriers to entry
- wide range of challenge levels
- real-time transparency of interaction
- social context of creative activity, e.g. group projects and sharing of creations
- aesthetic appearance (to be refined in focus groups)

The proposed design toolkit consists of a wearable or smart device with attachable sensors that can be programmed with a graphical, cloud-based tool, as schematically depicted in Figure 3.5. This activity, conceived in 2013 [92] and now developed as "Qwartzi" [93], will allow users to build their own smart devices, such as a smart watch, medical bracelet, physical activity monitoring or other device. Thus, a variety of products or experimental setups can be created, potentially serving the needs of a variety of design learners.

FIGURE 3.5: Concept of the presented design toolkit. A wearable or smart device with (potentially attachable) sensors can be reconfigured wirelessly by using a graphical web application.

The goal has been to develop a modular platform for building smart devices, starting from a computing unit that can be extended through both functional modules and purely decorative elements, such as jewelry. The functional modules can consist of sensors or other components and allow girls to build their own hardware. This approach would make a girl's creation more tangible to her than just code-based software customization, and let her build "real" devices that can be used to fulfill meaningful purposes.

The integration of sensors should be configurable through software. Possible uses include medical uses or attachment to non-human wearers (e.g. pets). In its most basic form, the format of this wearable can be a smart watch or smart bracelet. This will create a purposeful, meaningful and collaborative building experience for middle school girls.

While previously developed learning experiences include wearable devices targeted at girls, which could be programmed [83], this platform will have two important features: real applications and aesthetic freedom. The presented wearable device ecosystem can cover a wider range of applications (including pseudo medical devices), which satisfy real needs as opposed to just notifications or play, and it can be customized for different styles, including "smart jewelry" configurations. Previous reprogrammable or even modular wearable devices [94], [95], and those which have been developed since the beginning of this project in 2013/14 [96], lack such features, partly because of a focus on coding education. There is only so much one can do with code alone. While the created platform may serve as a tool for coding education, the primary goal is to build a platform that creates excitement in girls about the power and versatility of engineering, through real-life utility for a wider variety of applications, not limited to teen girls' needs. Examples could include animal activity monitoring for pets (e.g. accelerometer on a dog collar), stress monitoring (e.g. pulse frequency), virtual referee in sports (e.g. the entire team is equipped) etc. Detailed examples will be given below.

3.4 Prototyping and Verifying the Experience

As engineers, we are often tempted to realize big chunks of our inventions and forget to keep our human users in the loop throughout the development process. Testing our inventions early on is often difficult, especially when there is nothing close to the finished product to put in front of users. The engineer then faces the challenge of prototyping the experience, which is conveyed by the product, separately to prototyping the product itself.

3.4.1 Prototyping the Experience: How We Teach Freshmen

An example for iterative, user-centered engineering design can be found in MIT's freshman class *Toy Product Design (2.00B)*. In this class, 80 students in 16 groups are guided through the process of inventing, refining and finalizing a toy product, i.e. something that was conceived and designed as a toy with a particular play experience. The milestones are roughly structured as shown in Table 3.4 (excl. design reviews with instructors).

As in this class structure, prototyping the experience itself before investing too much into the development of a product is key for quick innovation cycles.

TABLE 3.3: MIT freshman course "Toy Product Design": Lab structure (class project), overview.

Week 3	Brainstorm a large number of ideas, select 3 using Pugh chart
Week 4	Create posters and short pitches for 3 ideas to demonstrate to kids, especially capturing the mood or "feel" of the play experience
Week 5	Present to kids, asking for feedback, e.g. what is the play?
Week 6	Reflect as a team, narrow down to 2 ideas
Week 7	For remaining 2 toy ideas, build (1) looks-like and (2) plays-like sketch models. (Plays-like models often involve manual behind-the-scenes animation.)
Week 8	Test both with a large number of kids
Week 9	Reflect as team, select best toy product concept
Week 10-11	Create final prototype that both looks and works, i.e. plays as intended
Week 12-14	Refine, present to the public

3.4.2 Research Method Development for Human-Centered Design

A number of human centered design methods were used in this work. Human centered design, a term mainly coined by Donald Norman [97] building on participatory design [98], [99], describes the close involvement of the end user in the design process. Since human centered design has long been used in specific fields, systems engineering and then computer interface design, and with specific end products in mind, the term "Design Thinking", which was originally conceived within architecture and urban planning [100], has emerged as both a set of design methods [101] and as a broader synonym for user centered design [102], often describing a more open-ended process. In the product design field, focusing on the needs of the user has become common practice. Good products are achieved if end users, including "extreme users" at either end of the spectrum, are involved in the process [103], [104], and if approaches and prototypes are tested whenever possible in the design process [105] and much before any particular solution approach is picked. The challenge for product designers is often to prototype the product, and to prototype the experience of using it. Since mass production techniques, such as the ones used to produce the eventual product, are not yet economical for single prototypes, and because some technologies might not be developed yet, prototyping techniques are a very important part of this profession.

Often, product designers will develop a mockup or sketch model prototype, something that looks "as if" but is non-functional, and show it to a group of users. Such interviews and focus groups may also encompass general questions that give the interviewer or focus group moderator a better insight to the users' needs, current solutions they might use to address these needs, and price point or other barriers to adapting a new solution.

In education, there are two groups of users: students and teachers. The goal is usually to educate the student. Teachers need to be able to support technology used in class.

In the work that follows, interviews and focus groups were used to extract information from users and to ask personal questions and follow up if answers called for it. Furthermore, booths at public events that attract young people were identified as an opportunity to reach a great number of people in a short amount of time.

In all these settings, asking the right questions was an important objective. Questions were collected and prioritized. Going into focus groups, three to four main questions should be chosen to guide the conversation. (See Appendix A for examples.)

Prototyping techniques for technical solutions required very short innovation cycles. Since the initial feedback loop needs to be much faster than technological development cycles, rudimentary techniques were used to create prototypes that appeal to users' imagination. Modeling clay for electrical housings, snaps for connectors, and presentation tools for web-applications are just a few examples for such rapid prototyping techniques, enabling "agile" ed-tech development.

Equally, to test an interactive experience, cardboard can be a useful medium. Already, interface designers commonly use cardboard for the internal verification of app layouts. However, this medium can also be used to test an interactive experience hands-on. By imitating an app, for example with cardboard and stickers for a drag-and-drop input function, a great number of users can be used at once. This allows designers to gather feedback from groups much bigger than what would be manageable in a focus group, and to even better imitate the actual environment of setting in which a technology would be used once deployed.

3.4.3 Fabrication of Sketch Model Prototypes

3.4.3.1 Prototypes of the Hardware

The device platform was prototyped as a set of simple mock-ups to allow developing the building experience with girls aged 11-14. In interviews and conversations, the goal was to refine what moves middle school girls, present the prototypes, and get their feedback, in order to create a user experience and draft detailed device and connection characteristics.

The concept is a modular platform for building smart devices, notably wearable devices, starting from a computing unit that can be extended through both functional modules and purely decorative elements like jewelry. The functional modules can house sensors or other components and allow girls to build their own hardware, as will be specified below.

To create device prototypes, modeling clay was used in lieu of 3D printing. Using FIMO, fully rigid look-alike device prototypes were created (see Figure 3.6, Figure 3.7, and Figure 3.10). Standard jewelry connectors were integrated before baking the polymer clay, making the connection very sturdy and realistic. Said jewelry connectors could then attach to bracelets, completing the smart jewelry prototypes. To simulate electromechanical connection with functional modules, metal snaps were used. Since they were on top of the polymer rather than mechanically locked into it, superglue was used to ensure a sturdy bonding between the materials.

FIGURE 3.6: Prototyping materials. Standard jewelry parts (L) and modeling clay (R) allowed for quick assembly.

FIGURE 3.7: Device prototype. The modules (black) symbolized components that would house sensors.

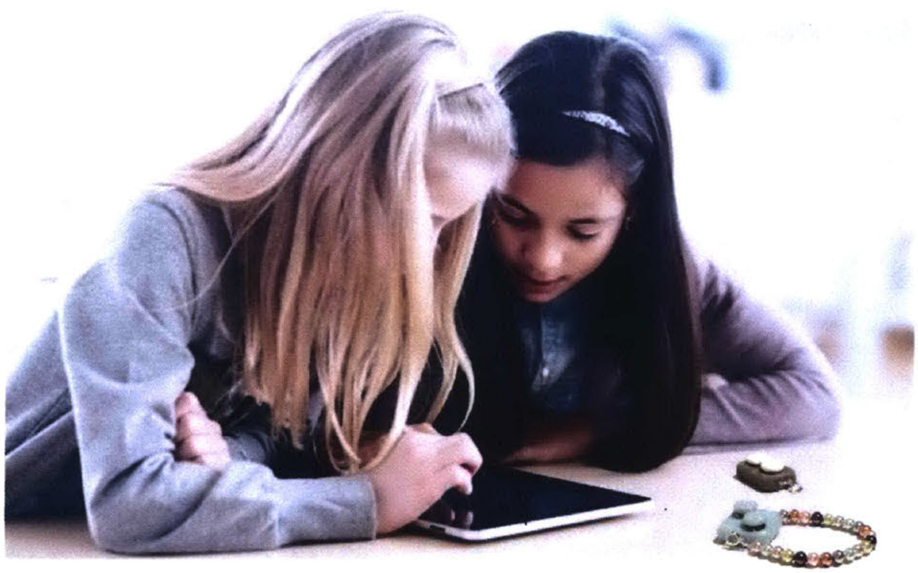


FIGURE 3.8: A vision for interaction: students configure or remix their creation via an interface on a connected device.

FIGURE 3.9: Acrylic was laser-engraved and painted to imitate specific sensor modules.

FIGURE 3.10: Snaps were used to imitate electrical connectors between sensor modules and the wearable

3.4.3.2 Prototypes of the Software

The interface was prototyped to simulate a mobile device connected to the wearable, which can be used to configure its functionality. The layout and complexity were an integral part of the building experience, as the creation of the wearable offers degrees of freedom covering both hardware and software. Focus group moderators used an iPad Mini 4, since a great number of middle and high school girls have access to iPad devices (as compared to other tablets), and because it has a larger display than a phone, making it more versatile for different prototype variations. Google Slides was used to rearrange shapes in a way that an App could be created for the iPad. Different shapes were created to symbolize different kinds of sensors or other modules that could be connected to a coupled device. Also, a project was created in Scratch and variables were named in a way that would indicate they could be connected to other hardware; and screenshot were taken and inserted it into the page to simulate integration with Scratch. With three different levels of exposure to code, the interface can grow with the learner so the level of challenge and autonomy is always optimal for the competency of the student.

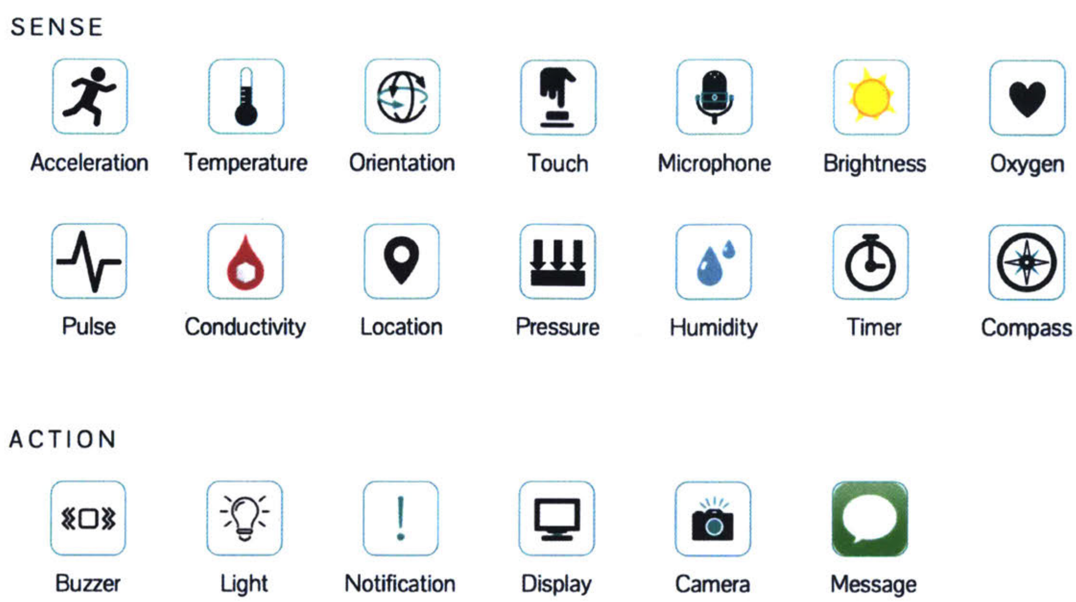


FIGURE 3.11: Icons were designed, each to symbolize inputs (sense) and outputs (action), including different sensors and indicators.

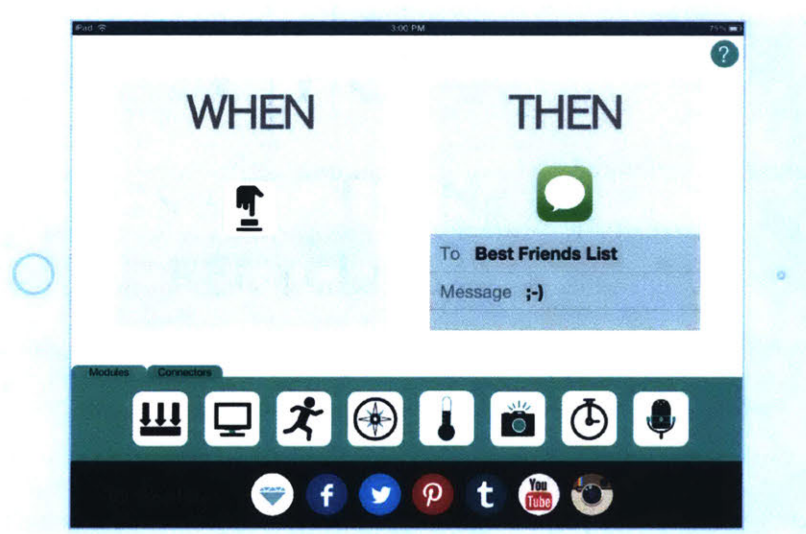


FIGURE 3.12: The "simple" interface, that would get users started, is an intuitive condition-action scheme with two parameters.

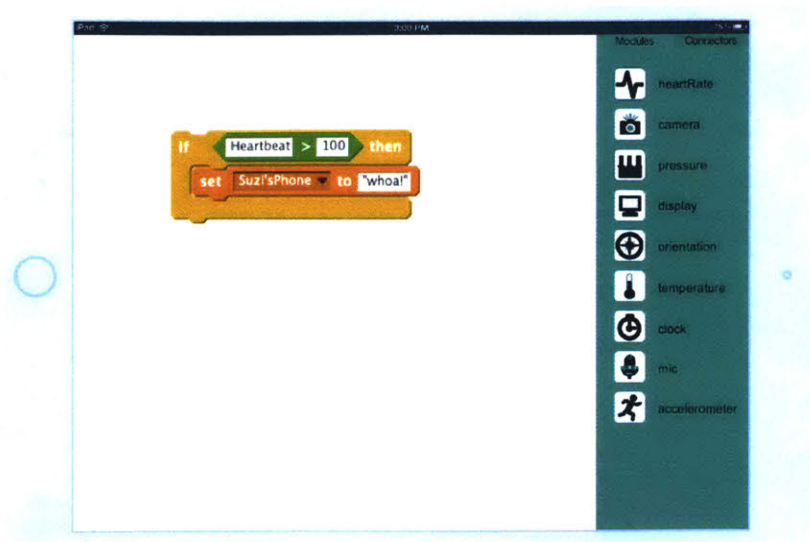


FIGURE 3.13: The "Scratch" interface would use the semi-graphical programming language Scratch to help kids code their device.

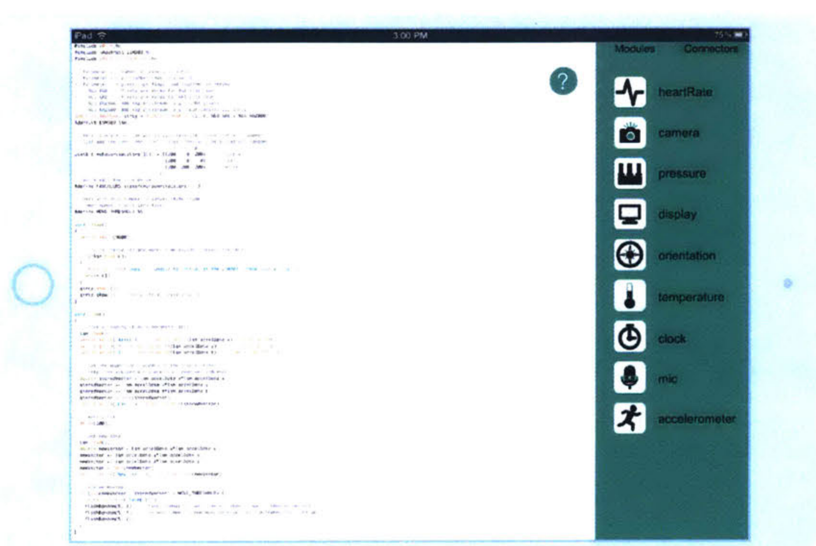


FIGURE 3.14: The code interface would let kids use native Arduino code to configure their device.

To test the interface in actual use, "cardboard prototypes" were developed. The simple interface was used as the basis, and a few elements were added that students would find on the website as they publish their project: a description and an image. To simulate the drag-and-drop of input and output symbols into their respective place on the WHEN-THEN interface, the formerly presented symbols of sensors and indicators were printed on a sheet of stickers (0.5 inch squared in size), as well as symbols of several phone-enabled functions.

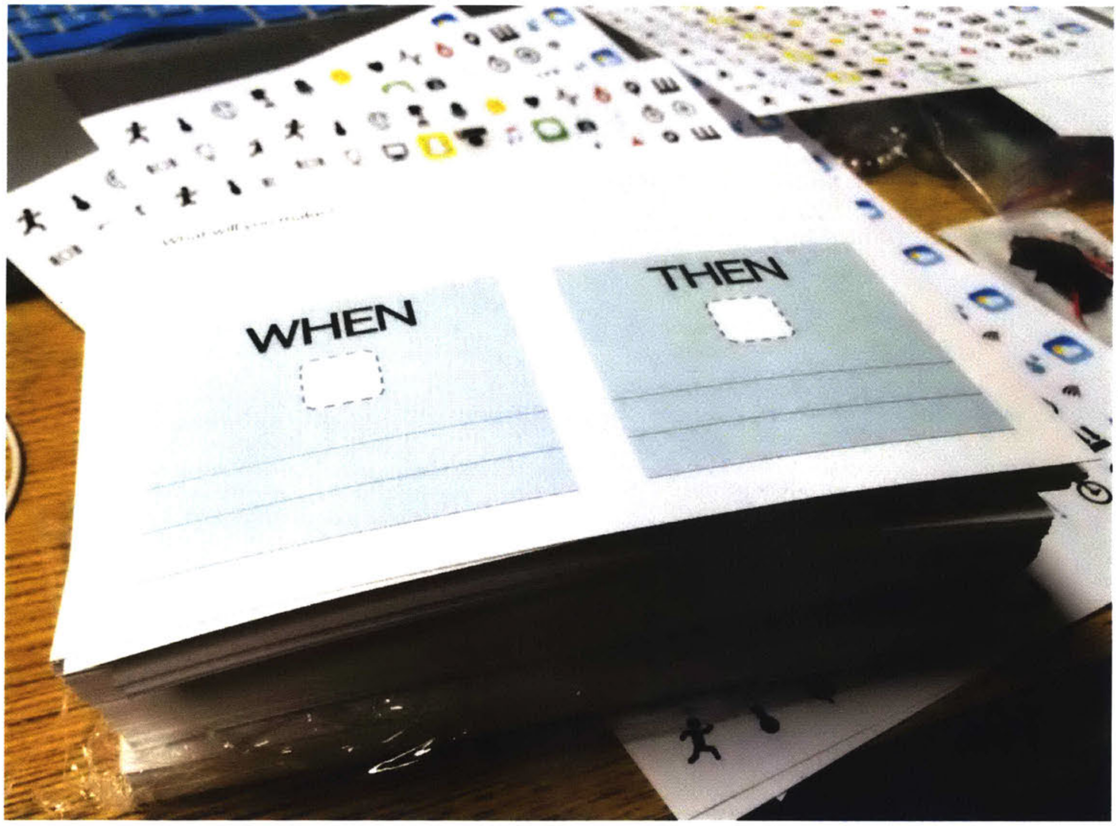


FIGURE 3.15: Cardboard and stickers were chosen as a medium to simulate the experience at the Cambridge Science Festival "playtesting" event (spring of 2016).

In designing the product, supporting materials were also considered, such as curricula and teacher communities; versus keeping our product an independent creative experience. Too rigid a curriculum around such a device could drastically reduce the creativity, as it has with Scratch in certain environments [106]. To keep the experience more self-motivated and allow middle-school girls to explore their own areas of technical creativity, it must not be too driven by formal structures. Especially at this age, when children begin to seek independence from parents and formal entities of control, girls need something they can make their own, independent of classroom or parent-driven activities.

"Generation Z" (born 2002 or later) grew up alongside social media, and does not react well to sales messages [107]. In an interview, a 12-year-old said that she and her classmates felt "used" by a big IT company because they took photos of them during a STEM outreach event. The device system needs to impact those social environments that do not currently encourage technical creativity in girls. Support materials in the form of documentation on a website – including a section describing different sensors and their functions, as well as a database of previously created projects (similar to Scratch) that students can adapt and remix – will invite and help onboarding students.

3.4.3.3 Prototypes of a Website for Sharing

Even if the goal was to make something for free tinkering alone, first interviews made clear that users would need some guidance to get started. Consequently, pages of sensor descriptions were prototyped as well as two mockup published projects. The most versatile sensors were prioritized, because their function is not obvious (by contrast: ambient pressure sensor – measures pressure). The sensors described were: Heart rate sensor, (skin) conductivity sensor, and accelerometer. Examples for a possible implementation were given in each case, but were kept general to not lead students in any particular direction, to accomplish the following goals simultaneously:

1. Perceived competency – they feel like they understand how this works. Part of this is to not show them too much technical detail upfront, but having a "Learn more about how it works" button in the description. Also, the text is in a "language" that is not too technical.
2. Autonomy – they can "own" it and the activity is not too structured. Examples are very open and "far from perfect." Given examples generally feature notifications, because the text is another opportunity to explain the measured value and because it does not lead students into any particular direction as to which action would be most appropriate.
3. Ratedness and context – the examples and references given are familiar with what adolescent girls know from media (e.g. general language similar to "Girl Meets World", "Degrassi: Next Class" or "Gilmore Girls" series on Netflix [108] or girl-authored Youtube-Vlogs [109], popular media according to our interviewees).
4. Satisfying curiosity – they can learn more if they want. This will also be addressed with a "Learn more about how it works" button.

Interpersonal motivators were not realized in these introductory descriptions. This may be principally possible through a comment feature. Such a feature may present another way in which students can learn from examples and by its collaborative and multi-threaded nature, addressing various interpersonal motivators.

For example, a heart rate sensor was described as follows:

"Heart Rate Sensors are for Feelings. Our pulse changes with stress levels. Like when someone sees you in an embarrassing moment - or when someone breaks your heart, literally. Also, heart rate sensors can measure physical activity - like when you are running or competing. So: you can use heart rate sensors to keep track of your stress level or use it for sports." (Example: WHEN rate > 100 / min, THEN: Notify my friend about my excitement)

An accelerometer would be described as follows:

"Acceleration = Action! When we start moving in any direction, an accelerometer can measure this movement. So this is great for capturing any movement or physical activity, like dancing, or working out in general. In fact, even gravity, which pulls us down, is measured! You can also use it to measure breathing (since your chest moves) or impact. So many possibilities!" (Example: WHEN x,y,z average > 15 m/s^2, THEN: cheer me on "go, go!" via phone)

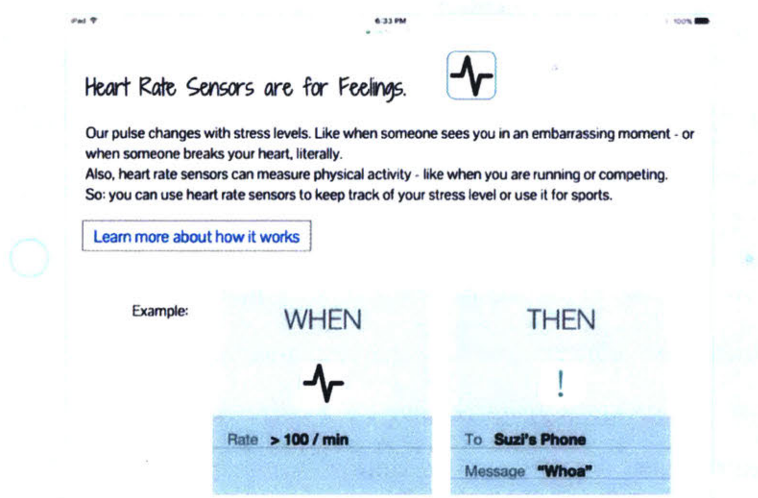


FIGURE 3.16: Sensors will be described in detail on the website; this picture shows a first draft. The introductory text for a heart rate sensor reads: "Heart Rate Sensors are for Feelings. Our pulse changes with stress levels. Like when someone sees you in an embarrassing moment – or when someone breaks your heart, literally. Also, heart rate sensors can measure physical activity – like when you are running or competing. So: you can use heart rate sensors to keep track of your stress level or use it for sports."

A skin conductivity sensor would be described as follows:

"Skin Conductivity comes from Sweat. This is how you make a lie detector! Or (according to recent research) you can even predict seizures. Some have tried using skin conductivity to measure blood sugar, which is important for everyone concerned with diabetes. Others just use it for monitoring their physical activity - if you work out enough to sweat, you're probably burning lots of calories." (Example: WHEN: conductivity > 0.1 Ω^{-1}, THEN: notify me "don't lie" via phone)

Mockups of published projects were prototyped as well. A simple layout was chosen to communicate a clear message. The two examples shown here are of a complex and demanding project, as well as of a very simple and personal project, just to demonstrate the breadth of possibilities. The idea was also to feature a space for users to comment and interact about an idea and ideally encourage each other or stimulate reflection. Code can be shared as well, so other users can remix projects and reference the original one, similar to Scratch [79], [110]. But in contrast to Scratch, projects can be collaborative and be published and administered by multiple users.

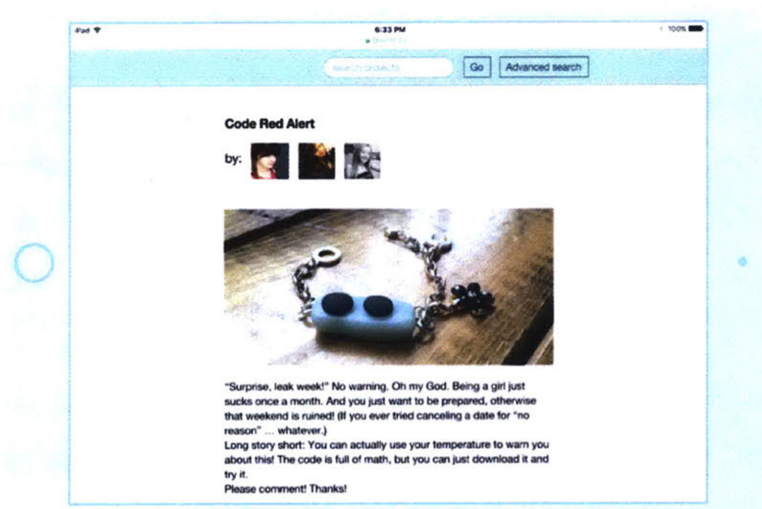


FIGURE 3.17: Mockup published project for a rather advanced application: Predicting the menstruation through continuous measurement of body temperature. In the text, the three fictive authors conclude with "Long story short: You can actually use your temperature to worn you about this! The code is full of math, but you can just download it and try it. Please comment. Thanks!"

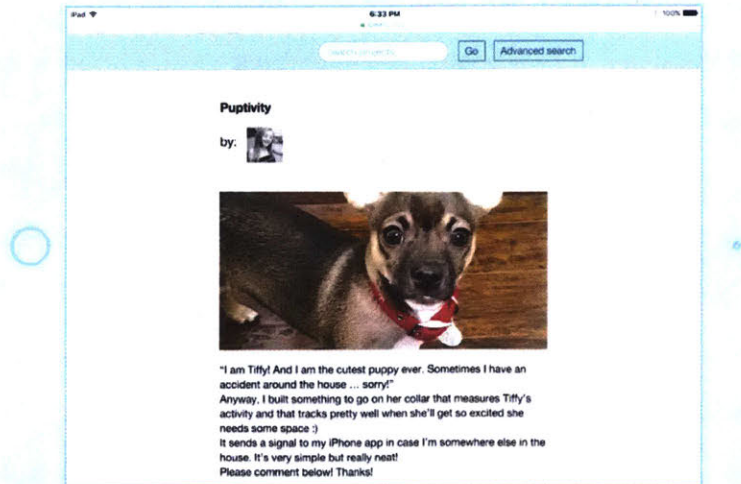


FIGURE 3.18: Mockup published project for a simple but personal application: An activity monitor for a pet. In the text, the fictive author concludes with: "It's very simple but [works] really neat! Please comment below! Thanks!"

Other elements of such a website may include:

- An interface to publish a project, asking for a project or device name, collaborators, one or more photos, a detailed description of the impact or application etc.
- A directory for projects that were published and ways to find related projects, e.g. by keywords
- Virtual groups that allow users to team up locally, stay in touch after a workshop, or find potential real-life collaborators online (local after-school groups may be a good venue for first meetings)
- Localized event calendars that list workshops that will give students the chance to learn in company (and workshop organizers a platform to advertise their workshop to potential participants)
- User profiles with published projects and updates about projects
- A place for conversation, e.g. a chat for members of certain group, as a space to "hang out," as Kafai successfully created with Whyville, where she observed that girls like to "hang out and chat" [111]
- Space to display monthly challenges, mentors to talk to etc.

As such a social network is grown, educators or engineers may be asked to volunteer as mentors to oversee online activity and offer advice where needed. As some users get more experienced, they could be asked as well to volunteer as student mentors to help less experienced users.

Girls would hear about this product either through friends, through searching the web for something related (e.g. they have a problem and learn about a potential solution on our website), through people they follow on social media like Instagram or Youtube, or through other news channels (e.g. "Ideas for finding a new fun hobby" articles), or through a local workshop that uses the toolkit. Sharing creations on Instagram or possible tutorials on Youtube would also be encouraged.

3.5 Focus Group Interviews

Preliminary interviews and focus groups were conducted to investigate adolescent girls' needs and perspectives in practice, to define the design requirements in more detail, and to receive feedback on early prototypes of the concept.

3.5.1 Research Method

After ideating toolkit concepts, a proposed toolkit was first prototyped using non-functional sketch models and presented to multiple focus groups before running formal experiments.

There were 3 focus groups of 3-4 individuals, as well as an interview with a single girl. Focus groups were generally structured into an hour of conversation, followed by an introduction to the prototype design toolkit. The first part of each interview was a conversation capturing the world the girls live in - what is important to them? In the second portion of our interviews, I presented the girls with our prototypes and gathered feedback.

The conversation was open. Discussion topics discussed included: School and classes, hobbies, social network and sources of reward, every-day problems, use of technology, perceptions of engineering. Whenever possible, questions were asked as follow-up to previous answers or to natural conversation between focus group participants. (A common flow: "Are you all at the same school?" – "Do you like it there?" – "What bothers you about [science class, people, etc., depending on previous comments] ?" – "Why? / How?").

The first interview with a 12-year-old and 4 of her friends was 2.5 hrs total on a Thursday between school and dinner. Not much was known about any of the girls before the focus group, so in the beginning, considerable time was spent discussing hobbies and friends.

Device sketch models were created in modeling clay and foam as depicted in Figure 3.19. Other sketch models had a round or square shape. It was explained that sensors could be attached to create a functional wearable or other smart device.

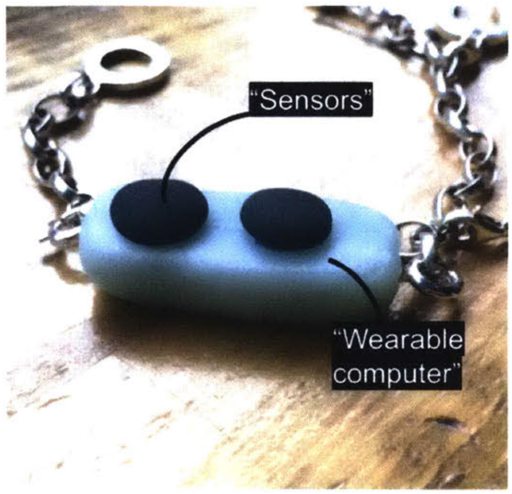


FIGURE 3.19: Photo of a sketch model prototype device that was presented in the focus groups.

Prototypes for the configuration interface were drafted and shown on an iPad Mini, as illustrated in Figure 3.20. The sketch model prototypes were explained briefly, for example: "Imagine this is a device that can measure things like temperature, motion, etc., and it is connected to an app where you can make it detect when something happens. In this example, my friend Suzi is alerted when my heart rate exceeds this number." An overview was given how one could extend and configure such a wearable device. Then, participants were challenged to come up with ideas for what they would build and what they would use such a device for.

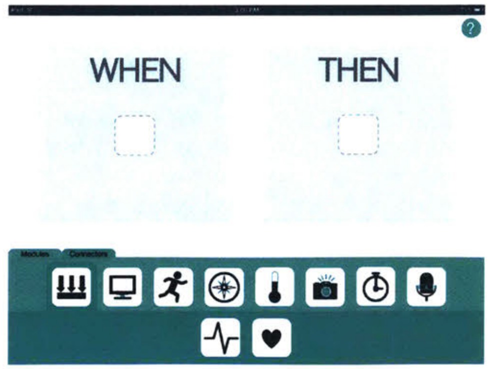


FIGURE 3.20: Digital interface model as shown to interviewees on an iPad Mini.

Using these preliminary tools, several notable observations were made.

3.5.2 Results

To the question whether they like "making things", the answer of most of the girls was "not really." One girl said she likes occasional painting, but they generally said they did not engage much in creative activities. That was both an interesting data point and a benchmark for the attractiveness of this build-your-own toolkit to this group.

Other hobbies they mentioned were dancing and baking or cooking. Social media such as Instagram was a hobby most of them stated they engaged rather frequently in. These are certainly creative activities, so one explanation could be that some girls do not like to see themselves as "builders", and it would be interesting to test different framings of "making", using variations of this device and similar toolkits, in future interviews to explore the impact of framing.

To the question whose opinions they care about, they mentioned close friends and people they care about. This was interesting, because from older girls, anecdotal evidence suggests that people they "want to be friends with" may become more important.

When the device prototypes were presented on a jewelry stand to transition to the second part of this interview, girls quickly started complimenting the prototypes ("they are so pretty! Did you make these?").

When challenged to come up with their own ideas for what to build, it was surprising how creative individual girls were in spite of their previous self-assessments – they enjoyed coming up with ideas for what to build and saw very practical use in those "inventions." For example, one girl said she would love to build a device that could transmit her location to a friend by the push of a button in dangerous situations.

One girl criticized the direct integration of Scratch into the configuration interface. Although she was the only one of the girls who had never used scratch in school and was unfamiliar with it, she pointed out that many kids and teens - especially in other countries - are unfamiliar with Scratch, have no prior coding experience, and may be intimidated to use it to configure their device for the first time. She suggested making a simpler interface, inspired by the iPhone's settings menu structure.

This interview revealed that the Apple Watch may be a status symbol, but most girls find it "too big, because it is always on you." Also, a number of needs were derived for tween girls, which may be applicable throughout teenage years: need for fun, social recognition, style, and something shareable.

A second interview was conducted a week later with two girls from the first group and a friend of theirs who had not been present at the earlier interview.

In the first part of that second interview, the girls were asked general questions covering a broader scope, discussing school life in particular. Their responses confirmed Papert's finding that students should be free to explore, similar to Bandura's agency dimension [67], [112] or Ryan and Deci's autonomy dimension [38]. The girls said that science classes would be much more fun if they could pick groups and think for themselves instead of being told what to do. The need for being free to tinker can certainly be derived from this statement.

When asked about their perceptions of engineering, some girls replied with stereotypes of designing and building bridges and other civil engineering activities.

When participants were shown prototypes, the two girls who already knew the project were keen on explaining its potential uses to the third girl. It was clear that the girls found the toolkit both useful and pretty, and that it would motivate them to tinker and build their own wearable devices for themselves.

After thoroughly exploring the toolkit, in the later part of the focus group, one girl asked: "Wait, is this 'engineering'? This is so cool!" It thus appeared that presenting the toolkit led to more relatable understanding of engineering than the girls previously had; with a rapid change in mindset. This engineering mindset change is reflected as a finding in Figure 3.21.

Another observation, which was repeatedly observed over the course of multiple focus groups, was girls who originally described themselves as "not very creative" and "not interested in engineering" were overcome with very creative ideas once they grasped the concept of the design toolkit. For example, participants asked "could you make a safety device that tracks your GPS and your heart rate and alerts people via text?" In many cases they detailed out specialized design ideas. This creative self-efficacy mindset change is reflected as a finding in Figure 3.21.

A possible interpretation of this finding was the reasoning that most K-12 learners have a creative energy based on their interests and exposure to different problems they encounter, and these ideas only come to light when the student is empowered with the tools to realize them.

Methods

1-5 girls

2 hours

Part 1: Discuss hobbies, dispositions, self-perception

Part 2: Discuss prototypes, potential use

Findings

Mindset Change:

- **Creative Self-Efficacy**

  [I'm not creative] - I would build a navigation that ...

- **Engineering Perception**

  [Engineers build bridges] - Wait, is *this* engineering?

Motivation: Relatedness

FIGURE 3.21: Focus group methods and findings: a mindset change was observed for both creative self-efficacy and engineering perception.

Aesthetic requirements were also refined in the focus groups. Many girls said that a compact design would be very favorable. Girls strongly favored a square shape over a round, watch-like shape. Different colors were also important to some. In general, many girls requested a graphical interface with low barriers to entry to ensure inclusiveness independent of prior technical experience.

3.6 100 People in a Day: MIT Girls' Day Exhibit

At the Girls' Day at the MIT Museum in spring 2016, the MIT Museum kindly provided the opportunity to present the project in a brief presentation and with a booth that during the exhibition time from noon to 4 pm. During that time, approximately 50 – 60 girls and their parents stopped by the booth to discuss the learning experience and product (Figure 3.22 shows a photo of the event).

The audience was very broad and included girls from elementary school to college. In contrast to the interview, which was conducted with girls that are regularly exposed to MIT and technology innovation, the public exhibit was a great opportunity to learn more accessible vocabulary. When a young girl and her mother visited the booth at the beginning of the exhibit period, the first explanation went completely over the girls' head. Thankfully, her mother rephrased it in a much better manner. "This is like a computer in a bracelet, which you can tell to do certain things for you." Later in the exhibition period, a high school girl rephrased the product, indicating what the essential elements were for her: "So is this like a bracelet that can connect to friends?" She also inquired about when the toolkit would become commercially available.

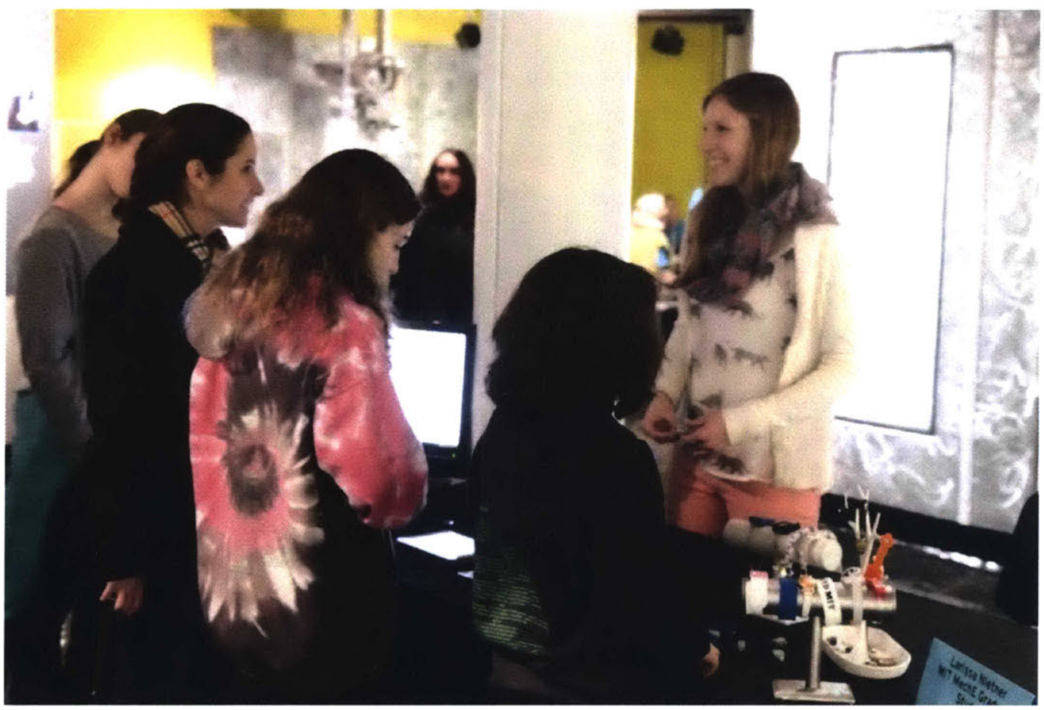


FIGURE 3.22: Discussion of the learning experience at MIT Museums' Girls' Day in the spring of 2016.

Another finding was that the girls were often not confident to ask questions, but their parents were. Once a discussion was started, they were quite curious about both potential functionality of the toolkit, and about how the name of the toolkit ("Qwartzi") was conceived and how components of the mockup prototypes were manufactured. They were also curious about the product design process as a whole.

From the different conversations was concluded that providing examples for different configurations are a critical element for getting started with a toolkit like this.

3.7 2D Prototypes: Mapping the Design Space

Since the preliminary interviews yielded positive initial results, it was important to test the design activity as an experiential process. In order to obtain experimental data early on, inexpensive cardboard models representing a possible device interface were employed.

For the Cambridge Science Festival (also in spring 2016, a month after Gils' Day), the MIT Museum offered another opportunity to engage with learners. This provided the unique opportunity to offer an activity. At that time, both hardware and software were still in the concept phase. Thus, an activity was offered, which would mimic interaction with an app: Cardboard prototypes, which invite to the conceptual design of a wearable similar to my learning experience.

3.7.1 Research Method

The design experience was prototyped as a creative task at an exhibit at the MIT Museum for the Cambridge Science Festival event. Kids and teens were prompted to come up with a design for a wearable device or other smart gadget solution. The cardboard and sticker graphics are depicted in Figure 3.23. Different sensors and output methods were presented to them to give them ideas. To prototype the creative experience, an interface draft was transferred onto cardboard with a representation of the configuration app that had formerly been successfully tested in focus groups.

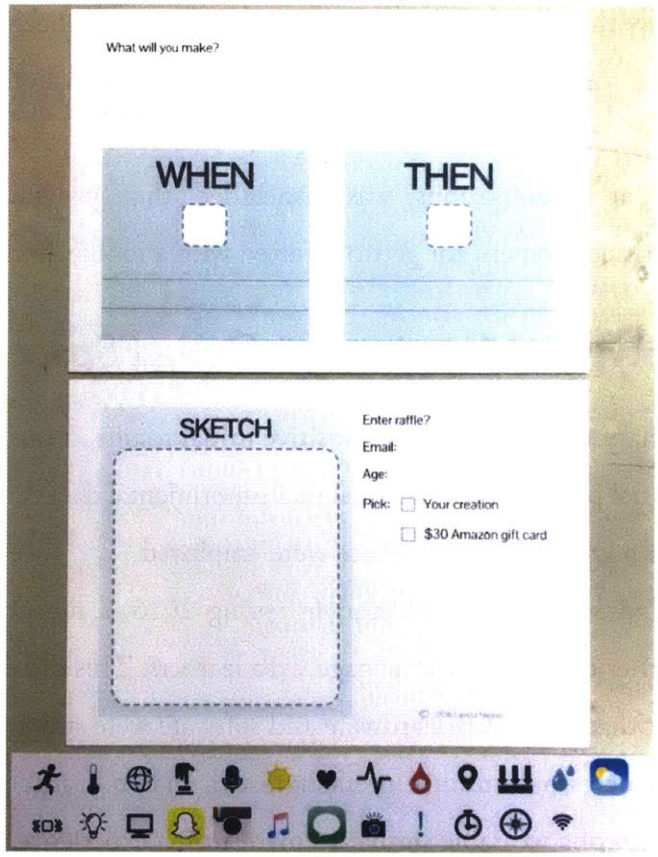


FIGURE 3.23: Front side and back side of carboard prototypes and print template for stickers. These were used for the design activity at the MIT Museum.

The cardboard dimensions were 5x7 inches, close to that of an iPad Mini, to be consistent with preliminary interviews and focus groups. The interface was conceived as a when-then schematic (condition and action) with symbols to go in each of both sections. Symbols were realized as stickers about the size of app icons. Sensors icons and indicator icons were designed in a way that would be intuitive to the young learners, often much different from how technical components are usually represented.

Icons not only reflected sensors that could be in a wearable device, but also other sources of information or media that might be familiar; so the participants would not feel limited to the wearable device space should they wish to create something outside this constraint. The potential scope was expanded beyond wearables in order to allow for an investigation into participants' design interests. Symbols of popular mobile applications were chosen for those data sources not covered by the developed sensor representations, such as teens' main communication apps, as identified in earlier focus groups.

The backside of each cardboard prototype had a prompt for sketching the invented device as well as a section asking for information with the incentive of entering a raffle.

A completed version is depicted in Figure 3.24, showing the freedom participants had with their ideas.

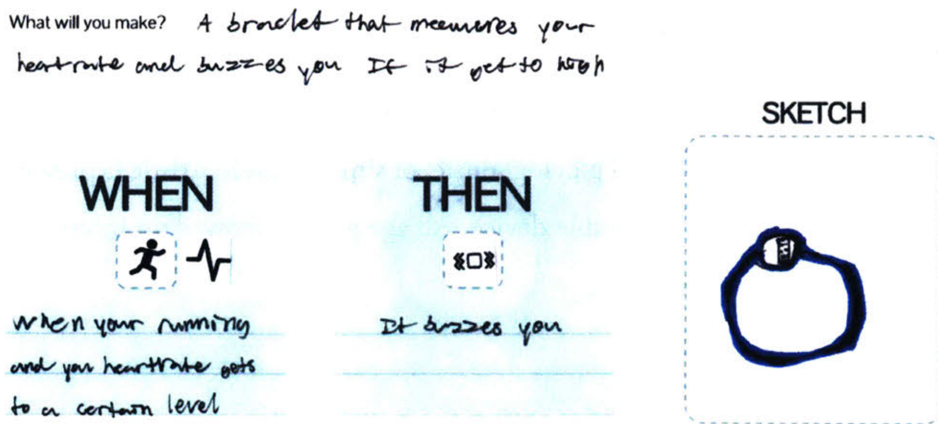


FIGURE 3.24: Cardboard prototype as completed by one of the participants. (Personal information redacted.)

3.7.2 Results

35 participants chose to complete the cardboard prototype. Of these, 26 participants revealed their age. The average age of these participants was 13.4. The average age of all participating minors was 10.6 (3 participants were 24 years old or older). There were more girls than boys who chose to participate.

Students were keen to learn about the different sensors and potential applications. They were very engaged in putting ideas down on the cardboard and kept adding detail, so in spite of its academic pen-and-paper nature, this was an activity that facilitated flow and had a good level of challenge for everyone who participated. Furthermore, curiosity was triggered by a sense of relatedness, autonomy and competency. As soon as examples were provided of devices "that are actually possible and not that hard to make," participants were eager to learn more. They were happy to use stickers, so this may have been a welcome element to increase control and perceived competency.

The outcome from the design experiment was a map of the design space by age and gender, which may be useful to design educators. It displays what kind of device kids chose to design, as shown in Figure 3.25. It can be seen that the older girls and boys embraced the idea of wearable devices for health, safety, and stress mitigation purposes, but these topics are of little interest for the girls up to the age of ten and boys up to the age of 12 that we surveyed. A cut-off age was observed around 11 for girls and 13 for boys, which is about when puberty sets in. While even young girls were very excited about this design concept in general, their desired project ideas were more embedded in the playful context of sports, taking photos and playing music, or simply purely artistic expressions of ideas around the form, shape and color of a wearable device. All age groups showed an interest in triggering music and using weather information.

Design Space by Age and Gender

Gender	Age	Wearable?	Health	Stress / Wellbeing	Safety	Privacy	Smart Home	Text Notification	Weather	Music	Picture	Device Technology	Action / Sports	Looks only
Male	8	No										x		
Male	11	Yes										x		
Male	12	Yes									x		x	
Female	4	Yes							x	x			x	
Female	6	Yes						x			x			
Female	8	Yes												x
Female	8	Could be							x					
Female	9	Could be								x				
Female	9	No					x							
Female	9	Yes	x											
Female	10	Yes										x		x
Male	13	No		x					x					
Male	14	Yes						x			x			
Male	14	Could be	x		x				x					
Male	14	Yes	x		x									
Female	12	Yes	x		x									
Female	12	No				x	x				x			
Female	13	Yes	x		x				x					
Female	13	Yes			x									
Female	13	Yes		x	x			x						
Female	14	Yes	x	x						x				

FIGURE 3.25: Design space map of different age groups for both boys and girls surveyed with the cardboard prototypes.

Figure 3.26 shows a photo of the booth at the MIT Museum with girls engaged in the design activity.

FIGURE 3.26: Photo of the activity with cardboard prototypes at the MIT Museum.

Out of the 35 completed cards we received, 25 opted to participate in a "raffle". Out of those 25, 22 picked their own invention as a prize (incl. all female participants). One girl debated for a very long time. $30 looked like a lot of money to her. But in the end, she decided to go for her creation instead. She reasoned: "Well, I have to pick my design. I can't get it anywhere else!" This shows that the autonomy to design their own wearable device is very appealing. This certainly shows the motivational, if not educational value of this activity. The three participants that picked the gift card prize instead were all from a group of adolescent boys, reflecting that they were not as interested as the girls in a toolkit like this. Unfortunately, the reasons for this were not investigated – it can be speculated that medical and social applications may be less appealing to adolescent boys than they are to girls, as argued by Andrews and Clark [48] as described earlier.

3.8 Conclusions

3.8.1 Use of Research Methods

The experiments presented in this chapter have laid out design affordances of different user groups, which are helpful in creating an optimal learning experience for a specific audience. Agile methods of user-centered design were developed for creating technology-enabled learning experiences. The presented techniques give engineers and designers practical guidelines for rapid prototyping of experiences and interaction that aim to impact students' mindset and perception and that are engaging and motivating to students. The experience targets motivational factors, specifically the relevancy / context dimension. The prototyping methods shown in this work help to test and refine user experiences early on, to make more confident system design decisions later on. This has been a valuable contribution to the field [113].

3.8.2 Strengths and Limits of the Designed Experience

Compared to similar learning experiences, the presented toolkit captures motivational dimensions that have largely been neglected when introducing youth to engineering – interpersonal motivation, a wide range of challenge levels, real-world applicability and youth-specific relevance. This was shown using the prototype-enabled experiments shown in this chapter.

With low barriers to entry but potential inputs for "real" code, this experience may offer a broad spectrum of challenge levels. Also, it may be designed to give immediate feedback and lets users pursue unique goals and customize their device in a specific direction in different ways. These factors qualify the learning experience as something that enables a flow experience in the learner.

It may also help learners establish a growth mindset in the STEM areas, specifically in engineering and design, since no particular configuration is better or "more right" than any other. By contrast, students can experiment with different configurations and see what works and what does not.

Another strength may be how fast a result can be reached, upon which the student can improve if desired. With different challenge levels, immediate feedback, and plenty of room for tuning and personalization, the experience is suitable for students with a wide range of tenacity levels [114], rewarding more perseverant students with more thoughtful results.

Lastly, the learning experience speaks to a number of the motivational factors cited in the Goals section. Addressed are not only factors for intrinsic motivation, such as (individual) relatedness, perceived autonomy, perceived, competency, and perceived control, but also Habgood and Ainsworth's [91] factors for interpersonal motivations, such as cooperation and peer recognition. This can be accomplished either with in-person workshops or with the online community we have designed.

A limitation may be that certain problem fields that may be relevant for many girls, such as renewable energy sources or manufacturing, cannot easily be incorporated to this kit.

Interview findings include the following (summarized in Table 3.4):

TABLE 3.4: Key interview findings.

• The toolkit concept was very positively received by girls, boys, parents, educators. • We were asked to make looks customizable. • Low barriers to entry are very important (i.e. no code, not even Scratch needed to get it working) and my "simple interface" idea was valuable. • Girls (and most boys) came up with applications incl. safety, sports, health, and were passionate about very impactful ideas. • Younger kids are eager to design, but their ideas are often not wearable but could rather be accomplished by a smartphone or homeware. • Profound mindset change observed in: (1) creative self-efficacy, (2) perspective on engineering

These learning points guide ensuing research and design.

Lead organizers from "Science Club for Girls" and "Learn to Teach, Teach to Learn" reacted very positively to the design and prototypes. They offered help testing it by hosting workshops with prototype toolkits. There is a possibility that, eventually, they could use this toolkit in their workshops and classes.

With "playtesting" and outreach it was assessed that youth, especially girls, enjoy the design activity and desire a device built after their own design, even over a cash prize. However, more questions remain to be answered about motivational dimensions of the design activity itself and of students who would engage in it.

The following step was to fully design and prototype the learning activity, and consequently evaluate it using experiment or focus group. As shown in Chapter 4, circuit boards, software, and electromechanical connectors had to be combined to fully develop the learning activity. As shown in Chapter 5, self-efficacy questions about engineering were asked before and after the activity in experiments and in focus groups to investigate whether self-efficacy in engineering had improved.

3.8.3 Next Design Steps

The next step was the development of hardware and software. From the mockup prototypes presented in this chapter, guidelines were to be derived for works-like prototypes. This was a necessary step to capture the interaction with the device and evaluate important aspects, such as immediate feedback and real-time collaboration. On a basic level, circuit boards, enclosures and connectors had to be assembled to physically implement the concept. The sensor modules needed to be on their own circuit boards and have unique identifiers for easy coupling and protocol communication. One essential design activity was to implement all the sensors and indicators that were used. This was needed to cover a wide range of applications that may be important to students.

Finally, a community website had to be designed and built to serve as a social hub for all students, especially those unable to locally connect to fellow students. A community can then grow and and provide more feedback as to how this learning experience can best fit the needs and motivations of middle school girls to encourage them about experimenting with STEM.

FIGURE 3.27: Vision for the device kit. In a box, the student would find a core device, sensor modules, a bracelet attachment, and instructions to get started.

Chapter 4

Designing a New Device Ecosystem

The initial studies with sketch model prototypes demonstrated a great potential and showed that the creative experience may deeply affect the mindset towards engineering. To investigate this in practice, a working solution had to be implemented. The findings from the previous two stages of initial testing were used to guide the transformation of the design activity concept into a workshop that would allow participants to design and create real devices.

4.1 Requirements

To create a modular device platform that is viable and applicable to the educational space, the following design requirements were derived over the course of multiple studies (see Appendix C for an overview of all studies):

TABLE 4.1: Key functional and technical feature requirements for the educational device system.

Requirement	*Observed in studies*
Microcontroller or –computer base unit with detachable sensors	all
Size limit: Apple Watch or other wearable	Focus groups
Connection to web interface accessible from computer, Chromebook, or iOS device	SCFG
Real-time graphing of sensor measured values	SCFG
Implementation of custom programs by user	SCFG
Display on device with sensor information	BS
Guidance materials	BS

Many iterations of the device platform were created and used in subsequent studies to extract and refine these requirements.

4.2 System Architecture

Since the original concept [92], the overall system was to consist of a microcontroller or microcomputer small enough to be worn on the wrist with provisions for attaching sensors. To engage with the output of those sensors in a meaningful way, the device would connect to a web interface accessible from a computer. The architecture was refined over the course of multiple studies to its present implementation.

4.2.1 Layout

For a singular user instance, the system works as shown in Figure 4.1.

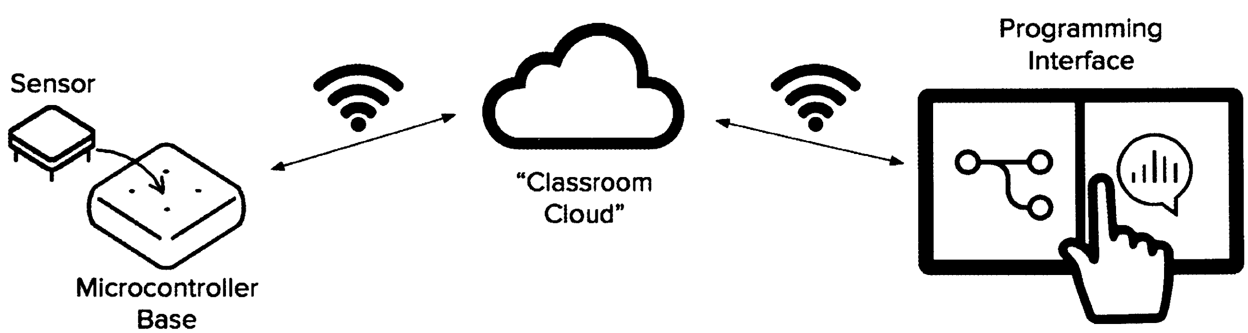


FIGURE 4.1: General system architecture. A base computing unit communicates with a sensor and streams sensor values to the cloud. A programming interface is also connected to the same channel.

Figure 4.1 shows the hardware modularity on the left-hand side and software modularity on the right-hand side. The implementation of both aspects will be detailed in the following.

4.2.2 Hardware Modularity

The purpose of hardware modularity was to allow the user to attach different sensors and thus use create a device for very different applications. These sensors can be digital or analog. Sensors usually require a power-input, ground, and an analog or a digital output. Many sensors today use a supply voltage of either 3.3V or 5V. Since 3.3V can be supplied by many compact batteries, this was the voltage chosen for the sensor connection.

While an analog sensor communicates with a voltage that's a fraction of the supply voltage using a single wire, digital communication is usually more complex. Here, I2C is a protocol that reduces this complexity to only two wires; one for providing a clock signal (SCL) and one for communicating (SDA). The protocol regulates how the master, here the base microcontroller, prompts sensors for their output signal. A number of sensor breakout boards can be obtained, which are already programmed for this type of communication. Suppliers provide an I2C address for each component.

To provide the connections for 3.3V, ground, analog, and two I2C-configured digital inputs on a base microcontroller board, female header pins were soldered to the board. In a first iteration, sensors had long lead wires that could be plugged in to these header pins.

Figure 4.2 illustrates how the connection procedure was implemented with embedded electronics.

The base microcontroller board was implemented using an ESP8266 breakout board. The ESP8266 is a system-on-a-chip with a Wi-Fi-connected microcontroller, which can create a Wi-Fi hotspot or connect to existing wireless networks. It can be programmed using Arduino IDE using available libraries.

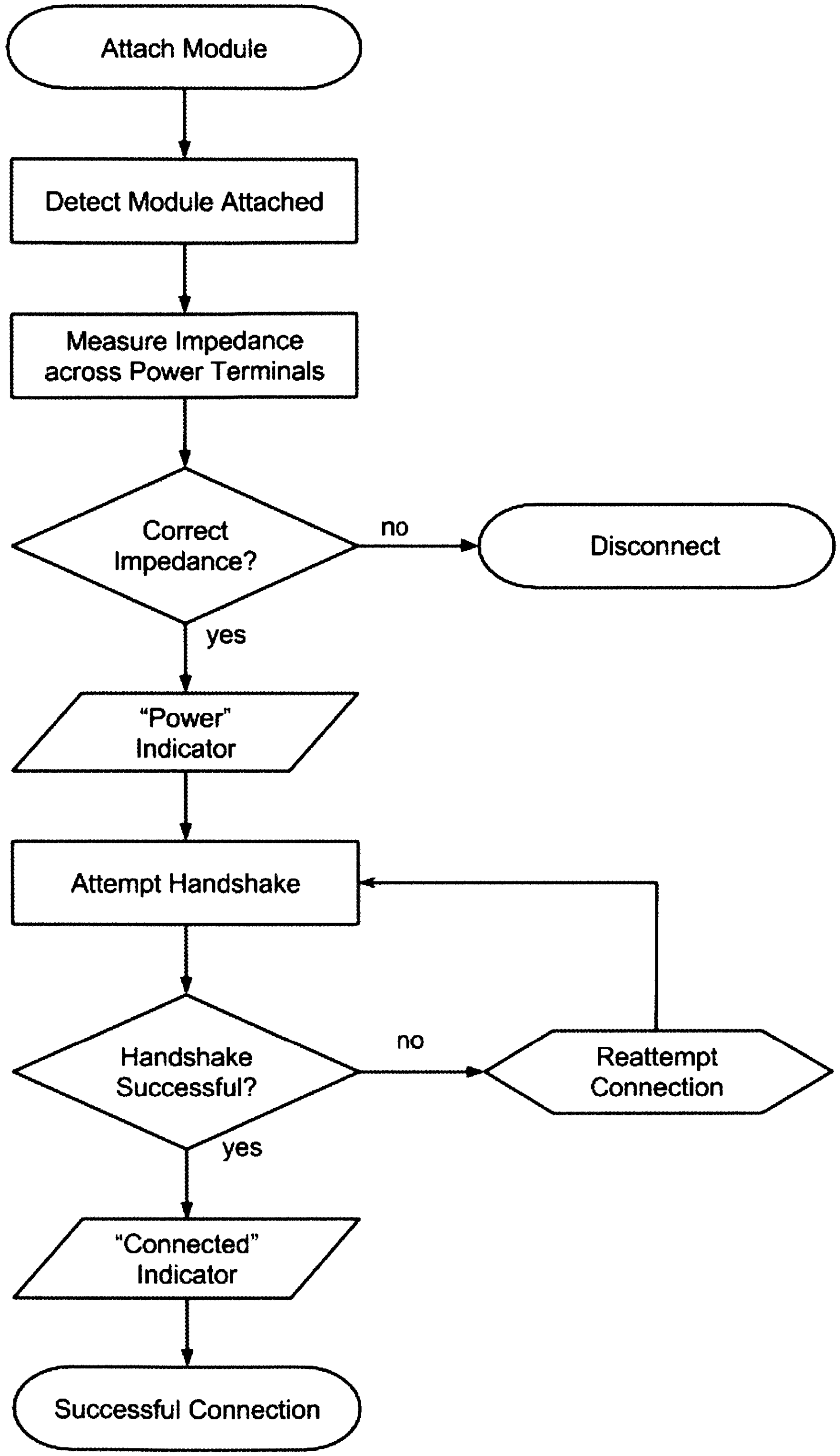


FIGURE 4.2: Flow chart for sensor attachment, from the author's filed patent application [92]. Later, an I2C address was also used as an identifier. The main device microcontroller automatically detects which type of sensor is attached to make subsequent steps easier and allow for a fluid assembly experience.

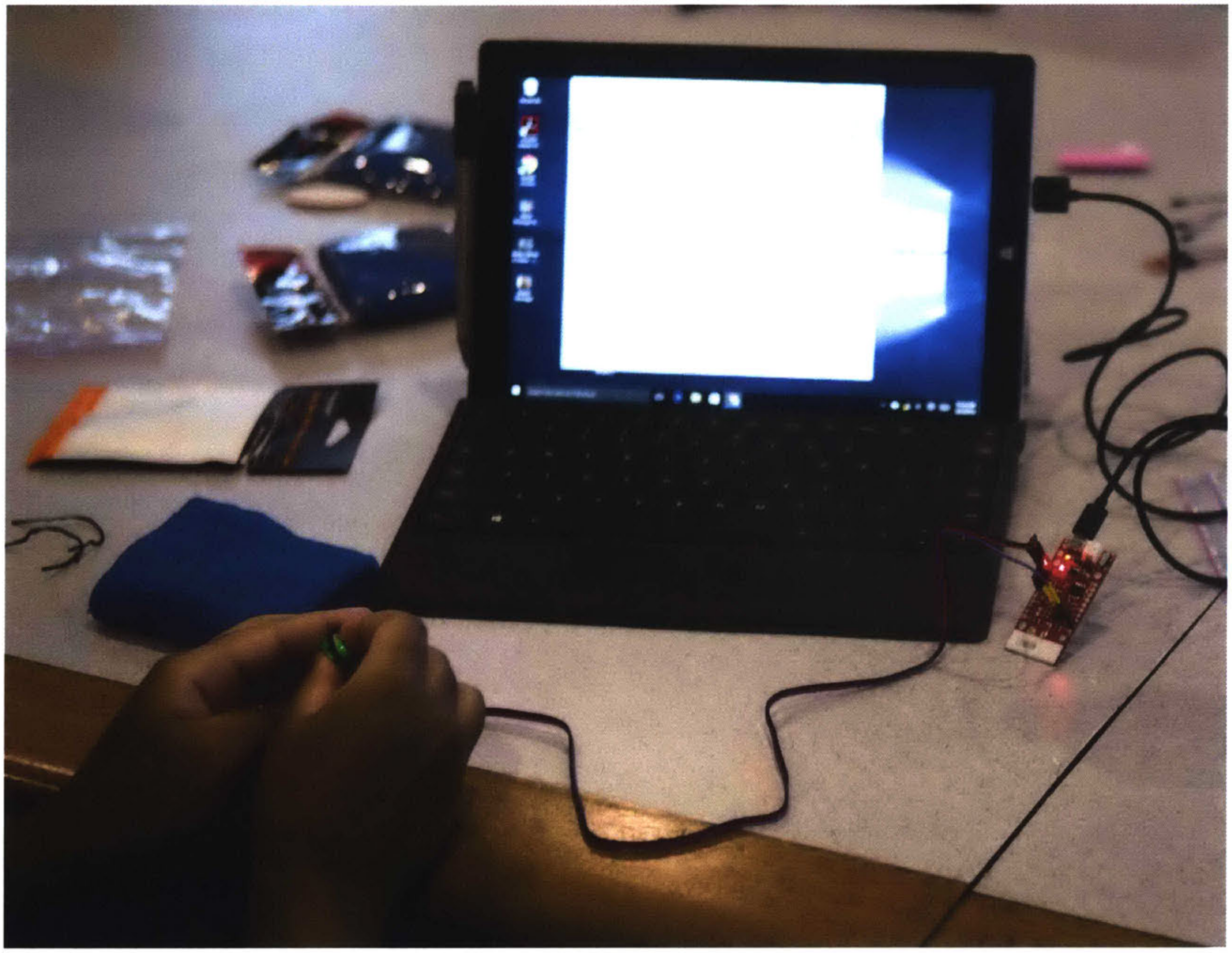


FIGURE 4.3: Device version as used at the first workshop in August 2016. A board was powered via USB; sensors could be connected by plugging into header pins. Sensors had long wires so they could be placed underneath a wristband and touch the skin, while the circuit board would be safely stored in a pocket. The interface allowed for checking live sensor values.

Once the size of base microcontroller board was reduced to that to a more compact smartwatch format, the sensors were designed in such a way that short, color-coded wires were rigidly attached, and extended from the sensor board in such a way that would fit with the header pin pattern on the base device.

FIGURE 4.4: Sensor with short, extended wires, attached in a compact fashion. Sensors can be connected by plugging wires into header pins. As in electrical standards, the red represents supply voltage and black represents ground. In addition, blue represents SDA, white represents SCL, and yellow (see empty pin on top left) represents the analog sensors signal.

Subsequent system iterations might have standard electrical connectors combining all the required connections, similar to many every-day electrical connectors. This might allow the attachment of multiple sensors at a time. However, in focus groups and experiments, many participants said that they enjoyed the activity of matching the wires with the pins.

Commonly used sensors in this kit were: acceleration (called "motion" for simplicity), temperature, and pulse. GPS was requested occasionally, but mostly in conjunction with other sensors. Light sensors or UV sensors were very rarely asked for, similarly to pressure sensors or force sensors.

4.2.3 Software Modularity

The original concept entailed a connected interface on which the creator could configure their device to respond in certain ways to a certain sensor measurement or other type of input. In an example shown in early focus groups, a given heart rate would trigger sending a text message to a friend. This early interface (see chapter 3.4.3.2) had a split layout with a condition ("when") on one side and an action ("then") on the other. A programming interface version was also proposed, in which the users could create a more complex program.

During workshops with the first modular-hardware prototypes, it became clear that participants wanted to "really make" something. Furthermore, it was observed that even real-time numerical sensor output was still confusing to some, and a graphical representation of the sensor output over a moving time frame helped enormously with the understanding. Thus, a way had to be found to represent sensor data in a time graph.

A number of open-source projects provide such real-time graphing abilities. Most of these require constant internet connection to use certain scripts to represent the graph visually. This determined how the modular hardware device would communicate with the interface device: via a cloud network through which a multitude of devices could pass their sensor signals and to which a multitude of interface devices could be connected.

To permit users to create their own programs graphically and without much prior coding knowledge, a particularly suitable solution was found in IBM's project "Node-Red". Node-Red is an open-source server application that runs on node.js and that can be installed on any personal computer (Windows, Mac, Linux) or server as small as a Raspberry Pi. It offers a graphical programming interface with blocks for inputs, outputs and logical functions. Inputs and outputs can be internal to the program and may be triggered directly by the user, as well as connect to various web services, such as send or receive email, to and from Twitter, etc. A graphical "user interface" can also be created.

Another popular web service for interfacing with Node-Red is MQTT, often hosted on the same server as Node-Red itself. MQTT may be explained as "walkie-talkie for data" – an MQTT broker can have any number of channels uniquely identified by name, and whatever is sent to a (public) channel can be read out by any connection "listening" to it. This makes MQTT very popular for IoT-purposes. Internet-connected devices will stream data to an MQTT channel, and a website can read them out, or vice versa.

To implement a graphical programming interface and connection to the device and sensors, Node-Red was used in combination with MQTT. Mosca was the MQTT broker of choice, as it is an open-source application for MQTT that can be installed on any Ubuntu server with ease.

One of the limitations of Node-Red is that only one user can make changes at a time. One can imagine that a classroom full of teenagers would not work this way. To allow for a multitude of parallel inputs, Node-Red configured to run inside a container on a Linux server, so multiple containers could be run and managed alongside each other.

The base microcontrollers were thus programmed to connect to a nearby wireless network and to stream sensor information to an MQTT channel. The chosen rate of 4 Hz was enough to perceive it as "real-time" in interacting with the device, but a rate low enough to ensure that neither the network nor server would be overloaded.

The first implementation of this was on an Ubuntu server installed on a MacBook Pro, which had a Wi-Fi USB adapter to create a local Wi-Fi network. The setup is shown in Figure 4.5.

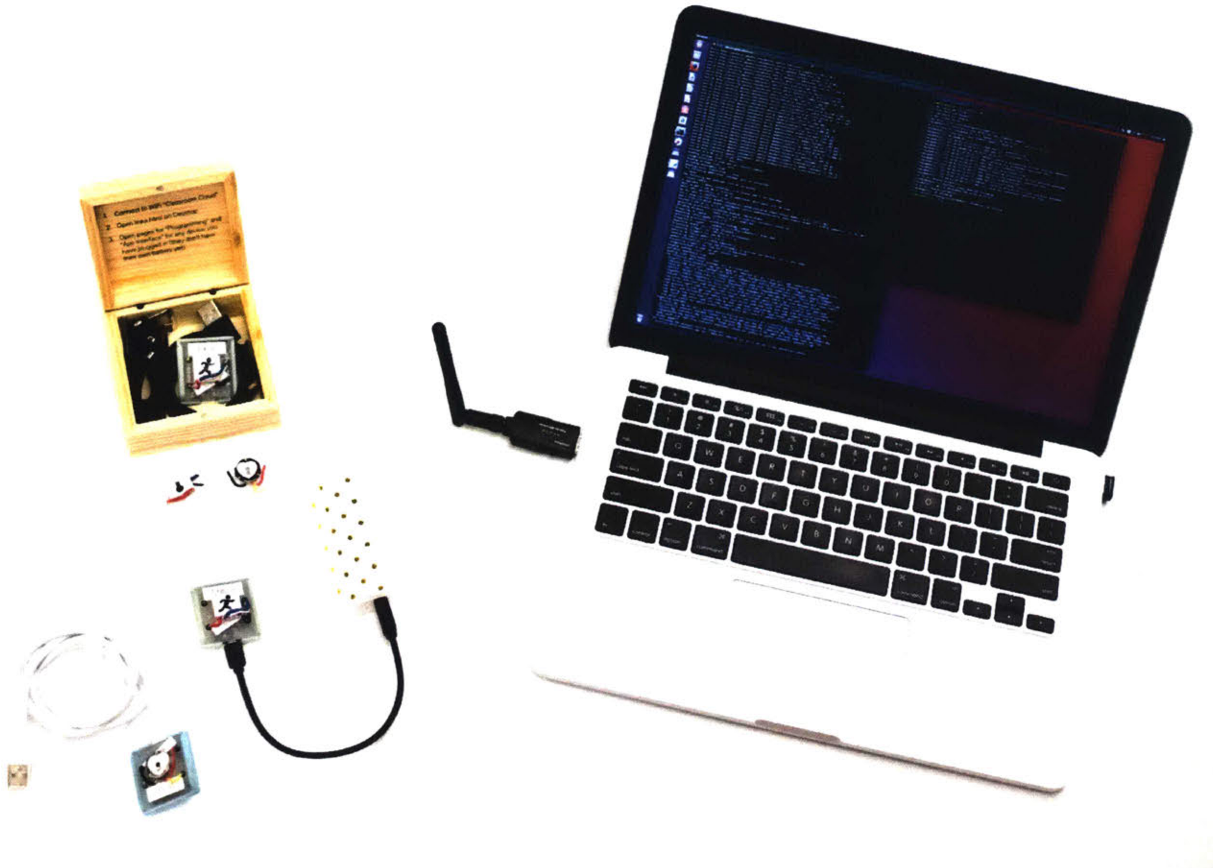


FIGURE 4.5: Server setup in fall 2016. The application was hosted on an Ubuntu server on a MacBook Pro, using a Wi-Fi dongle to create a wireless access point.

The multi-instance Node-Red application and MQTT service were later migrated to a high-performance Ubuntu server on MIT's network.

Node-Red is developed by IBM computer scientists using vocabulary that speaks primarily to other computer scientists. Much of the work of this dissertation was spent changing the vocabulary and info descriptions in a way that would speak more to the common middle school or high school student or non-engineer. High school students with STEM outreach experience contributed significantly towards this goal by helping to rewrite the entire frontend content.

4.2.4 Challenges

There were a number of technical challenges that had to be overcome over the course of the development. For example, Node-Red is a relatively new open source project. A number of extensions are available from 3rd party developers. However, many issues still exist in practice. Graphs may not show data before applying certain formatting options, features may be poorly documented, etc.

On the hardware side, a number of ESP8266 boards were less durable than others. For example, Sparkfun boards would stop working for no particular reason, while others were more reliable.

Also, as some components were sourced directly from Shenzhen, China, where they were produced, it was experienced first-hand that the design might change, e.g. dimensions of a breakout board might change without warning.

4.2.5 Conclusion: A New Hybrid Mode

It was observed that for many learners, a wait between connecting something physically and seeing it work (or not) once powered can be very distressful. This was especially true for context of learning electronics, such as wiring circuits or programming Arduino microcontrollers. This moment of uncertainty had to be overcome; or as constructionists would say, the experience had to be "tinkerable", with every change immediately reflected and the creator always being perfectly in the loop about his or her creation at any given point in time. Preprogramming the microcontroller boards to automatically detect and stream sensor values achieved this purpose of closing the loop around the creator. Few existing solutions combine the openness of this modular piece of hardware with the added comfort of a microcontroller pre-programmed to act in ways that give the creator so much freedom.

4.3 Features and Design Iterations

4.3.1 Hardware Discussion

4.3.1.1 Sensors

All toolkits were made with a motion sensor and a pulse sensor. It was observed that students generally knew that both are used in Fitbit devices, and they were expecting these sensors and curious to try them.

Students were also interested in Temperature sensors. In an early study, a few students kept asking until a temperature sensor was available. Temperature sensors can be used to monitor a person's health, create "lie detectors", and measure ambient temperature. All these applications were interesting to the students, although individual interest certainly varied.

Some students asked for GPS. Students generally did not ask for light sensors, UV sensors, orientation sensors (magnetometers) or pressure sensors, but some of the desired applications may benefit from using these different sensors. It would thus be worthwhile to explain to students how these sensors can be used.

One of the most desired applications for students across the board was measuring "emotion". Other desired applications included sports-monitoring, e.g. gauging how a ball is thrown, as well as simple communication tasks, such as sending kind text messages to family members.

4.3.1.2 Display

Since many girls asked for a display in the earlier workshops and experiments (7 of 10 girls said a display would help and provide guidance, when they were asked how a display would change their experience, with no comment from 3 of 10 girls), it was clear that a display should be integrated. Of course, this would increase the overall size of the device – a sensitive point for the target group, as identified in early focus groups. It was hoped that a thickness increase of 3-4 millimeters would be tolerated, but it was important to test this assumption. Especially preliminary focus groups revealed that it was important to girls that the device has aesthetic appeal and is very compact. In this light, alternatives should be discussed. For example, there may be a way to provide the clarity and guidance that a display promises without an actual display. However, it was confusing for many girls that a device with sensors in it would not have a display; even a small one; given the technology we are surrounded by nowadays (smartphones etc.)

A display was integrated using a commercially available I2C-compatible breakout board with a 0.96" display. It was connected to the I2C connections of the main microcontroller board. The device housing, then 3D printed for rapid prototyping purposes, was adjusted accordingly, roughly aiming for the format of an Apple Watch. A picture is shown in Figure 4.6.

The microcontroller was reprogrammed to display sensor information on the first line and to display incoming data from a display-specific MQTT channel below, i.e. the opportunity was used to let students display information, even automatically generated information, on the display of their device.

Participants in workshops after the display implementation reacted positively to the design change.

FIGURE 4.6: Device with display.

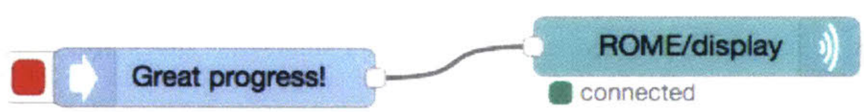


FIGURE 4.7: Exemplary program for sending pre-defined text to a display.

4.3.1.3 Discussion: Reduction to Digital Modularity

The idea of using an iPhone app with access to iPhone-integrated sensors as an alternative to the design activity was discussed, but rejected by female learners. It was brought up because workshop leaders may want to save money and run an actual workshop with smartphones and the cloud interface. However, students would be likely to say "why develop a step-counting app for my phone if my phone already has one?" Furthermore, underprivileged students, who we need to think of especially, may not have a smartphone, so we would discriminate a group that may benefit from this project the most.

4.3.2 Levels of Built-In Guidance

Since many students had asked for guidance, multiple paths were chosen for answering any questions during the activity. A key objective was to offer help in places that are easily visible and accessible during all aspects of the creative process: the web editor as well as hands-on hardware creation. These guidance materials may be supplemented by an additional documentation given on a website.

4.3.2.1 Guidebook

A guidebook was created in the form of a booklet with 8 pages. It was meant to offer guidance with big-picture questions, such as "what can I make with this?", or "how else can I personalize this creation?" It contained general advice for getting started: how to assemble the device, how to access the web editor, and where to find more help and detailed information about the different elements.

The guide booklet was structured as laid out in Table 4.4.

TABLE 4.2: Guide booklet structure.

Page 1: Simplified, graphical overview with 4 steps
Page 2: Welcome, connect device to internet, access program editor and overview
Page 3: Program editor: how-to; button and sensor examples
Page 4: "Design your App", options, first example, fun facts
Page 5: "Making it Wearable", ideas for materials and design tools
Page 6: "Share and Make Followers", web sharing platform link
Page 7: "Stuff you Can Make", list of examples (easy, medium, hard), encouragement
Page 8: Thank you, web link for ideas, more guidance, and contact

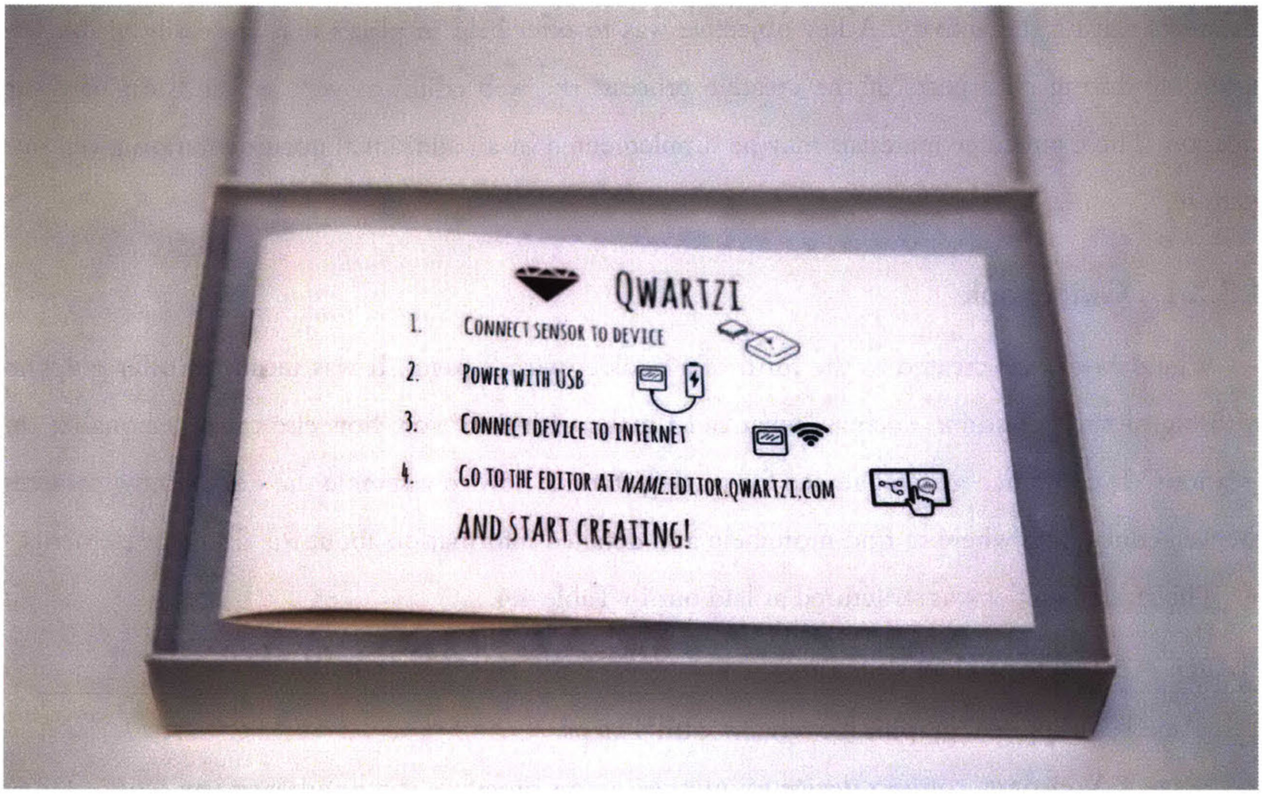


FIGURE 4.8: Guide booklet on top of toolkit with quick overview.

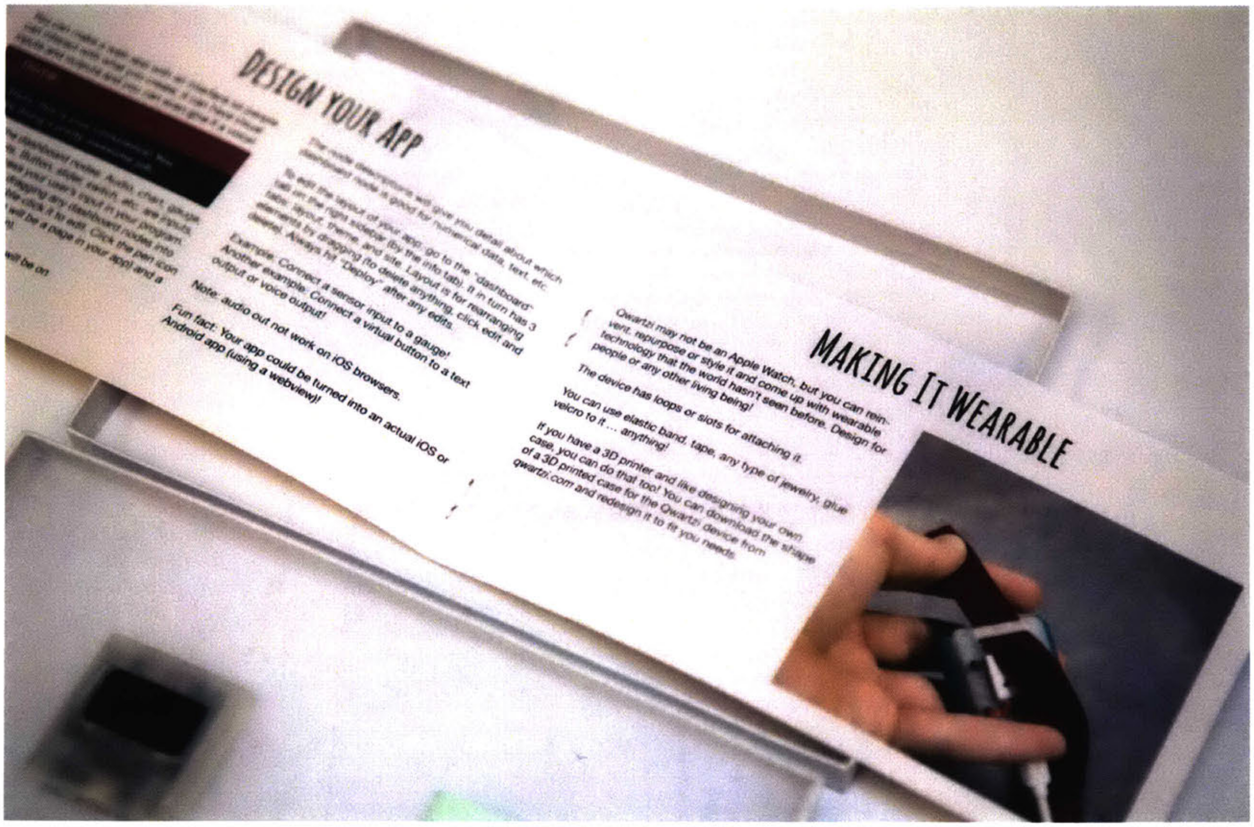


FIGURE 4.9: Ideas and inspiration for personalization and activities: the main purpose of the booklet.

The complete guidebook can be found in Appendix G.

4.3.2.2 Editor Info Tab

Experience shows: students want access to help, like a book that can answer all their questions, but they want to never really have to use it. The key is thus to have guidance always available just a single click or swipe away. Certainly, attempting to explain all the editor interface's elements in a document would yield a very long list. Equally, drastically reducing the number of nodes (or functional elements) from the interface would result in a rather limited creative activity. The key is to have the information ready, right where it is needed. Conveniently, Node-Red has a built-in feature for displaying node-specific information in a side bar. Originally with Node-Red, of course, descriptions are targeted at a much more technical audience than teenagers, so they had to be rewritten for the sake of this educational toolkit.

Examples are shown in Figure 4.11 and Figure 4.12.

FIGURE 4.10: Toolkit with program editor on device. Editor with info-tab on the right-hand sidebar.

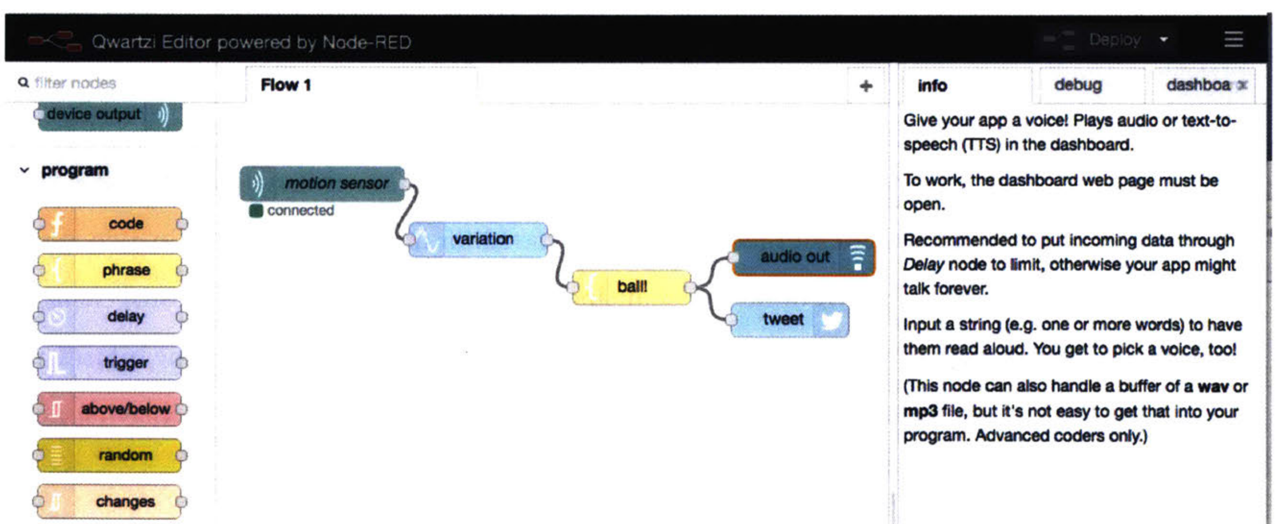


FIGURE 4.11: Editor with info-tab on the right-hand sidebar.

Write your own code to solve challenging problems!

This has to be Javascript. (Many websites and mobile apps are coded in Javascript. Hint: It's very different from Java, don't confuse the two.)

Some example code (the input is a number here and this will add 1 to that number):

```
var input = msg.payload;
var output = input + 1;
return {payload : output};
```

Some rules to get you started:

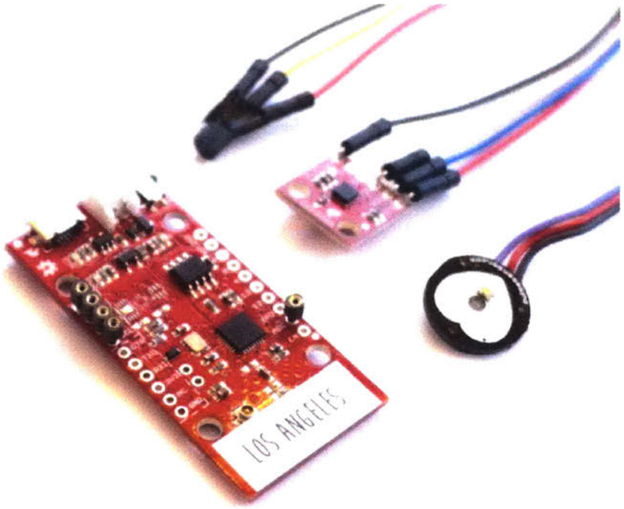
- Refer to the incoming data as *msg.payload*
- Define variables with *var some_new_variable_name*
- Every line has to end with a semicolon ;
- Variable names can not have punctuation in them except underscore _
- If you are working with numbers, keep the math simple (+,-,*,/). For more advanced math, use the Javascript Math functions.
- To work with text, put quotes around things you want to add, like *var name = "Anna"; var greeting = "Hello " + name;*
- You can overwrite variables as often as you want, like *some_variable = some_variable + 1* to augment *some_variable* by 1
- At the end of your code, create an output using *return {payload : some_variable};*

FIGURE 4.12: Description for the *Code* node. A few quick steps have the most important instructions for writing JavaScript code and illustrate its significance.

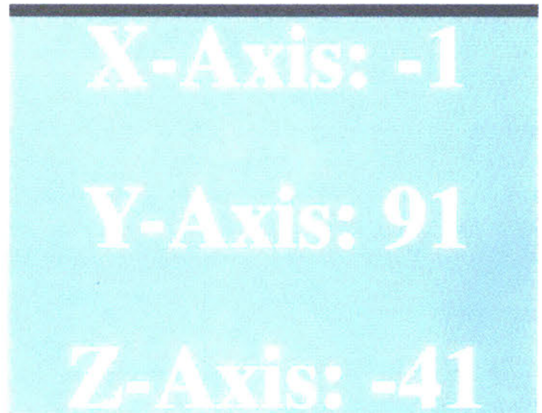
4.3.3 Design Iterations

4.3.3.1 Revision I: Wireless, modular hardware kit

The first revision of wirelessly connected, functional prototypes consisted of a microcontroller board with an analog temperature sensor, an analog pulse sensor, and a digital 3-axis accelerometer. The microcontroller was configured to create a Wi-Fi hotspot. Upon login to that hotspot, a window would open that allowed users to select live sensor measurements. Both hardware and interface are shown in Figure 4.13.



(a)



(b)

FIGURE 4.13: Device version as used at the first workshop in August 2016 with Science Club for Girls. (a) A board was powered via USB, sensors (temperature, acceleration, pulse) could be connected by plugging wires into header pins. (b) The interface allowed for checking live sensor values (here: 3-axis acceleration).

FIGURE 4.14: Photos from workshop in summer 2016.

All electrical components were sourced from Sparkfun. For 13 workshop participants in a multi-day workshop, there were 13 microcontroller breakout boards, 10 acceleration sensors, 3 temperature sensors, and 3 pulse sensors. Furthermore, participants were given sweatbands with zipper pockets in which the microcontroller boards fit. Microcontroller boards were programmed to broadcast a Wi-Fi network and to provide a website that provided sensor values.

4.3.3.2 Revision II: Modular Visual Editor for Modular Hardware

A second revision included a modular visual editor for this modular hardware. The visual editor was created using Node-Red as described above. The complete kit is shown in Figure 4.15.

FIGURE 4.15: Overview of device with connected programming interface. This was used for workshops in the fall of 2016 with a middle school science club and a group from Big Sister of Boston.

FIGURE 4.16: Girls navigating the interface during a workshop.

The process of designing this version of the toolkit consisted of the following steps:

- Assessment from previous workshops (software):
    - Participants need creative freedom and experience truly creating something
    - Participants need better graphical representation of sensor values, e.g. time graph
- Comparison of existing solutions for both (e.g. various time graph packages)
- Identification of Node-Red, which allows to solve both problems in an integrated solution
- Limitation: Only one connection at a time can make changes on any Node-Red applications, solution: creation of a multi-instance manager via Docker to simulate multiple systems on the same server
- Identification of MQTT and service for wireless communication of devices with server
- Implementation on Ubuntu server on portable computer:
    - Node-Red with multi-instance manager (Docker application)
    - MQTT (using Mosquitto service)
- Program devices to:
    - Recognize attachment of sensors via I2C
    - Continuously take measurements with attached sensors
    - Broadcast sensor measurements via MQTT

- Assessment of previous workshops (hardware):
    - Relatively large breakout boards and large wires were unfamiliar objects
    - Analog temperature sensors broke easily, furthermore with temperature sensor and pulse sensor both analog, automatic identification by microcontroller was not possible
- Identification of smaller and more robust microcontroller board with same functions as before
- Design and 3D printing of enclosures, roughly "Apple Watch" form factor, removable (3D printed hinge and snap closure)
- Identification and implementation of robust temperature sensor breakout board (I2C)

About 20 devices of this revision were created for workshops.

4.3.3.3 Revision III: Intuitive, Instantaneous-Feedback, Modular System

In a next revision, a display was added to the device to guide the user as discussed above, and the interface was significantly improved.

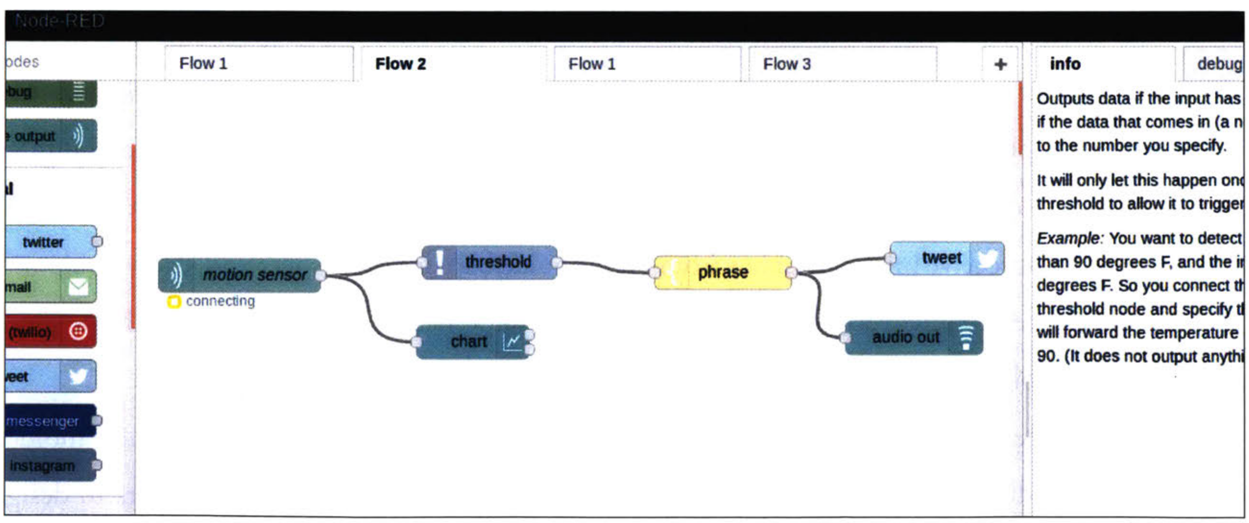


FIGURE 4.17: The interface after changes to the language in early 2017.

The Node-Red based interface received a thorough make-over. Many nodes (function blocks) were added, changed or removed. The vocabulary was changed significantly, both of node names and node descriptions. Unreliable or very confusing nodes were removed. Also, the Node-Red core system was updated inside the Docker multi-instance manager – not a trivial task, as certain parameters sent conflicting information, resulting in a repeated breakdown of the multi-instance manager until a seemingly insignificant condition statement in the core Node-Red files was manually changed. This upgrade, however, improved the system's overall reliability and added valuable features (such as merge changes).

A display was added to the design and the case was re-designed as discussed in chapter 4.3.1.2. The case lid with display cutout was re-designed multiple times to compensate for the material's brittleness in case a device is dropped.

A guidebook was designed and printed to guide students in case they get lost and for at-home activities.

About 30 devices of this revision were created for workshops.

4.4 Final Toolkit

After the third and last revision, the resulting toolkit was a product consisting of a core device and sensors, complete with a printed getting-started guide. It was packaged in a glossy white box with dimensions of 8 inches wide by 5.5 inches deep by 1.25 inches tall. The device was placed on the left, with sensors next to it in a row, while different color ribbon was placed on the right-hand side, inviting to "actually make it a wearable", as one of the girls had expressed her wish in an earlier workshop. The printed guide was printed on glossy, thick paper, formatted as a booklet with a saddle-stapled binding. It was placed on top of the toolkit, similar to how many electronic devices are packaged. This way, students would first receive initial guidance from on the guide booklet cover sheet and know to identify the components, before uncovering the toolkit as laid out underneath, ready to get started, the guide reassuringly available for any eventual questions.

The core device was enclosed in a 3D printed case. Although the case could be injection molded in the future to reduce production costs, the 3D printed case was meant to invite students to design their own case and 3D print it at their school, library, or makerspace. The device was equipped with a micro-USB connector; through which it was powered with a USB battery pack that was supplied with the toolkit. The device name is noted on the device with a sticker. Device names are taken from big cities with names that have less than 6 characters.

FIGURE 4.18: The complete toolkit with device, sensors, ribbon and guidebook.

As soon as the device was powered up, with or without a sensor attached, it tried connecting to the internet. If a wireless connection was previously set up, the device automatically connected to that network as soon as it was powered. If no stored network was in range, the device broadcast its own wireless network with the device name to allow for setting up a connection. The program editor could be reached using any internet-capable device at http://*devicename*.editor.qwartzi.com. Should students choose to create their own app to go with their device, their app could be reached at http://*devicename*.app.qwartzi.com.

At workshops, creative tools such as scissors and pens were supplied as well.

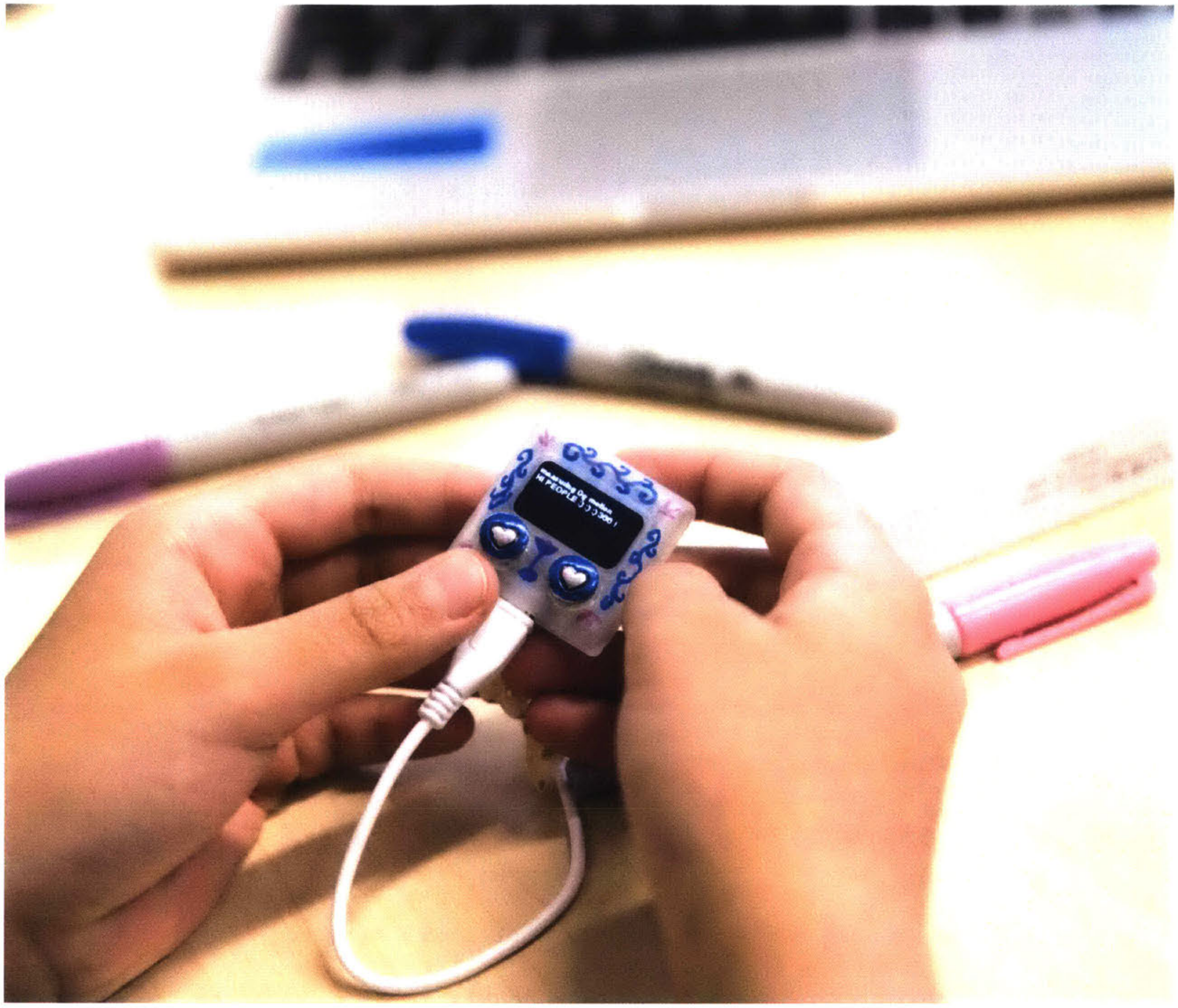


FIGURE 4.19: A personal device created during a workshop.

4.5 Curriculum Development

To use the developed system in a STEM learning environment, a 2-hour curriculum was developed. The curriculum was originally conceived together with educators from Science Club for Girls [115] for a 1-week workshop, which also encompassed activities like a Fitbit site visit and outreach to younger girls based on what was learned during the previous days. The workshop participants were high school students from the Boston area They had participated in science outreach activities before, but only one student noted prior coding experience. The purpose was to introduce students to wearable technology, understand how the technology works at a fundamental level (sensor input, computation, output), empower them to create a device of their own, to reflect meaningfully about engineering and their own inventive skills, and to share their knowledge with younger students at the end of the week.

The workshop days were structured as laid out in Table 4.3.

TABLE 4.3: Structure of a 5-day workshop conducted with Science Club for Girls.

Day 1 – Intro:

- Intro to product design, brainstorming, user centered design (20 min)
- *Maybe*: Activity "design a Swiss army knife for a target group of your choice" (15 min)
- Intro to wearables, quantified self, assistive tech, quizzing examples (20 min)
- Intro to this week's project (20 min)
- Computing (30 min) - input, computations, output
- Sensor & input / output basics
- Different categories / industrial applications (15 min)
- Intro: Wearables in athletics (15 min)
- How does a pedometer work? How does the Fitbit use math? (15 min)
- *Lunch*
- Brief intro to challenges with: design, production, marketing, IP; activity (45 min)
- Ideate questions to Fitbit (15 min)

Day 2 – Build your own:

- Intro to toolkit (10 min)
- Brainstorm devices with available modules (10 min)
- Activity (groups): tinker with toolkit. Remix examples to sketch concepts, present to group of ≈3, critique, create a device of your own (45 min)
- *Lunch*
- Ideate a product and marketing campaign (30 min)
- Present to group (30 min)

(continued)

TABLE 4.3: Structure of a 5-day workshop conducted with Science Club for Girls (continued).

Day 3 - Fitbit visit:

- Go over Fitbit questions (9:30 am - 10 am)
- Head over to Fitbit (10:15 am - 10:45 am)
- Fitbit tour (11 am - 1 pm)
- *Lunch*

Day 4 – Prep for teaching:

- *Maybe*: Advanced sensors; brainstorm cool devices (45 min) - if there is time
- PD Workshop (10 am - 11 am)
- Prepare design activities (1 - 1.5 hrs), *break for Lunch*

Day 5 – Share and reflect:

- Get ready for teaching (+ transport?)
- Teach back (9 am - 11:30 am)
- Debrief / reflection, *Lunch*

From this curriculum, a shorter 2-hour workshop format was derived. This shorter workshop was used in a number of workshops and was the basis for most experiments discussed in the next chapter. It is laid out in Table 4.4. Introductory examples may vary by students' experience level.

TABLE 4.4: Two-hour workshop procedure.

5 min	Complete pre-questionnaires
10 min	Introduction to wearables, sensors, input / output
5 min	Intro to toolkit with example
25 min	Activity: Create application with toolkit based on examples and own ideas
10 min	Break
25 min	Continue building activity
10 min	Present to another match (groups of 2 matches), critique (2 x 5 min)
5 min	Reflect upon product purpose
15 min	Present to the class
10 min	Post-workshop questionnaire

In collaboration with Buckingham Browne and Nichols Middle School Science Club, a curriculum was developed for the course of multiple weeks. Over this period of time, every class can be themed in a way that allows contextualizing the activity and diving deeper into individual concepts.

Lessons can build on each other as follows:

Week 1: Introduction, motion sensors, first use and discussion

Week 2: Temperature sensors, context: health, stress, feelings

Week 3: Pulse sensors, excurse: how does our pulse work?

Week 4: Final challenge or individual project

By allotting a sufficient amount of time to this learning activity, it is possible to leverage the potential for contextualized learning. The developed toolkit is applicable to a variety of real-world problems that might be an integral part of any science curriculum. It can be used to monitor greenhouses or understand the body (biology) or physical and mechanic phenomena (physics). Next Generation Science Standards (NGSS) offer various contexts for using the presented activity and learning concepts in a practical and intuitive way, while also deepening technical ability and confidence.

4.6 Summary

A modular system was developed for creating smart devices – open hardware and open software. In its current form and with changes implemented in response to the presented studies, the toolkit consists of a wireless microcontroller with a display and attachable sensors, which can be programmatically extended using a graphical programming interface. The graphical programming interface runs on any internet-connected browser. Possible creations based on this toolkit include custom activity trackers, smart home devices, simple health devices, etc. This design toolkit is meant to make technical creativity more socially relevant to teenagers and other socially motivated learners.

Many features were implemented as a response to user feedback. The result is a less than 1.5-by-1.5-inch sized device (1.4" by 1.5" by 0.5"; or 36mm by 37mm by 13mm), which can act as an accelerometer, a thermometer, or a pulse sensor, which shows sensor information and user-specified output on a display. A graphical programming interface let users drag-and-drop functional, digital modules to create a program with or without coding. A functional smart device can be created in minutes.

The design of this device toolkit was led by the needs of 12- to 15-year-old girls. However, such a modular, open hardware platform may equally serve rapid prototyping needs of engineers and inventors of any age, gender, or professional background. The toolkit allows users to create functional embedded devices for a number of purposes, making it a potential prototyping tool for a variety of industries.

Chapter 5

Experiments and Analysis

To test the efficacy of the developed system for STEM education purposes, workshops were arranged and participants were asked to provide quantitative and qualitative feedback that would allow detailed analysis and testing of the original hypothesis: If a toolkit such as the one developed can increase teen girls' self-efficacy in and perception of technical and creative areas.

5.1 Questionnaire Development

To judge the efficacy of the developed learning experience for raising middle school girls' perspective on engineering, questionnaires were used to assess students' perspectives both before and after a workshop, so experiments could be conducted with groups as big as a school class.

5.1.1 Conceptual Basis

It was expected that by making engineering problems more engaging and relatable, it would be possible to build self-efficacy and intrinsic motivation in middle and high school girls and to promote creativity and "invention" of innovative products.

The questionnaire was constructed to assess the following:

- Can the presented toolkit help increase self-efficacy in "technical creativity"?
- Can the presented toolkit help increase self-efficacy and interest in STEM?
- May STEM and engineering interest be coupled more with "technical creativity" or product design self-efficacy than with math self-efficacy?
- How are different aspects of the toolkit and activity rated and what can be improved?

Separate question clusters for self-efficacy and interest were used to specifically answer these research questions.

5.1.2 Initial Questionnaire

Pre- and post-workshop questionnaires were drafted with the following elements: (1) self-efficacy questions, (2) interest questions, (3) general feedback, and (4) motivation-related questions. Pre-workshop questionnaires were to consist of self-efficacy and interest questions only, while post-workshop questionnaires were to consist of both an identical set of self-efficacy and interest questions (to determine a possible change), as well as general feedback and motivation / engagement questions to judge aspects of the activity directly. To test a potential increase in self-efficacy in "technical creativity" and self-efficacy and interest in STEM, different questions were added about aspects of each. To test a possible correlation of STEM interest with technical creativity vs. math self-efficacy, a question was added about math self-efficacy as well.

In addition, the questionnaires included an open question about any prior STEM exposure, and asked for participants' age and name.

Questions were drafted with guidance from Dr. Bill Lucas (MIT). Notable points were to make self-efficacy questions short (max. 3 lines per item) and as specific as possible to prevent different interpretations. Bandura's findings were considered as well [116], including his finding that an 11-point scale is suitable for teenagers. Engagement questions drew from the "Intrinsic Motivation Inventory (IMI)" questions [117] that were also used by Ryan, Koestner and Deci [118] to assess engagement and motivation.

Questionnaires were proof-read and corrected by educators before they were used in experiments. The first questionnaire version can be found in Appendix D.

5.1.3 Revision of Questions after First Experiments

Initial questionnaires were used for an experimental 2-hour-workshop and a 5-week after-school-club intervention. The results of these experiments were used to review each question individually in order to shorten and improve the questionnaire. The pre-workshop questionnaire was thus shortened to fit on a single page, and the post-workshop questionnaire to fit on 2 pages.

Each of the questions is discussed in the following.

5.1.3.1 Prior experience question (open question)

This question was only on the pre-workshop questionnaires:

"What is your experience with science, engineering or technology?"

This question was designed to measure previous STEM experience and exposure that might influence the way participants learn, e.g. to relate a moderate self-efficacy increase to previous knowledge. The word "prior" was added so it reads "What is your prior experience with science, engineering or technology?"

5.1.3.2 Self-efficacy questions (11-point scale)

These questions were on the pre- and post-workshop questionnaires. The scale ranged from 0 (not confident at all) to 10 (absolutely confident).

"Come up with a product that people like and use"

This question was very helpful. In the 2-hour workshop, the average difference between post- and pre-workshop results was a 2-point increase on the 11-point scale (with a standard deviation of 1.94). It also increased for girls with prior coding experience, the conclusion being that this activity gave their skills significant new meaning and social relevance. "Come up with" was rephrased as "Create" and "would" was added to the second part of the sentence, so the question reads: "Create a product that people would like and use". This will leave the question comparable to results from earlier experiments. It is suggested to move this question down to #5.

"Come up with useful product ideas"

Note that "useful" is different from "that people like and use" in the earlier question. This differentiation is helpful. This question was sufficiently specific and remained as it was. The average change in the experiments was an increase by 2.3 points (standard deviation: 2.67). A likely explanation would be that the participants were asked to come up with ideas for devices (with or without use) and were asked to present their ideas. However, they could not fully implement these ideas due to the limitations of the early server application. This might explain why later questions might not have seen the same increase. It is suggested to change "product idea" to "technical things" and to move this question down to #3.

"Make a product that has technology, like a thermometer"

This question was sufficiently specific. It is important to note though that some participants may build an actual thermometer, while some go on to build something else, which results in great deviation. The average increase here was 1.2 with a standard deviation of 2.86. It is suggested to move this question down to #4.

"Solve math questions, like find the equation for a line"

The purpose of this question was to investigate a side-hypothesis: if there is an increase a creative (engineering design) design self efficacy, it doesn't take an increase in math self-efficacy to change the perspective on a STEM career. Results show that math self-efficacy barely increased (0.8 points with 1.4 points standard deviation). Looking at the ensuing questions though, it seems that a better measure for STEM interest needs to be found. It was thus decided to keep this question in the questionnaire. It was suggested to move it up to #1, however we may not want to lead with this question.

"Solve science problems, like design an experiment for examining 2 factors"

This question was useful to investigate participants' perspectives on their scientific understanding, as compared to technical or mathematical understanding. This question had an increase of 1.5 with a standard deviation of 2.42.

"Create technology that has an impact on people's lives"

This question had an increase of 1.5 with a standard deviation of 2.12. It could be merged with "Come up with a product that people like and use" into "Design and build a product that people will like and use" as described above, or with "Make a difference in people's lives with my engineering skills" below. It was suggested to do the latter and rephrase it as "Make a difference in people's lives with technical solutions I come up with" and move this question down.

"Obtain skills to be an engineer"

In the workshops, we hardly spoke about engineering, not to mention which skills and engineer might need on the job. Thus it was unsurprising that this question resulted in an increase of only 0.9 points with a 3.28-point standard deviation. It was decided to drop it from the questionnaire.

"Have a positive impact on people's lives"

This question was originally created as a control for the next question, "Make a difference in people's lives with my engineering skills." However, this question was very open and as such has little value in an experiment. In the 2-hour workshop, it essentially stayed unchanged with a very slight decrease of 0.1 point and a standard deviation of 1.85. It was suggested to drop this question as it can be interpreted differently by every subject and it is thus not clear whether it can serve as a control variable toward the next question.

"Make a difference in people's lives with my engineering skills"

This question is more specific (could be reworded "positive difference") but the problem again is that the term engineering was not used in the workshop. It saw an increase of only 0.6 with a standard deviation of 3.72. The wording was thus simplified and the question was merged as described above to "Make a difference in people's lives with technical solutions I come up with".

Since it wasn't discussed, the meaning of "engineering" might be confusing to girls, as it might be a loaded term full of cultural expectation. Furthermore, modern engineering subjects including coding / computer science / EECS are not branded as "engineering" these days. High school intern Lucy said that people wouldn't usually agree that CS is engineering.

Consequently, instead of asking about engineering, the solution was to pick a few engineering tasks (such as "create technology" or even "create a wearable") that are specific, but neutral, part of teens' daily vocabulary, and easy to understand.

While this activity promised to be a wonderful opportunity to explain what engineering is (see chapter : "wait, is *this* engineering?"), the 2-hour workshop time frame, which permitted recruitment of a diverse group of participants, also required setting very strict timing priorities. Since deep engagement with the toolkit was one of the most important objectives of the studies, self-efficacy questions were designed to be easy to understand and non-ambiguous to accurately assess girls' self-efficacy in technical and creative tasks. Girls' perception of 'engineering' was assessed using the perspective questions discussed in the following.

5.1.3.3 Interest and Perspective questions (7-point scale)

These questions were on the pre- and post-workshop questionnaires. The scale ranged from "strongly agree" to "strongly disagree".

"Product designers can have a positive impact on people's lives"

The term "product designer" was not discussed in the workshops. Even though product design was performed in the workshop, the term "product designer" is its own term and branded in a way that may be perceived differently by all the girls. Furthermore, it was not a goal of this work to influence the way in which participants think about product design. Consequently, it was suggested to drop this question. In 2-hour workshop, this question saw a 0.4-point increase on a 7-point scale with a 0.73-point standard deviation.

"Engineers can have a positive impact on people's lives"

In spite of the "what is engineering?" vocabulary problematic, this question should stay because it is word-for-word the question asked in a piece of prior art, which defines the problem we want to solve (i.e. we want girls to say "engineers can have a positive impact on people's lives" more after the workshop than before). In the 2-hour workshop, this question saw a 0.6-point increase on a 7-point scale with a 1.24-point standard deviation. So if we want to get a significant change here, we should definitely make sure "engineering" is discussed before the end of the workshop. It would be great if we could reproduce the "wait, is this engineering??" discussion from one of the early focus groups.

"I could see myself as an engineer one day"

There are so many factors contributing to an answer to this question, it's tough to specify it sufficiently. We might drop it completely. In the first iteration this question was "I could *not* see myself as an engineer one day," in order to have people think deeper ("switch" the agree/disagree to positive/negative logic) as advised by Dr. Bill Lucas (MIT). However, wording it that way changes its meaning into the extreme so we decided to drop the "not". Unfortunately, participants had old versions of the pre-questionnaire and new versions of the post-questionnaire, so the results of this comparison were not useful.

"I would enjoy creating technology for people"

This question does not use the term engineering but a more specific activity, which is good. This question resulted in an average 1.2-point increase on a 7-point scale (the highest in this cluster) with a standard deviation of 2.44.

"Engineering has a positive impact on my life"

This question did not have a direct connection to the content of the workshop, since the projects weren't finished; engineering wasn't discussed; and several participants chose to pursue a project that either would have a positive impact on someone else's life or be simply playful. It was suggested to drop it from the questionnaire. This question had a 0.3-point increase with a (relatively high) 1.22 point standard deviation.

"In my career, I would definitely like to have a positive impact on people's lives"

It is not clear how the workshop could have affected this result. And this question had an even 0.0-point change and a standard deviation (in this case noise?) of 0.71 points. It might be best to drop this question, unless it could serve as a control variable; but some girls started with "strongly agree" and stayed there, so this is an "obvious one" and thus not very helpful.

5.1.3.4 Direct feedback (open questions)

These questions were only on the post-workshop questionnaires.

"How did you enjoy the session overall? (What did you like, what could have been better?)"

The question has too many parts and the first part can be answered in a neutral, nice way. Instead, reword to: "What was your favorite, what your least favorite part of the session", if this is what is asked for. (If a general rating of the session is what's asked for, drop the second part.)

"How did you enjoy the activity / technology used?"

This question was left unchanged.

"What did you make?"

This question did not exist in the first iteration of the questionnaire but it would have been very helpful to have, so it was added in the revision.

"What was fun / cool / meaningful about making hardware?"

More adjectives were added here to inspire a wider range of quotes from the participants.

"What can be improved (design, editor, sensors, what you can do with it, device shape, guidance)?"

Different options were added here to make it easier for the participants to think about what would have helped them, if they ever felt lost.

"How would your experience have been different if…"

Three scenarios were given in this question: "sensors were all built-in to the device", "just the editor (no device)", and "the device had a display". Since so many participants asked for a display, the device design was changed accordingly and the third scenario was changed to "if the device had a battery".

Other open questions were found helpful and can be changed if appropriate. For example, should the next version have a display (since 7 of 7 girls said "yes", they want a display), this space could be used to ask what if it didn't require USB power etc.

5.1.3.5 Intrinsic motivation and engagement questions (7-point scale)

These questions were only on the post-workshop questionnaires.

"I enjoyed doing this activity very much"

This question had a positive result, although this might depend on the educator running the workshop. It was decided to keep it as is (see "would like to do this again" question discussion below). The average was a 5.1 on a 7-point scale (somewhat agree) with a standard deviation of 1.2.

"This activity did not hold my attention at all"

This question was negative, i.e. the type of feedback it communicates is flipped from the surrounding questions (completely agreeing means the activity was not fun at all, opposite to other questions, creating the same problem as with the original wording of "I could not see myself as an engineer one day", which created a very large variance until the wording was adjusted). Better would be "I felt very engaged". The average was a 2.9 (somewhat disagree) with a (high) standard deviation of 2.0.

"I did pretty well at this"

It's a measure of perceived competency, so we might want to keep it. The average was a 4.6 with a standard deviation of 1.2.

"After a while I felt pretty competent about this"

It's a measure of perceived competency, so we might want to keep it. The average was a 4.6 with a standard deviation of 1.0.

"I put a lot of effort into this"

This was a good indicator of engagement and it was decided to keep this question as is. The average was a 5.1 with a standard deviation of 1.3.

"It was important to me to do well at this task"

There are a lot of factors leading into this question. (Could it be a control factor for the previous question?) The average was a 4.5 with a standard deviation of 1.2.

"I was free to create what I wanted"

This question may not so much have served to inquire about emotional perspectives but rather the actual workshop format incl. mentors helping with the task or guidance given by the educator. The result was relatively positive (but also kids were most likely very free in what to create, so that's not surprising). The result was a 5.6 with a standard deviation of 1.4. A better question would be "I was free to create something I care about" to really measure the wide-walls aspect (Mitch Resnick / constructionism).

"I think I could make something valuable with this"

The average result of this question was a 5.2 with a standard deviation of 1.3.

"I would like to do this again (honest answer)"

This could be a very helpful question to indicate how widely (sustainably) interesting this activity was, although there is no correlation between this question and "I enjoyed doing this activity very much", yet they had similar results. It was decided to drop "(honest answer)" to make this question more coherent with the other questions. The average result of this question was a 4.2 with a standard deviation of 1.5.

"I could have a big impact designing wearables"

The problem with this question is that not every girl ended up designing purposefully impactful wearables. Since "I think I could make something valuable with this" captures most of the useful parts of this question, it was decided to drop this question and keep "I think I could make something valuable with this". The average result of this question was a 4.4 with a standard deviation of 1.7.

Additional questions were added: "I learned valuable skills" and "I learned some of what engineers do".

5.2 Workshop Procedure

Based on preliminary workshops with the MIT Museum [119], "Science Club for Girls" [115] and "Buckingham Browne and Nichols" school in Cambridge [120], a workshop was planned and conducted with a group of 10 girls from "Big Sister Association of Boston" [121], each with their respective mentor (procedure see Table 5.1). The design toolkit provided was a working implementation of the concept of a configurable modular smart device with an early version of a corresponding graphical interface [92].

TABLE 5.1: 1h 45 min schedule for the design workshop with working prototypes.

5 min	Complete pre-questionnaires
10 min	Introduction to wearables, sensors, input / output
5 min	Intro to toolkit with example
25 min	Activity: Create application with toolkit based on examples and own ideas
10 min	Break
25 min	Continue building activity
10 min	Present to another match (groups of 2 matches), critique (2 x 5 min)
5 min	Reflect upon product purpose
15 min	Present to the class
10 min	Post-workshop questionnaire

Wireless microcontrollers were programmed to accept acceleration, pulse, or temperature sensors. The workshop was planned for 1 h 45 min. The structure is summarized in Table 5.1. This workshop format was followed with a group from Big Sister Association of Boston and it was adapted from a longer schedule that was created in cooperation with a group from Science Club for Girls.

5.3 Research Method

The design activity was tested with groups of 8 to 10 girls, generally between 11 and 14 years old, with an average age of each group between 12.3 and 13.3 years.

A number of studies were conducted, largely following the same 1 h 45 min procedure.

The fall 2016 study consisted of a group of 10 girls with an average age of 13.3, as well as a mostly-boys secondary group. 9 students of the secondary group, 8 boys and 1 girl (average age 12.9 years)[2], submitted pre- and post-questionnaires identical to those completed by the all-girls group, but they followed a four-week format with 4 one-hour sessions. Results from this secondary group are in Appendix E, while results from the all girls-group from the fall 2016 study are discussed in the following.

The spring 2017 study consisted of two all-girls groups, one with female instructors and one with male instructors. 8 girls in each group submitted both pre- and post-questionnaires. The average age of each group was 12.25 years. Both groups followed the same format (expanded to 2 h with a slightly longer building activity).

A shorter workshop was run at a high school later in the spring of 2017, but not enough students submitted questionnaires to allow for analytical consideration.

5.4 Observed Scope of Projects

The project design scope reflected the discoveries from experiments documented above. Many were wearable devices, but other contexts came up as well. Creations from the fall workshops:

- A baby monitor that checks in on body temperature
- A device with an email news update
- A fitness tracker that triggers songs, depending on performance
- A smart basketball that measures impact and flight parameters
- Something that measures temperature in Celsius and converts it to Fahrenheit

With the revision of the questionnaires, a new question was added and participants were asked in writing: "What did you make?" The following are direct quotes from the completed questionnaires:

[2] A significant change in self-efficacy was not expected in the secondary group, since this group had been thoroughly exposed to STEM before and being predominantly male, the secondary group was expected to already perceive engineering as socially relevant prior to the intervention, in addition to being motivated by factors that may not have been addressed by this activity (e.g. competition).

- "I made a device that tracked how fast you were throwing"
- "I made a compliment bot called complibot that sends you different messages based on your temperature, I made this specifically for my mom."
- "I originally had the pulse sensor, but switched to the temperature. I plan to try to program it to send a message when your body temperature is above the optimum."
- "I made something that tracks how fast you are throwing a Lacrosse ball"
- "A heart rate sensor which tells you if your heart rate is too slow or fast"
- "I made a device that tells you if you are not moving at the target speed"
- "I made a sensor that would detect how fast you are going, and it will send you messages depending on how fast you are going"
- "A pedometer"
- "A device that measures your pulse and if it gets too high it tells you and if it gets too low it tells you"

5.5 Qualitative Results

5.5.1 Technical Features

Students were generally positive about the design experience, but asked for more guidance in the earlier experiments.

From the qualitative section of the Fall 2016 workshop, three quantitative measures were extracted:

- 4 out of 9 girls would like more guidance
- 7 out of 7 girls want a display
- 5 out of 6 girls would *not* want to have the hardware aspect dropped from the activity

Between the Fall 2016 workshops and Spring 2017 workshops, a display was added, so that one of the questions ("Would you prefer if it had a display?") was obsolete and could be replaced. Consequently, in the Spring 2017 version of the questionnaire, students were asked: "How would your experience have been different if the device had a built-in battery?" 14 out of 15 girls said a built-in battery would be preferable, because it would make their device more portable.

Some of the comments on technical features could be assessed more clearly when connected to the motivational factors they enabled.

5.5.2 Motivational Factors and Perception

Many of the comments from the qualitative results section in the post-workshop questionnaires reflect that important goals were achieved by meeting requirements set out earlier. Quotes were extracted from the responses (qualitative method) and categorized by the design objectives set out in the beginning of this thesis (such as having social impact or creative freedom):

- Having social impact:

  "I liked how we thought of ideas to impact people's lives."

  "I enjoyed it because I made something useful."

- Relatedness areas:

  "I made a compliment bot called complibot that sends you different messages based on your temperature, I made this specifically for my mom." (social)

  "Something that was really fun was about, how you could use these in different ways to help the people around you." (social)

  "I made something that tracks how fast you are throwing a Lacrosse ball." (physiological)

  "A heart rate sensor which tells you if your heart rate is too slow or fast." (health)

  "I made a device that monitors heart rate and when you clicked the buttons on the app, it sends encouraging messages to the wristband." (combination)

  "I made a Fitbit [that announces the number of steps in French, and that is decorated in a certain way]." (artistic)

  "I liked it because you could make what you want."

  "I liked how you could make whatever you wanted to."

- Ownership (constructionist ideal), autonomy:

  "I liked that we got to make our own ideas."

  "I like that we were encouraged to be creative."

"How we each got the chance to personalize it."

"It was really fun because I could be creative as well as make something original."

"I enjoyed the activity because you could choose what you made and the technology was cool."

- Sharing:

  "I liked the part of sharing ideas with others."

- Perceived competency:

  "I enjoyed it really well, because it was simple and easy to use, but it did a lot at the same time."

  "I did enjoy this session especially I did the coding and it actually worked."

- Optimum level of challenge:

  "I enjoyed learning the app and seeing the finished project."

  "I enjoyed the activity a lot and enjoyed playing with the many different possible features of my device."

- Continuous engagement:

  "I think it was great I just wished I had [...] more time so I could decorate the device."

Another indicator of engagement was that certain students, who were especially passionate about their creation and were "still in the zone" when they took the post-workshop questionnaire, would interpret activity-related questions as questions pertaining to their individual creations.

Areas for improvement were also identified:

"[If the sensors were in device] It would have been easier to find out what the sensor was for." – this shows that it was not as quick and easy to try out different sensors as this student preferred. (Note: the majority of students liked being able to swap sensors and did not negatively comment on the implementation, although students did ask for some initial guidance: "I feel like, it would have been better if you carefully went through the instructions."

Instructors often talked students through what was happening at any time, complementing instructions in the printed guide and notifications on the device display ("connecting", "measuring temperature", etc.) This shows that the *continuous engagement* aspect may have been the one that was most lacking relative to the goals that were set out at the beginning.

- Meaningful objects:
  "It was fun to actually make something."
  "[Without the hardware aspect, it would have been] not as fun and creative."
  "The device made it more meaningful"

- Features unique to this implementation:
  "It was fun using sensors."
  "I enjoyed the making of my custom fit-bit."
  "It was cool to basically create an app."
  "It was fun to actually know how fast I was throwing."
  "I enjoyed being able to make it wearable, being able to take it home, and being able to watch it happen on the screen."

These quotes show that participants identified, appreciated and benefitted from the motivational and engagement-related experience design goals set in Chapter 2 and 3 of this thesis. Not only does this result show that the experience successfully meets these goals, but also that they are in fact desired by the audience of adolescent females it was tested with.

A more detailed discussion is found in Chapter 6.

5.6 Quantitative Results

5.6.1 Analytical Methods

Quantitative results were captured on an 11-point scale (self-efficacy) and 7-point scale (interest / perspective and engagement questions). Both self-efficacy questions and interest / perspective questions were asked both before and after each workshop to enable a comparison. Subjects were asked for their names to allow the pairing of results. As such, it was possible to determine the difference between paired results and to investigate the variation and distribution of differences in subjects' self-efficacy and interest / perspective, as opposed to just the difference between the means and distributions before and after the intervention. The analysis of the mean and distribution of the change itself was very insightful.

Two statistical measures are often derived from a sample of values: the mean and the standard deviation. While the standard deviation is a good indicator for the spread of values, its statistical power is limited if the sample size is small or the distribution is non-normal.

To test a hypothesis, the t-test is often used. This has precedence in self-efficacy research. However, a sample size of 30 is usually necessary to derive reliable results from this method.

By contrast, the bootstrap method has been found to yield reliable results with sample sizes as small as 8 [122]. The bootstrap method has been shown to be superior to ANOVA for small samples and asymmetrical or non-normal distributions [123]. It uses computation[3] instead of more traditional distributional assumptions to make statistical inferences about samples, which makes it very suitable for non-normal distributions or small samples [123].

Bootstrap was shown to be an adequate method to determine the statistical significance, i.e. test a null-hypothesis, using differences of paired data [125]. A 95% confidence interval is common to determine statistical significance in self-efficacy studies. To determine the bounds of the 95% confidence intervals using the bootstrap method, MATLAB's *bootci* command [126] was used in the analysis that follows.

To visualize how the resampling improves accuracy, data is plotted on a histogram for an exemplary data set: self-efficacy in "Make a difference in people's lives with technical solutions I come

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[3] How bootstrapping works: The recorded values are resampled many times over, meaning that out of the available sample values, a sample is taken (with replacement!) that is as big as the sample itself, so the mean is different every time it is resampled. Using thousands of resampling cycles (the results in this thesis use 100,000, although results tended to converge starting with 500 cycles – usually 1,000 to 2,000 bootstrap samples are necessary to find a confidence interval [124]), thousands of means are available for statistical analysis of the mean. The 95% confidence interval bounds are the 2.5^{th} and 97.5^{th} centiles of these values. Bootstrapping allows for extracting statistical values from data that might otherwise be too small or irregularly distributed for traditional statistical methods. However, it does not guarantee that a small sample is representative of a large population.

up with" from the later workshop (spring 2017). A histogram of the raw data is shown in Figure 5.1; a histogram for the mean values of 10,000 resampling cycles is shown in Figure 5.2.

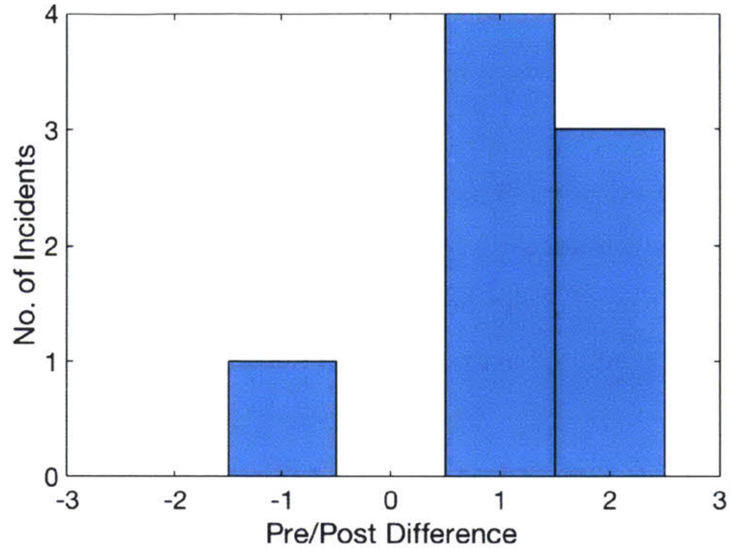

FIGURE 5.1: Histogram for raw data (paired differences, "Make a difference in people's lives with technical solutions I come up with", experiment April 2017), 8 data points total.

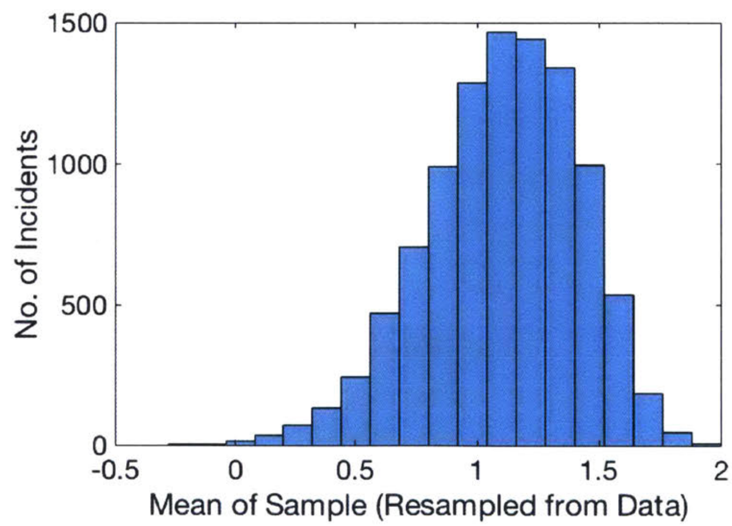

FIGURE 5.2: Histogram for mean values of 10,000 samples taken from data (discretized for graphing).

5.6.2 Self-Efficacy Increase

Comparing pre- and post-workshop questionnaires, there was a general increase in self-efficacy and interest in STEM and product design, although not every statement increased to a statistically significant degree. A graph is shown in Figure 5.3.

The 2-hour workshop in the fall of 2016 had issues of an unreliable system and the majority of girls did not fully complete a functional product. In the limited 1h and 45-minute time frame, ideas could rarely be fully transformed into complete, working products (with a few exceptions). The group presentations gave projects some closure, although it was expected that this time limitation and thus limited realization of projects would allow for only moderate growth in engineering self-efficacy and interest. However, a rapid change of mindset was expected, based on the experience in the earlier focus groups.

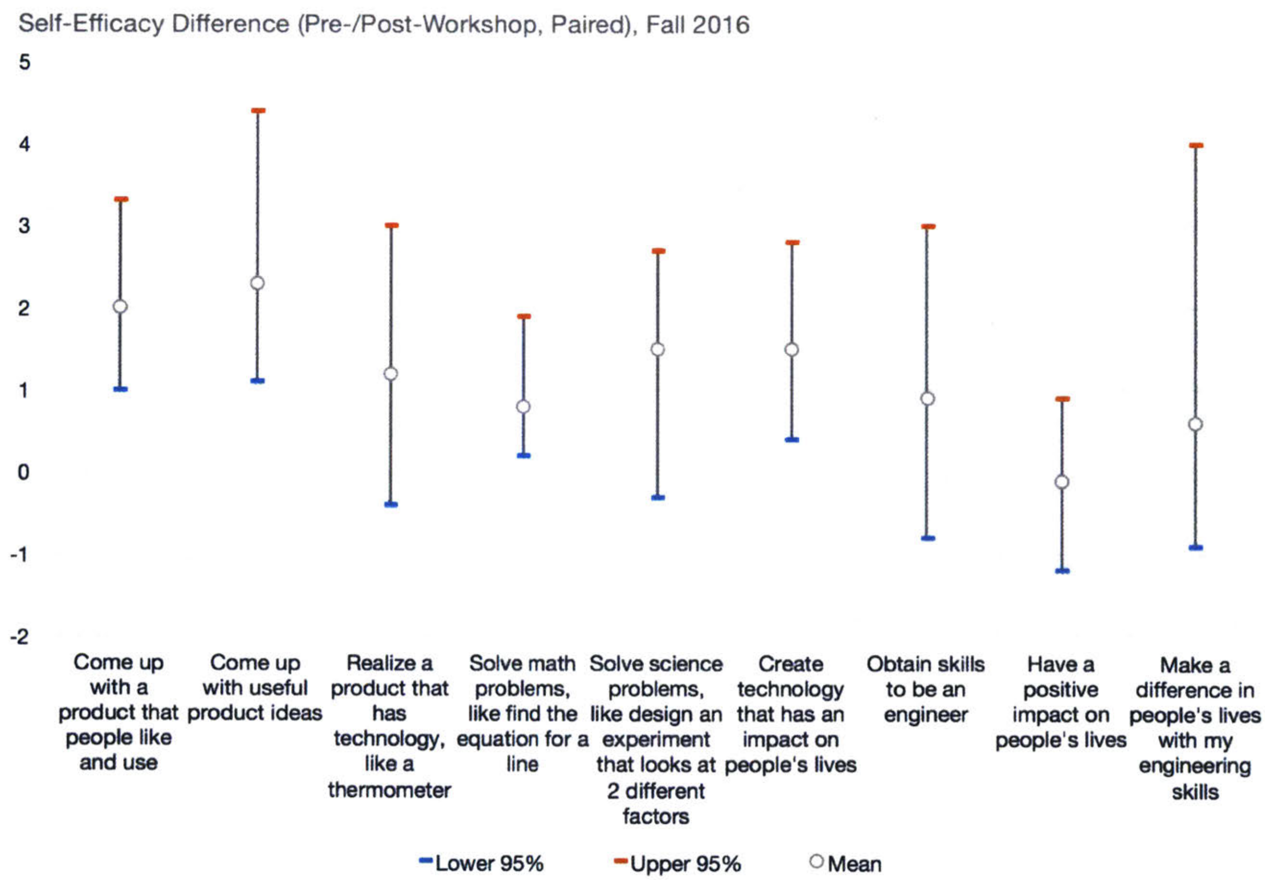

FIGURE 5.3: Graph of self-efficacy increase (difference of pairs) with upper and lower bounds of 95% confidence intervals, early toolkit iteration. Absence of zero from the confidence interval indicates statistical significance. Thus, product conception statements showed a significant increase, whereas engineering-related statements did not.

The confidence intervals allow for the assessment statistical significance. If zero is not on the confidence interval of a value, the null hypothesis can be rejected and the change seen in the population is significant. Table 5.2 lists the questions and summarizes this result from the workshop.

TABLE 5.2: Significance of increase in self-efficacy for design and engineering among 10 girls with an average age of 13.3 years in the fall of 2016 (positive average change denotes increase).

Self-efficacy question	*Average change*	*Statistical significance*
Come up with a product that people like and use	2.0	significant
Come up with useful product ideas	2.3	significant
Realize a product that has technology, like a thermometer	1.2	insignificant
Solve math problems, like find the equation for a line	0.8	significant
Solve science problems, like design an experiment that looks at 2 different factors	1.5	insignificant
Create technology that has an impact on people's lives	1.5	insignificant
Obtain skills to be an engineer	0.9	insignificant

The average difference and standard deviation of the students' self-efficacy change for each statement are summarized in

TABLE 5.3: Increase in self-efficacy for design and engineering among 10 girls with an average age of 13.3 years: average values and standard deviation.

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TABLE 5.3: Increase in self-efficacy for design and engineering among 10 girls with an average age of 13.3 years: average values and standard deviation.

Self-efficacy questions (11-point scale)	*Average change*	*Std. dev.*
Come up with a product that people like and use	2.0	1.94
Come up with useful product ideas	2.3	2.67
Realize a product that has technology, like a thermometer	1.2	2.86
Solve math problems, like find the equation for a line	0.8	1.40
Solve science problems, like design an experiment that looks at 2 different factors	1.5	2.42
Create technology that has an impact on people's lives	1.5	2.12
Obtain skills to be an engineer	0.9	3.28

As discussed, the toolkit development was in an early stage at the time of this workshop, so reliability issues affected the possible self-efficacy gain. A workshop was conducted 6 months later with a more reliable toolkit, with the display implemented and more guidance. The results are shown in Figure 5.4. Note that there are fewer questions that in the previous workshops since the questionnaire was revised.

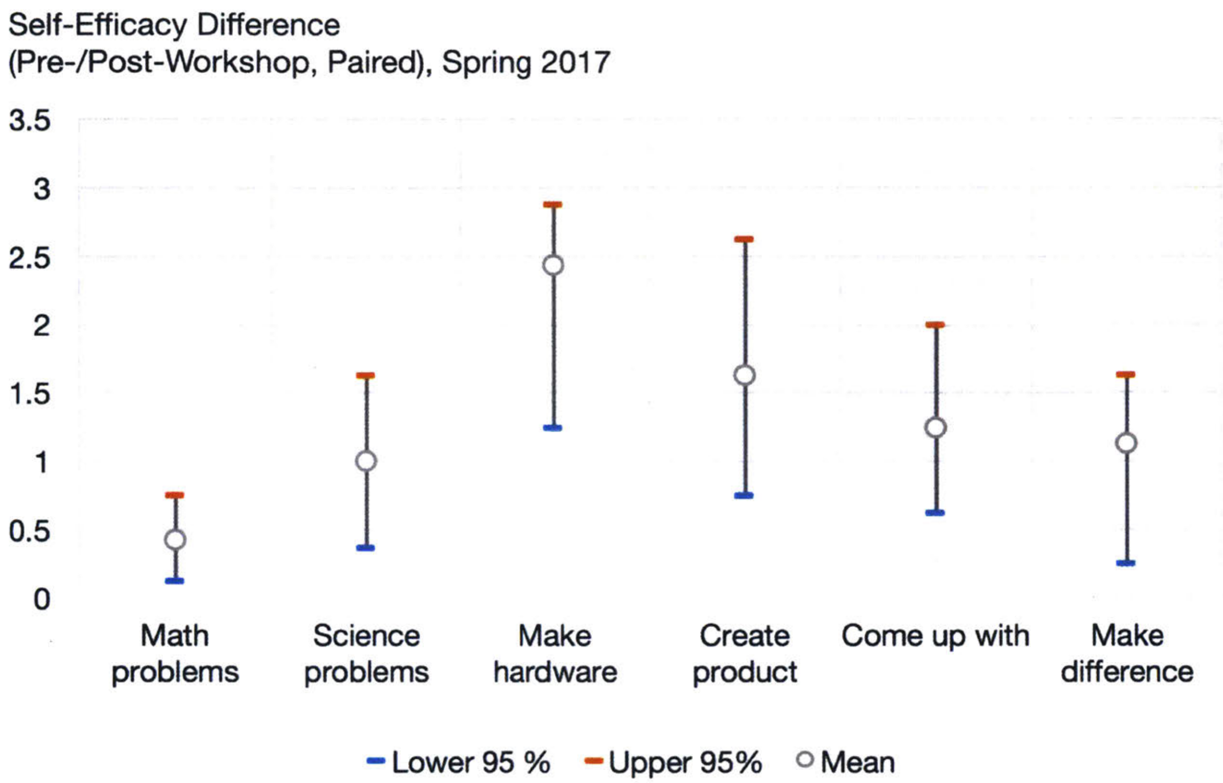

FIGURE 5.4: Graph of self-efficacy increase (difference of pairs) with upper and lower bounds of 95% confidence intervals, later toolkit iteration. Absence of zero from the confidence interval indicates statistical significance.

TABLE 5.4: Significance of increase in self-efficacy for design and engineering in later workshop (positive average change denotes increase)

Self-efficacy question	*Average change*	*Statistical significance*
Solve math problems, like calculate the equation for a line	0.43	significant
Design a scientific experiment to test the influence of a factor	1.00	significant
Make hardware with technology, like a thermometer	2.43	significant
Create a product that people would like and use	1.63	significant
Come up with ideas for useful technical things	1.25	significant
Make a difference in people's lives with technical solutions I come up with	1.13	significant

5.6.3 Interest Increase and Perspective Change

The results from interest related questions from Fall 2016 are summarized in Figure 5.5. Note that "I would enjoy creating technology for people" changed the most significantly. It can be observed from the results that self-efficacy and interest regarding questions using official terminology such as "product design" or "engineering" changes to a less significant degree than for concrete examples. These terms were not discussed as part of the workshop; thus no significant change is expected.

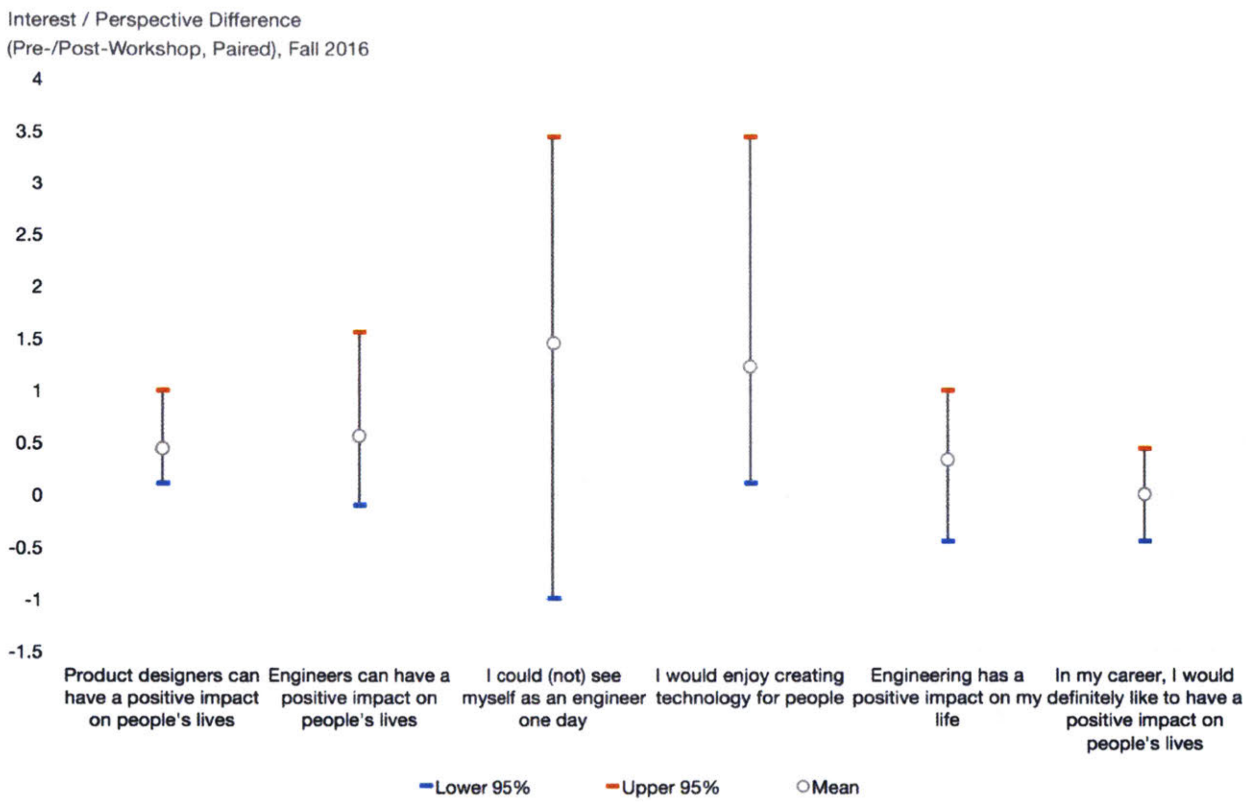

FIGURE 5.5: Graph of perspective / interest increase (difference of pairs) with upper and lower bounds of 95% confidence intervals, early toolkit iteration. Absence of zero from the confidence interval indicates statistical significance.

TABLE 5.5: Significance of improvement in interest or self-perception among 10 girls with an average age of 13.30 years. (Terms like engineering or product design were not discussed in the workshop.)

Interest questions (7-point scale)	*Average change*	*Significance*
Product designers can have a positive impact on people's lives	0.44	significant
Engineers can have a positive impact on people's lives	0.56	insignificant
I could (not) see myself as an engineer one day	dropped from analysis (errors)	
I would enjoy creating technology for people	1.22	significant
Engineering has a positive impact on my life	0.33	insignificant
In my career, I would definitely like to have a positive impact on people's lives	0.00	insignificant

In a later workshop 6 months after this, many of the technical issues were fixed, and the questionnaires were shortened. The result is shown in Figure 5.6.

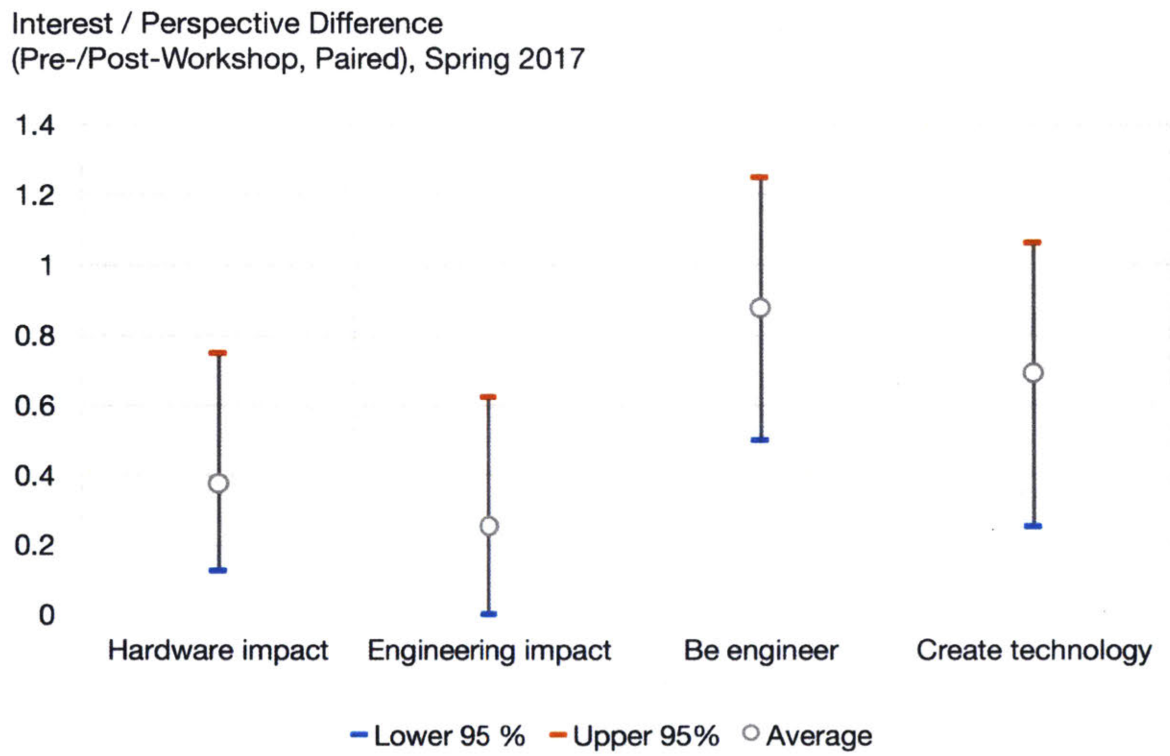

FIGURE 5.6: Graph of perspective / interest increase (difference of pairs) with upper and lower bounds of 95% confidence intervals, later toolkit iteration. Absence of zero from the confidence interval indicates statistical significance.

TABLE 5.6: Significance of improvement in interest or self-perception, later workshop and toolkit iteration. (Terms like engineering or product design were not discussed in the workshop.)

Interest questions (7-point scale)	*Average change*	*Significance*
People who design hardware can have an impact on people's lives	0.38	significant
Engineering can have a big impact on people's lives	0.25	insignificant[4]
I could see myself as an engineer one day	0.88	significant
I would enjoy creating technology for people	0.69	significant

[4] zero is lower bound of confidence region

5.6.4 Social Impact Self-Efficacy Increase over Prior Experience

A noteworthy point was that girls both with and without prior coding experience reported a much higher perceived confidence for "Come up with a product that people like and use" – a gain between 0 and +5 points on an 11-point scale. A similar gain was seen with regard to "Create technology that has an impact on people's lives." For example, a girl who stated she had no prior experience in science, engineering or technology, reported an 8-point self-efficacy rating in this category, from 3-points before the workshop — a 5-point increase. Another girl who stated she had prior experience in both science and coding reported a 9-point self-efficacy rating after the workshop compared to 5-point before the workshop — a 4-point increase. It can thus be concluded that there is evidence that this activity with real-world elements achieves its goal of conveying the experience of social impact of STEM, i.e. "with engineering I could have an impact on people's lives", a key factor identified by the NAE (2008) study [62], since even girls who had prior exposure to science or coding could benefit from this activity in a way that surpasses other learning experiences.

Individual answers to the self-efficacy question "create technology that has an impact on people's lives" are detailed in Figure 5.7, as this represents one of the most significant findings of this study. The remarkable increase for the participant that stated no prior experience is expected, since this might be the first meaningful introduction to an engineering-related activity, which provides an "easy" opportunity for self-efficacy increase. However, the large gain in self-efficacy among individuals who had previously been involved with STEM clubs like Girls Who Code, FIRST Robotics and others shows that the activity gives meaning and purpose to the skills these girls had already acquired.

Put differently, even girls who had already experienced "what engineering is" were now given the chance to experience "what engineering is *about*" and that it can in fact have great social impact. This can imply that even schools that have technical programs might benefit from an activity such as this one.

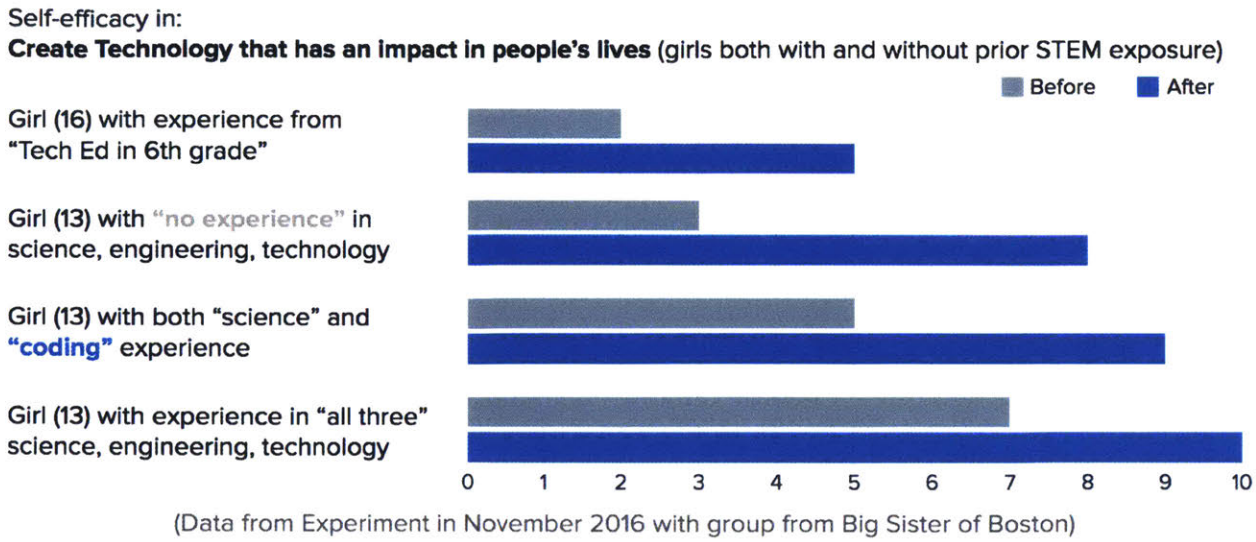

FIGURE 5.7: Self-efficacy in "creating technology that has an impact on people's lives" (on an 11-point scale) before and after the workshop respectively for four different participants. The increase in self-efficacy for participants with prior exposure shows that the engineering design activity has impacted the participants beyond other STEM experiences, including engineering workshops, coding and science classes

5.6.5 Correlation Analysis

Initial interviews had shown that girls, that already had confidence in their engineering skills, were less excited about the toolkit and did not show a mindset change the way that most other girls did. For example, girls that started out thinking of themselves as "not creative" and "not technical".

It was thus investigated whether the starting self-efficacy was correlated to the change in self-efficacy.

The analysis is detailed for the data collected for "making a difference in people's lives with technical solutions I come up with". Figure 5.8 shows a point cloud that may indicate a possible correlation.

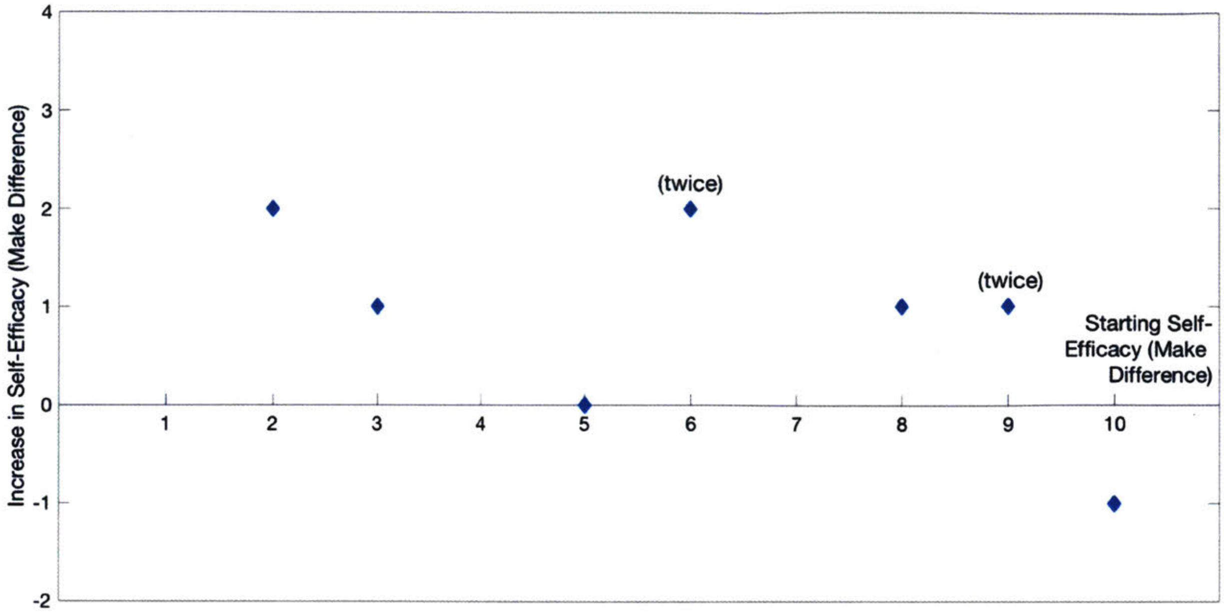

FIGURE 5.8: Self-efficacy increase vs. starting self-efficacy in "making a difference on people's lives with technical solutions I come up with" (on an 11-point scale). The data set, although small, lends itself to statistical analysis.

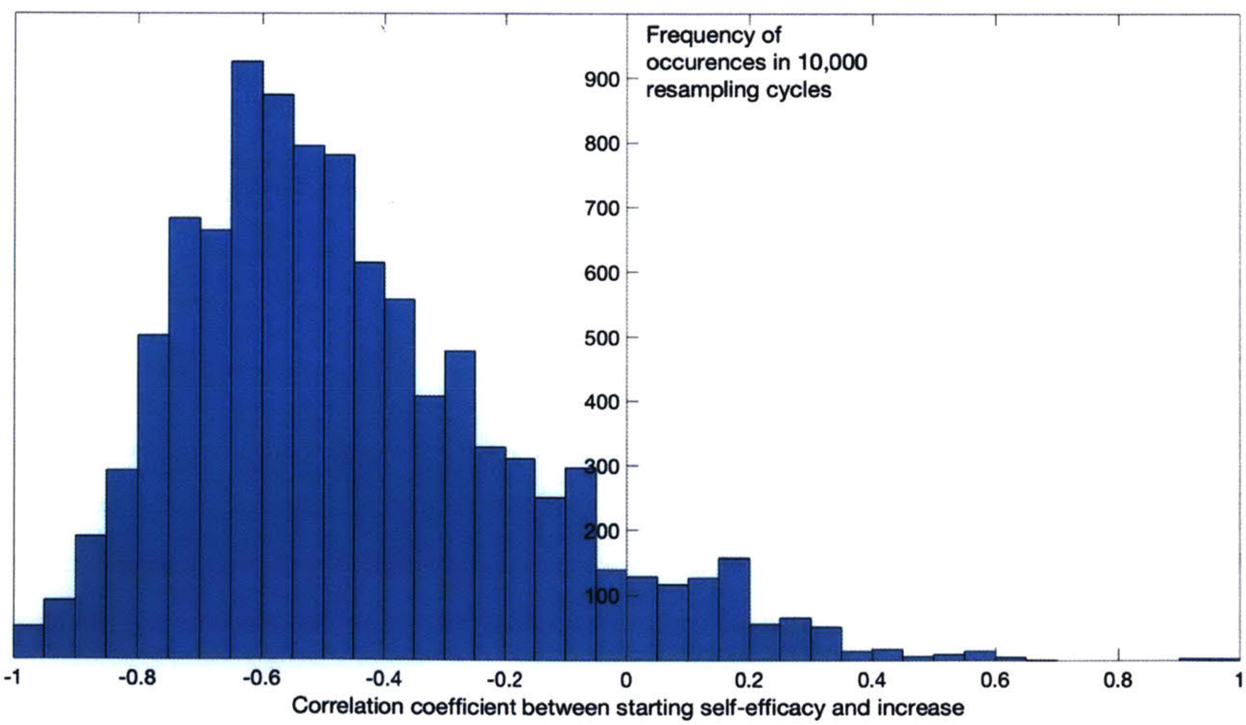

FIGURE 5.9: Histogram of correlation coefficients using 10,000 bootstrap cycles.

Using the bootstrap method[5], the 95% confidence interval for the correlation coefficient is determined as $[-0.9072;\ 0.1543]$ with 10,000 bootstrap cycles. Null is in this interval, meaning the correlation is not significant. The histogram of correlation values for 10,000 bootstrap cycles is plotted in Figure 5.9.

A cross-correlation matric was created with 95% confidence intervals for the respective correlation-efficients. It is shown in Table 5.7.

TABLE 5.7: Confidence intervals for cross-correlation coefficients. No significant correlation was found between starting self-efficacy and change in self-efficacy.

		Difference in self-efficacy:				
		Science problems	Make hardware	Create product	Come up with	Make difference
Starting self-efficacy:	Science problems	[-0.8847, 0.5453]	[-0.1735, 0.7696]	[-0.7206, 0.7155]	[-0.7069, 0.6097]	[-0.9435, 0.5669]
	Make hardware	[-0.6340, 0.6875]	[-0.9701, 0.2260]	[-0.8075, 0.1375]	[-0.8077, 0.5108]	[-0.9134, 0.6197]
	Create product	[-0.3333, 0.8498]	[-0.5647, 0.5790]	[-0.8839, 0.3467]	[-0.7593, 0.7067]	[-0.7920, 0.4714]
	Come up with	[-0.6614, 0.7841]	[-0.4398, 0.7884]	[-0.7766, 0.9062]	[-0.8262, 0.4384]	[-0.8881, 0.1684]
	Make difference	[-0.6551, 0.7898]	[-0.6407, 0.8257]	[-0.7049, 0.8483]	[-0.7856, 0.6258]	[-0.9072, 0.1543]

5.7 Instructor Influence

A workshop conducted in the spring of 2017 had attracted a lot of demand. To allow more girls from the wait list to be part of the workshop, two groups were formed. Ostensibly, the two groups differed in just one regard: the gender of their instructors. However, it was soon assessed that the instruction style differed in a number of ways, with substantial effects on the learning focus and outcome.

[5] *bootci* command (for specific implementation see Appendix F)

5.7.1 Observed Instructor Influence

The toolkit is the result of an effort to package what gets girls excited about engineering into a format that is accessible to all. Therefore, the opportunity was recognized to have different instructors introduce girls to engineering and to investigate efficacy, possible pitfalls, and how those can be circumvented.

5.7.1.1 Experimental Method

As mentioned in chapter 5.3, in a spring 2017 study, a 2-hour workshop was split into 2 groups with 8 girls each, both using the same materials and following the same curriculum. One group (group A) had two female instructors, one of whom had extensive outreach experience; a graduate and an undergraduate engineering student. One group (group B) had two male instructors, one of whom had extensive outreach experience; a graduate and an undergraduate engineering student. None of the instructors were professional educators. All instructors had previously been involved with the technical realization of the toolkit, the male instructors (group B) more intimately than the female instructors (group A). Instructors were trained to follow the curriculum shown in chapter 5.2.

The expectation was that results of both groups would not considerably deviate from one another, as the experiential activity was to help increase girls' self-efficacy independent of instructor identification.

5.7.1.2 Observation

Both groups of instructors deviated from the curriculum protocol.

The instructor duo in group A (female instructors) began the workshop with an introduction and asked all participants about their hobbies. Subsequently, they encouraged participants to design for their hobby or sports team, emphasizing social impact.

The instructor duo that had been more intimately involved with the realization of the toolkit platform (group B) deviated from the curriculum protocol in a different way. They rarely emphasized social impact. Instead, they prompted participants to try and understand how the technology, for example how a pedometer works. Furthermore, they used words like "accelerometer" instead of "motion sensor".

5.7.1.3 Quantitative Results

A direct comparison of self-efficacy increase and confidence intervals is shown in Figure 5.10. It can be seen that 5 of 6 self-efficacy dimensions that increased significantly in group A did not increase to the same degree in group B. The only self-efficacy dimension that showed a significant increase in group B was to "Make hardware with technology, like a thermometer", although it increased less significantly in group B than in group A.

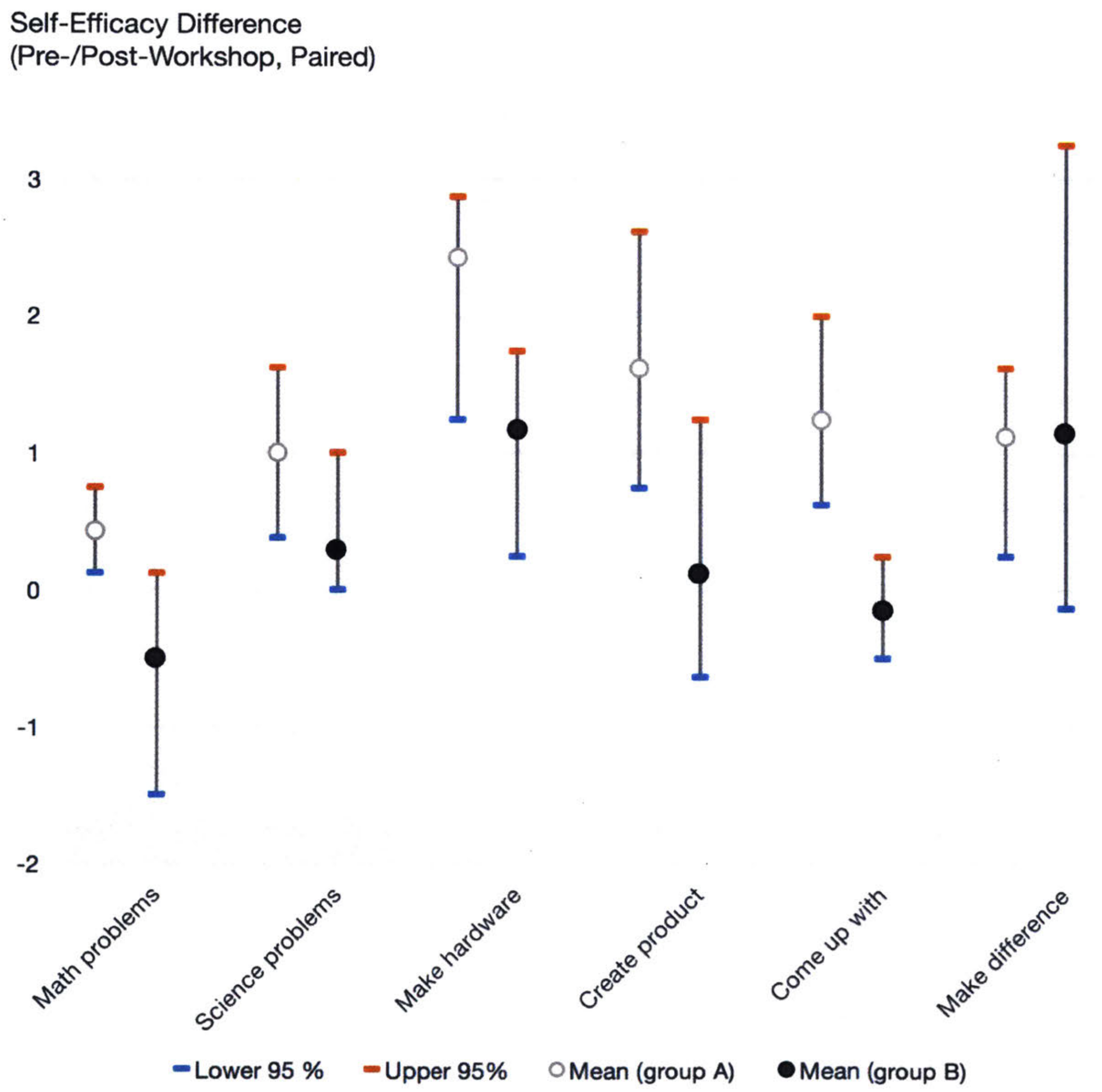

FIGURE 5.10: Self-efficacy change in both groups, side-by-side. In tendency, the self-efficacy gain was lower in group B (taught by male instructors with direct involvement in the toolkit development). 5 of 6 factors that increased significantly in group A did not increase significantly in group B.

5.7.1.4 Discussion

The groups' average self-efficacy gains differ considerably. At a closer look, this might be best explained by the instruction style: The instructor team in group A emphasized social context, while the instructor team in group B emphasized the underlying technology using vocabulary that was not familiar to all participants in the group. Why did this happen? Three explanations are possible:

- The instructor team leading group B had been more involved with the realization of the toolkit itself, so they knew about its technical attributes in more detail and may have been excited to share features, while switching to a more accessible vocabulary may have required a bigger effort from them than from the instructors in group A, who may have been introduced to the features using more accessible language, as it was developed over the course of the toolkit's implementation.
- The range of STEM skill levels in group B was wider than in group A, while self-efficacy levels were higher from the outset (average: 1.6 points higher on an 11-point scale in the pre-workshop condition, ranging from 1.125 points higher to 2.25 points higher than the respective pre-workshop-average in group A). The average age in group A ranged from 11 to 14 (average: 12.25). The average age in group B ranged from 9 to 14 in (average: 12.25). In group A, the prior exposure to STEM ranged from science festival visits to involvement in coding-related after-school clubs. In group B, the prior exposure to STEM ranged from having recently joined a science Olympiad team to one girl having multiple years of coding experience and publishing her own science-related YouTube shows. It is possible that the presence of another participant, who is much more outspoken and clearly more experienced, discouraged some of the girls in group B[6], and the higher confidence levels of the more experienced girls did not leave much room for measuring growth.

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[6] In fact, the participant with the least prior STEM exposure was the only participant who had a decrease in her self-efficacy in having social impact with technology. It is known that self-efficacy can grow and shrink as students compare their skills to their classmates' skills. Two of the four girls, whose self-efficacy in having social impact with technology did not change, had selected 100% in the pre-workshop questionnaire, so a measured increase was not possible.

- The gender of the instructors differed. However, no generalization can be made about teaching styles and instructor gender from a single experiment. It is likely that the instructors' personalities would be much more closely correlated to their teaching styles, but personality inventories were not obtained from any of the instructors.

5.7.2 Prior Research: Effect of Instructor Gender

It has been a topic of investigation in education how different teaching styles affect student perception, and what effect it has if teachers share ethnicity, gender or cultural background with their students. A shared background can make it easier to empathize or to make students feel that teachers understand them better. A problem arises with STEM education. Traditionally, engineering has been a white-male-dominated field, so that most engineering-inclined teachers and possible mentors are white and male.

A recent industry study finds that "girls are much more likely to be engaged in computer science if they have female teachers, while the gender of the instructor does not influence boys' interest" [127]. Various other studies support this conclusion [3], [128], including studies that correlate the success in recruiting girls into technical roles of FIRST robotics teams with the involvement of female mentors in those sub-teams [129], [130]. Dee finds that teacher gender has a significant effect on girls' achievement, including test scores, teacher perceptions and subject engagement, including when controlling for factors such as race-ethnicity, teacher experience, number of students in the class, and students' English proficiency [131]. At the middle and high school level, both boys and girls perform better in science and English when assigned to a teacher of the same gender in the respective class, and girls tend to perceive classes as more relevant to their future if they have a female teacher [132]. Dee finds: "when assigned to a female science teacher, girls are significantly less likely to claim that science is not useful for their future" [131, p. 24]. [131, p. 25]. Dee explains the influence of teachers' gender as follows: "One theory asserts that the teacher's gender shapes communications between teacher and pupil, while another says the teacher acts as a gender-specific role model" [132, p. 70]. It is argued that "a year with a female teacher would close the gender gap in science achievement among 13 year olds by half and eliminate entirely the smaller achievement gap in mathematics." Similarly, ethnic minorities tend to perform better academically when their teachers share their ethnicity, e.g. black students who perform better with black teachers than white teachers [133].

The effect of instructor gender seems to fade once students advance to college: studies at the college level show that sharing ethnicity positively influences students' persistence to stay enrolled in a subject to a significant degree, while sharing gender does not [134]. However, female students participate more and may have a higher self-efficacy gain if STEM subjects are taught by female faculty [135], and female students with female mentors tend to engage more in informal opportunities for interaction than female students with male mentors [136].

In ten in-depth interviews with female technology educators, McCarthy and Berger identify that male relatives, who helped them feel comfortable with "fluid gender roles", and male teachers, who nurtured their interest in technology, had a great influence in their decision to pursue technical careers [137]. The authors assess that "a good deal of the literature (...) suggests that children develop self-image best through same-gender role modeling. However, these respondents suggested that girls benefit from positive male role models who support the girls' explorations in hands-on, problem solving activities early in their youth and continuing throughout their youth, including their middle and high school experiences." This would support the hypothesis that instruction style may be more influential than instructor gender. It has also been shown in other studies that even the positive effects of single sex education are trumped by the effects of good pedagogy and instruction [138].

5.7.3 Instructions for Instructors: Mitigate Adverse Effects

This toolkit can provide the social purpose requirement, but if instructors focus solely on the technology, this benefit may get lost. Therefore, instructors need to be given specific direction. Instructions must include the following:

- Encourage students to think about how and by whom it will be used and what impact their creation will have
- Use accessible language, for example do not say "accelerometer" but "motion sensor"
- Encourage students to personalize their creations

5.7.4 Follow-Up Study

It was observed that the self-efficacy gain varied greatly between groups with different instructors. This brings up an additional research question: If instructors, male or female, apply a narrative and approach identical to the one that was employed by the instructors that taught group A in the previous experiment, will their female students have the same self-efficacy gain, overcoming the issues discussed in section 5.7.1.4 (including potential "gender barriers")?

5.7.4.1 Experimental Method

A focus group was planned for 2 girls with two instructors: female (instructor A*) and male (instructor B*), both graduated engineers with some outreach experience. Instructions to both included the following: Make girls think about how it will be used, use accessible language, make them decorate their creations. The 2-hour workshop procedure was amended to include detailed descriptions of every procedural step:

TABLE 5.8: Workshop procedure with detailed descriptions and instructions for all instructors (left column has times for a workshop from 10 a.m. to noon).

10:00	**Complete pre-questionnaires**
5 min	If some girls get done early, do small-talk, like where they live, what their summer plans are, whether they did anything like this before etc.
10:05	**Let everyone introduce themselves (first name + what they like to do in their free time)**
5 min	**+ instructors, too (easy English)**
	Try to remember their hobby for product ideas later on.
10:10	**Introduction to wearables, sensors, input / output**
5 min	(Conversation. Smart devices measure things, do something with that information, and react in a certain way. Examples: fitbit, notification devices, pet trackers, remote-starting cars, …)
10:15	**Intro to toolkit** with **virtual button to NAME/display (+ deploy)** example, everyone
5 min	replicate, … (name.editor.qwartzi.com)
10:20	… and **sensor to gauge in app**, everyone replicate
5 min	(device sensor, NAME/accel or NAME/pulse or NAME/temp, to dashboard: gauge, open app in: name.app.qwartzi.com)
10:25	**Before we brainstorm: examples of what you could make**
5 min	A pedometer for your dog using a motion sensor, a heart rate monitor, a climate chamber

(continued)

TABLE 5.8: Workshop procedure with detailed descriptions and instructions for all instructors (left column has times for a workshop from 10 a.m. to noon) – (continued).

10:30 5 min	**Ask: What would you like to make?** Ideas? If they don't say anything, throw in (1) your silliest ideas (2) ideas you can come up with that have to do with their hobbies
10:35 15 min	**Activity: Create** product / application / solution with toolkit based on examples and own ideas **Important:** Emphasize **who** and **what** it's **for (real-life)**, like their mom or sports team etc. Make it **easy**. Say "motion" sensor ("accelerometer" is too complicated). Don't tell them about x, y, z unless they ask. If they have questions and you don't know a simple answer, avoid saying "this is hard", but say "we could make something kind of **like** this" and improvise (doesn't need to be accurate etc.) Encourage them to **decorate** and personalize it. Ribbon, tape, marker, modeling clay ...
10:50 10 min	[**Break**, ask how they like it, how they compare it to school or free time activities, what they hope to achieve etc.]
11:00 25 min	Continue **building** activity (don't forget to decorate).
11:25 10 min	If there is time: **Discuss** in groups of 2 (2 x 5 min)
11:35 15 min	Ask them to **present to class** React positively ("this sounds useful! Will you share this with your team?")
11:50 10 min	**Post-workshop questionnaire**

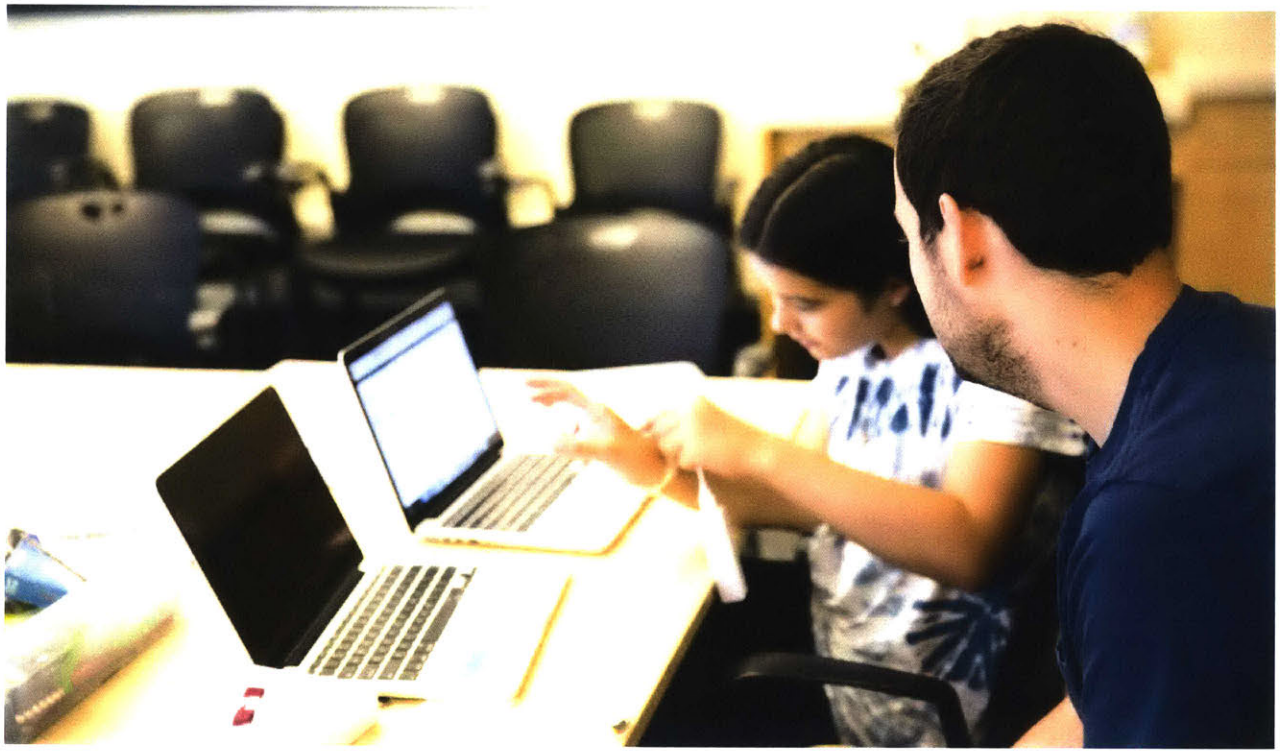

FIGURE 5.11: Photo of focus group participant and instructor in follow-up experiment. The instructors received special instruction to ensure the student receives prompts leading to the experience of social impact, agency and empowerment. The picture shows instructor B* (male).

5.7.4.2 Results

Since only two girls were observed, their prior self-efficacy must be considered. Figure 5.12 shows the absolute values.

For comparative purposes, Figure 5.13 shows the change in self-efficacy for both participants in the same format as preceding figures.

It can be seen that both participants have a similar self-efficacy gain. The participant paired up with instructor A* had a greater increase in her self-efficacy in solving science problems (her initial self-efficacy in this category was also lower than that of the other participant, so a larger gain was expected). The participant paired up with instructor B* had a greater increase in her self-efficacy in making hardware and creating a product (she also had the lower self-efficacy in these categories before the workshop, so a larger gain was expected). Both participants had the same increase in their self-efficacy in having social impact with engineering: an increase by 1 point on an 11-point scale.

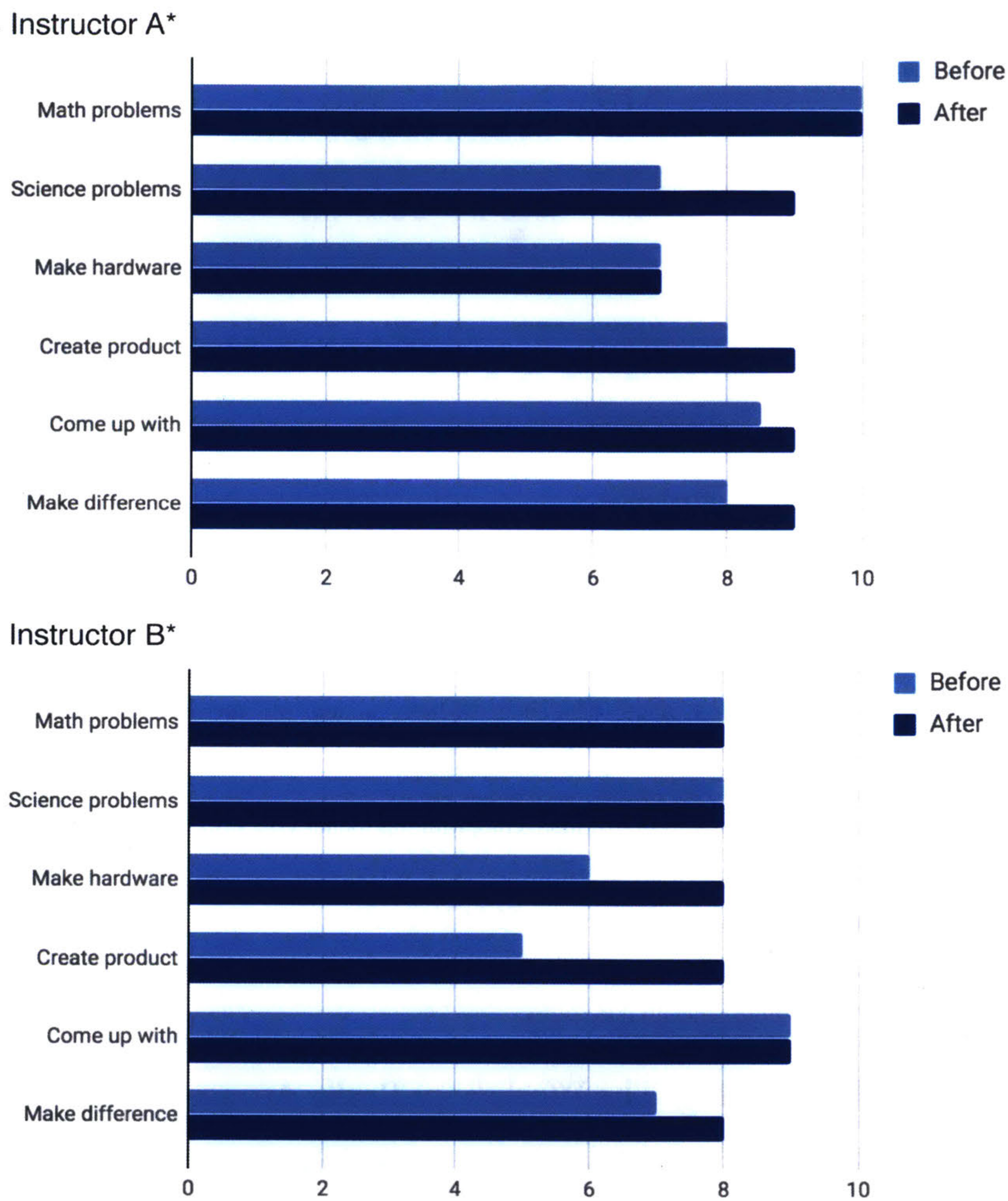

FIGURE 5.12: Self-efficacy before and after workshop; participants with different instructors. Both instructors received training to emphasize social impact. Instructor A* was female, instructor B* was male.

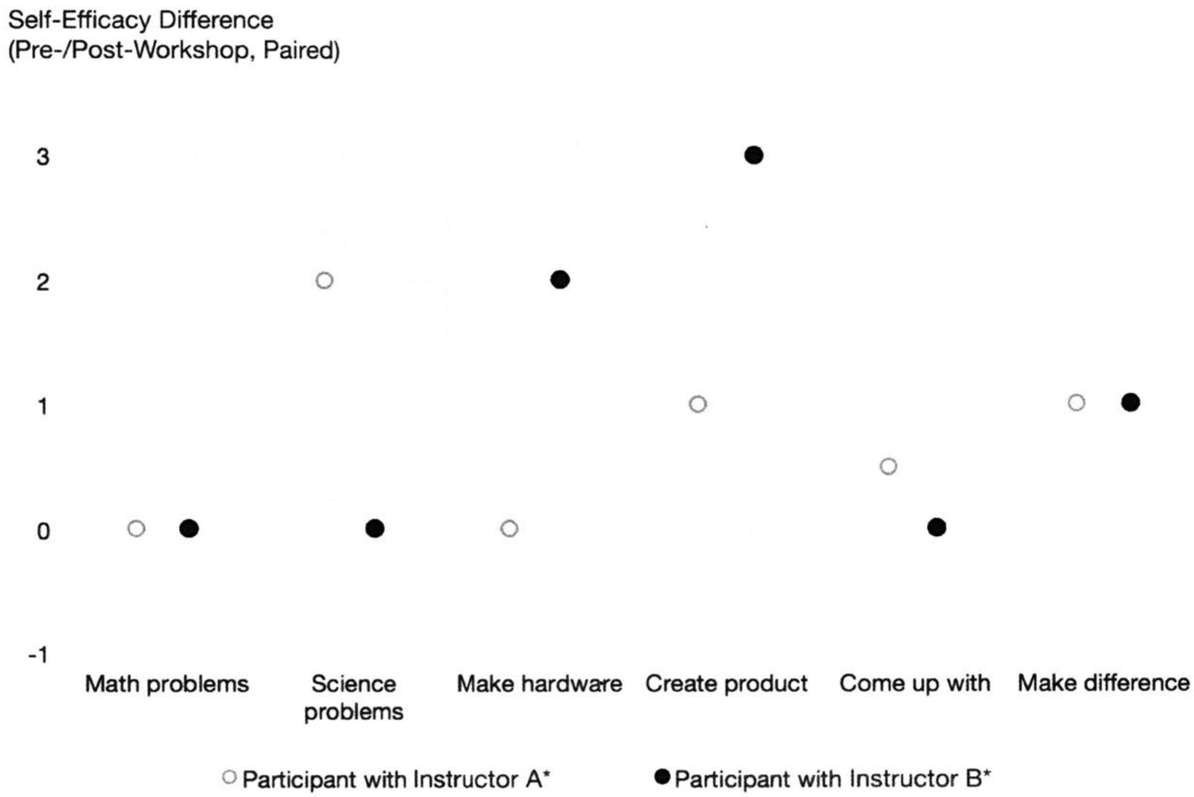

FIGURE 5.13: Self-efficacy change (difference) of both participants after specific instructor training, side-by-side.

These results are a first indication that interacting with this toolkit via a workshop such as the one developed for this thesis may allow for an instruction narrative that nourishes girls' engineering interest and increases their self-efficacy with regard to product design and engineering.

Similar studies should follow, potentially over the course of multiple sessions, to refine these discoveries and derive more generalizable results.

5.8 Another Finding: The Workshops Really Attract Girls

It was a desired goal to compare the developed learning experience to the "status quo". But teenagers interviewed in the greater Boston area reported that they had very little opportunity for learning about technology or engineering as part of their school curriculum. They relied on after-school organizations such as Science Club for Girls, Girls Who Code, and others. For example, a student from Boston Latin reported that no computer science education is available at the school before AP[7] Computer Science. Consequently, with virtually no previous computer science experience, very few girls signed up for AP Computer Science. This makes it especially important to attract those girls that say about themselves: "I am not technical", or "I am not creative," as seen in the earlier focus groups.

As a result, the "status quo" in Massachusetts is not science or tech education in school, but after-school clubs and activities. The question becomes: Can this activity attract girls enough to spend their free time with it? And looking at the previously shown research results, according to which the activity gives girls self-efficacy beyond other tech experience: how does it compare?

In organizing the workshops that went into this dissertation, girls were mostly recruited by research partners, such as the MIT Museum, Big Sister of Boston, Science Club for Girls, or the Edgerton Center. There were limited occasions to get in touch with parents of workshop participants directly. This makes the limited encounters all the more important. Two examples are presented here, as direct quotes are available from these encounters.

In one case, a parent called to inquire about workshop logistics. She emphasized: "My daughter saw it and absolutely loves the idea. She really, really wants to come to the workshop."

In another case, a parent came to pick up her daughter and requested a photo. She explained: "My daughter saw this and really wanted to do this. So we planned our trip from Canada accordingly. She has never done much with STEM before."

These were very promising results and they reflect that this activity can indeed attract girls from a variety of backgrounds, to give them the opportunity to interact with STEM in a meaningful and personal way.

5.9 Summary

A number of studies were conducted to investigate the educational value of a modular hardware toolkit and to test the hypothesis: if such a toolkit can in fact increase the technical and creative self-efficacy and perception of middle school girls, in particular regarding the social impact of engineering.

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[7] AP = Advanced Placement, classes offered during senior year of high school, which may count towards college-level class credit

The following results were extracted from the studies:

- 2-hour-interaction with the toolkit in fact increases girls' self-efficacy in having social impact with technology they create, to a statistically significant amount.
- This was also the case for girls who had previous STEM experience or coding experience
- Other self-efficacy dimensions also increased significantly, for example in "come up with a product people would like and use" or "make hardware with technology, like a thermometer".
- Girls' perspective changed significantly in ways related to engineering and product design, for example "I could see myself as an engineer one day".
- The self-efficacy in solving math problems increase by only 0.5 points on an 11-point scale (average value). That means engineering related self-efficacy increased along with creativity and product design related self-efficacy, whereas it was not required to increase math self-efficacy to the same degree.
- Instructor gender made a difference, but not simply for identification reasons, but because instructors emphasized different things. Training male instructors to be sensitive towards girls' perception and value system can improve the educational outcome.
- Girls very much enjoyed the activity and enjoyed thinking about "creating things for people" or solutions that are "useful".

The implementation of the toolkit lacked a built-in battery and 100% of girls stated that a more compact built-in battery would be useful. However, in spite of these limitations, the positive change in self-efficacy and perspective, i.e. the intervention's educational impact, was already significant.

Chapter 6

Reflection

A new learning experience was designed, implemented and tested. Multiple stages of iterative testing allowed for optimizing the experience and the technology that delivers it. Findings can be extracted to inform similar educational tools, and educational design in general.

6.1 Discussion

This work presents a concept of a design activity that takes into account the needs of middle and high school girls, and the implementation of this concept over many stages. It also shows both quantitative and qualitative results of the interaction with this design activity. The thesis outlines the process and experiments used to develop the kit, and what as learned along the way.

The findings from this project encompass design spaces of relevance to different age groups for both male and female learners. These broader motivational factors are a crucial foundation to design education and may be applied much beyond the scope of this project and K-12 design pedagogy.

6.1.1 General Findings

The different design stages of the toolkit provide insightful examples for testing interactive design experiences at the early stages of development. In a first study, physical and digital sketch models were used to communicate the concept and appearance in focus groups and interviews. One key finding was that, once "given the tools" to think about solving problems in a certain way, middle school girls showed a spike in creativity and a rapid change of mindset was observed by the researchers. In a second study, cardboard and stickers were used to mimic the design experience. One important result was a design space map, illuminating tendencies in design interest by different age groups and genders. In a third study, a simple implementation of a working modular smart device was used in an experimental workshop with both a group of 10 girls and with a predominantly male science club as a control group.

Self-efficacy and interest questions were used before and after the workshop to gauge the effect of the design activity on students' perception and motivation. Similar to the initial focus groups, data indicated a rapid change in mindset. Engineering perception was not significantly improved, as the terms 'engineering' and 'product design' were not discussed in the experimental workshops.

Girls' creations ranged from playful takes on popular wearable devices (e.g. a playfully decorated and programmed activity tracker) to specific solutions to problems. Many creations were health- (physical or mental) or sports-related, or were meant to send messages to people (e.g. make compliments).

Whereas early implementations of the toolkit insufficiently encouraged playful activities, which might be more appropriate to younger students, the addition of features such as voice output addressed this limitation. As expected, it was observed that younger girls (middle school) made more use of playful features than older girls (high school).

Overwhelmingly, girls chose to create wearable devices. This may partly be attributed to prior self-selection. Although care was taken to keep the solution space open when advertising workshops, e.g. as "girl powered smart devices" to keep it as general as possible, many girls were signed up to workshops by their parents, who may have used their own narrative when discussing the opportunity with their daughters. Also, certain affordances in the design of the devices and guides may have inspired girls in this direction. Although instructors brought up other examples of smart devices in the workshops, the quick-start guides contained instructions for turning devices into wearables. A great number of the girls came in to the workshops with the goal to create a "custom Fitbit", and most of them set this goal for themselves ahead of time. It is certainly possible that this is a contemporary phenomenon.

6.1.2 Motivation and Engagement Dimensions

The results of the studies in this thesis have to be measured using the goals this thesis set out for a change in students' mindset. Chapters 2 and 3 lay out motivational dimensions and needs to be met. Assessing whether needs have been met, and with which result, is possible through the qualitative data presented in Chapter 5.5.2. Figure 6.1 visualizes how quotes from participants match the motivational requirements.

These dimensions were derived from a rich body of literature connecting motivation and learning. The presented results confirm: Content learning is not enough; STEM learning experiences have to impact students' motivation and change their mindset to create new pathways into STEM.

While the factors relatedness, autonomy, perceived competency and meaningful objects were confirmed by a great number of participants, not all students expressed an optimally high level of challenge. More specific prompts and more guidance might solve this issue. On the one hand, autonomy and guidance are always competing factors that have to be carefully balanced, and in striving for giving students the autonomy they desired, the workshop implementation may not have given insecure students enough guidance. On the other hand, guidance could be provided in a more playful way, e.g. by giving students specific challenges they have to address. This would improve the result for optimum level of challenge.

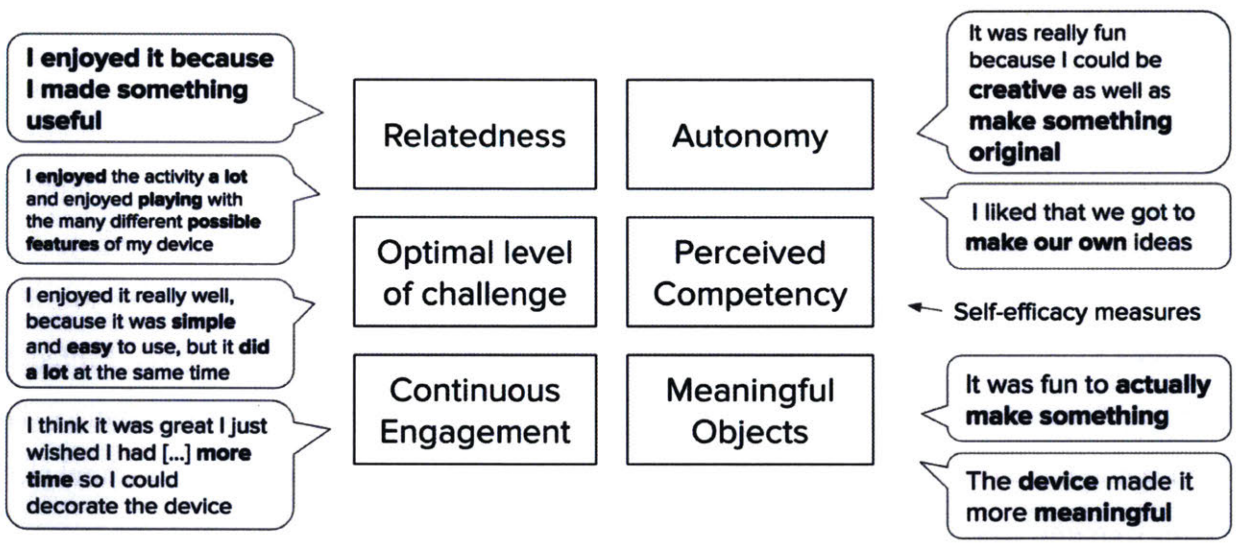

FIGURE 6.1: Qualitative observation of motivational factors. Relatedness, autonomy, optimal level of challenge, perceived competency, continuous engagement, and meaningful objects are aspects that were identified as requirements for a motivating and engaging experience. Quotes from participants were matched to assess the success of designing for these motivational factors.

Resnick and Rosenbaum's design principles are also reflected in the presented solution. This toolkit's approach is "characterized by a playful, experimental, iterative style of engagement" as the authors describe [75, p. 164], through:

(1) Immediate feedback, i.e. seeing the result and the process, is reflected in the plug'n'play / hot-swapping of sensors. Moreover, notification about successful connection has been a key attribute.

(2) Fluid experimentation, i.e. the ease of getting started and connect, is provided by both the modularity of the hardware and software and the immediacy with which program changes can take effect. Functional blocks are explained in the program and no compilation is required to implement custom code. Guided assembly has been a core attribute.

(3) Open exploration, i.e. the variety of materials & genres, is provided for by virtual and mechanical connection points.

By taking into consideration basic motivational needs, the constructionist methods of education research, and highly technical tools from today's engineering world, an educational method was developed that has the power to allow even layman to apply advanced engineering to the world in an open-ended and truly meaningful way.

Turkle's concept of evocative objects [73] is complemented by a truly social form of technology. In her 2016 publication "Reclaiming Conversation" [139], Turkle describes how the use of connected technologies hinders teenagers' emotional and empathic development. As she puts it, the ubiquity of mobile phones and superficial communication is in the way of building up deep relationships, threatening to forget about "*caring, friend, companionship,* and *conversation*" [139, p. 52]. Moreover, referencing Gardner and Davis [140], youth may see friendships as things to collect and manage, like apps on a phone; and this mindset "can show up as a lack of creativity and innovation" in school [139, p. 323]. Certainly, the solution is not to shut youth out from using the technologies and means of communication their parents use [141], but to give youth agency and ownership and let them take an active stance in creating it for their own purposes and that of their immediate social environment. The toolkit developed in this thesis offers a framework for this approach. Ultimately, it will be the responsibility of educators to encourage young people to create socially impactful solutions through an empathic dialogue, see technology as something shapeable, relational and meaningful, and reflect on personal and humanistic dimensions at all stages of the creative process. The toolkit offers a platform for this pedagogical avenue.

6.1.3 Social Impact with Engineering, Experienced

The studies discussed in chapter 5 reveal that it is indeed possible to convey to girls the experience that they can make a difference in people's lives with engineering – the key factor according to important findings cited in the prior art section, including the NAE (2008) study [62]. What is needed is an experiential activity that lets female students experience their own "technical creativity" as socially impactful. A constructionist approach, in which students design and build something of their own accord, something physical, personalized and shareable, is particularly suitable for achieving the experiential aspect. What was contributed in this work was the expansion of constructionist methods to an area that is otherwise reserved to engineers, but that is extremely powerful – using advanced tools to create solutions that drastically change people's lives.

A very interesting finding was that the gain in self-efficacy in making a difference in people's lives with technology was not significantly correlated to the incoming self-efficacy in this area. Furthermore, an interesting observation was that the incoming self-efficacy in making a difference in people's lives with technology was not correlated to a significant degree with participants' prior STEM experience, i.e. even girls that had plenty of STEM experience may not think about it in an impactful way prior to the workshops. This is shown again in Figure 6.2.

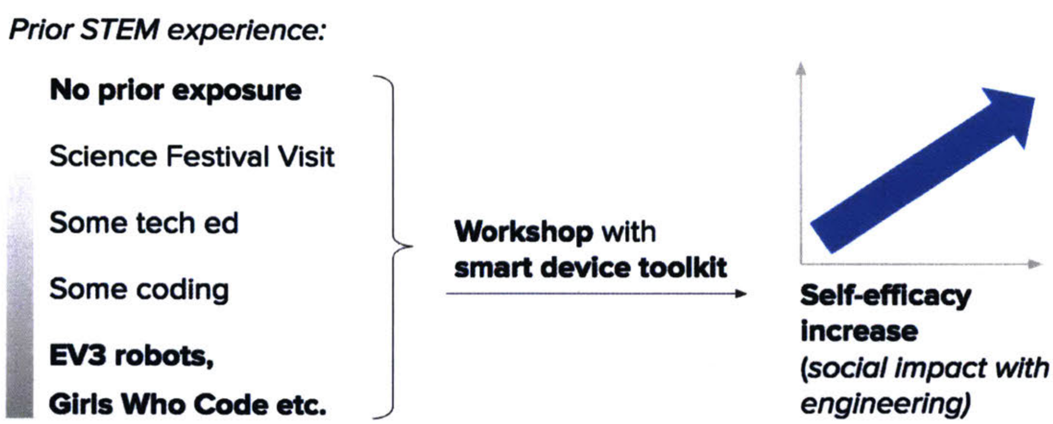

FIGURE 6.2: Finding of this work: social impact self-efficacy increase is independent of prior exposure to STEM.

As education, empowered by means of digital learning, is ready to give students more freedom and provides more personalized and more self-driven ways of learning, it is important to address those individual needs with appropriate context options. Only if the relevance aspect is satisfied will many middle-school-aged girls be intrinsically motivated and fully benefit from discovery-driven design education, serving technical education and beyond.

6.2 Derivation of Design Principles

The following design principles can be derived from the knowledge gained in experiments, interviews and focus groups, to inform the design of STEM experiences for teen girls. In addition, many parents have asked for advice how to introduce their daughters to engineering in a way that they might enjoy. The following is a collection of design goals that were found to be especially impactful. This list complements existing guidelines for designing STEM activities and curricula [142]–[144] that may already be widely used in education. For example, it is already known that a curriculum should always build on skills and knowledge that was previously gained [143], [144], tasks should build on each other [143], students should be given opportunities to collaborate and work in groups [142], content needs to be accessible and visible, including learner-constructed visual elements [142], activities need to promote autonomy [142], and students should be encouraged to discuss their own and each other's thinking to promote metacognitive learning [144].

The following design principles apply beyond technology-supported activities, but they were found or reaffirmed through this work that is focused on a technology-supported activity.

Real-world social purpose

Students need to be given the opportunity to do things that are socially rewarded and valued in their system. While we as teachers often see what a learning opportunity may be useful for in the future of the student, it is very difficult for the student to make that connection if they have to rely on a verbal explanation. Make it tangible and real! Let students experience not just what engineering is, but what engineering is about! Examples for real-world learning opportunities generally include: product design, medical device design, and mobile app design.

Physical objects

Physical objects can carry a lot of meaning and value. However, it is important to give students the opportunity to personalize those objects creatively and artistically. Students may have to be prompted to do so.

Instructors emphasize social impact

It is crucial that instructors give individual feedback about social impact. Students need to be prompted to reflect about the social impact they can have with what they learn. Be encouraging and empowering.

Error modes are clear

Even the best educational technology can fail in class. But it is important that students do not feel like they broke it, unless this is the intended teaching message. If students are tested by their ability to program a robot, and the hardware turns out to be unreliable in a way that students are not capable of fixing, make it obvious to the student that this failure is not their fault. Create error modes that make it easy to detect and solve problems.

Autonomy

Students need the opportunity to "own" their learning experience. They need freedom in picking a learning speed, trajectory, and outcome. This can be difficult to achieve in a classroom of 30 students, but it will significantly increase students' motivation.

Guidance

Keep students engaged by always having a prompt or challenge, even from the very beginning of a class or workshop. Prompts should reflect their challenge level so students are not overly discouraged if they try a problem that is much harder to solve than they expected.

These design principals can be applied to other STEM learning experiences and may inform new learning activities and curricula.

Chapter 7

Deployment at Scale

The best learning experience is worthless if it is not presented in a format that could easily be deployed in schools and made accessible to kids. The American education system is very diverse, ranging from private and charter to public schools that are subject to various jurisdictions and home-schooling. To investigate how the presented solution could be deployed in practice, numerous informal interviews and focus groups were conducted with educators and parents.

7.1 Educators' Perspectives

Educators' feedback on the toolkit itself was very positive. Educators were positively surprised by the concept and implementation. Most educators immediately recognized that the learning activity was exactly what girls would need to experience STEM on their own terms.

However, several important conditions were identified.

A big learning point from talking to schools was: In spite of all the STEM education efforts, many schools do not plan on making tech education part of the middle school core curriculum any time soon. While public schools often cite inflexibility of the given curricula or a shortage of skilled teachers, many private schools simply prioritize traditional sciences, such as geography, chemistry or biology (interestingly: fields in which women are well-represented) over engineering and computer science education. Very often, teachers and parents will disagree on the relative importance of tech education [145], [146]. An informal survey I conducted among Boston public and private schools showed that even progressive schools with state-of-the-art lesson plans may not introduce technology, coding, or engineering until high school, in many cases not before AP Computer Science. Browsing the web for "technology education" in many schools today, one may get the impression that it mainly entails using iPads in biology class.

Also, funding is often a challenge. Overall in the United States, public schools are spending $21 billion on "technology" (this figure includes laptops and projectors), while about 52 million K-12 students are projected to be enrolled [147]. So, for public schools, this results in a $400 budget per kid per year on average, which is barely enough to buy a low-cost personal computer. And in adopting new curricula to satisfy Next Generation Science Standards (NGSS), many educators budget $10 per kid or $100 per class for the entire school year.

Interestingly, the finding that girls desire social impact as part of their STEM education was news to many educators. For example, surveyed educators were in the process of writing curricula for Next Generation Science Standards (NGSS) and did not provide for perceived social relevance in student assignments or even creative room in project based learning activities. But most educators, who learned about girls' needs through my work, were open to adapting their teaching style accordingly. Given that my work builds heavily on extensive prior art regarding girls' desire for social impact in tech education, it would seem that an important task lies in educating educators about these findings.

Another point to consider was teacher training. In spite of the intuitive nature of the developed toolkit, in just talking about it, it was perceived as "new and different" and yet something else to train a teacher about. By contrast, "old" technology like Arduino, Raspberry Pie and others, although they take much longer to set up and have a steeper learning curve, schools can find experts they can hire for particular tasks. This is a problem that any new educational technology faces.

7.2 Long-Term Engagement is Required

Fellow researchers have pointed out that a self-efficacy increase this significantly after just a 2-hour intervention is not a common result. Strictly speaking, the effect of the toolkit can only be assessed with certainly after a long-term intervention with multiple settings. Not only to strengthen a self-efficacy increase that may have taken place in a first setting, but to avoid a possible slump. Such a slump is in fact possible. Figure 7.1 visualizes this in a very vivid and descriptive way.

Educators need curricula that guide their teaching over an extended period of time. And beyond school settings, young learners need opportunities to connect and stay engaged long after a workshop. Means are required to keep young people engaged engaged: assistance and mentorship.

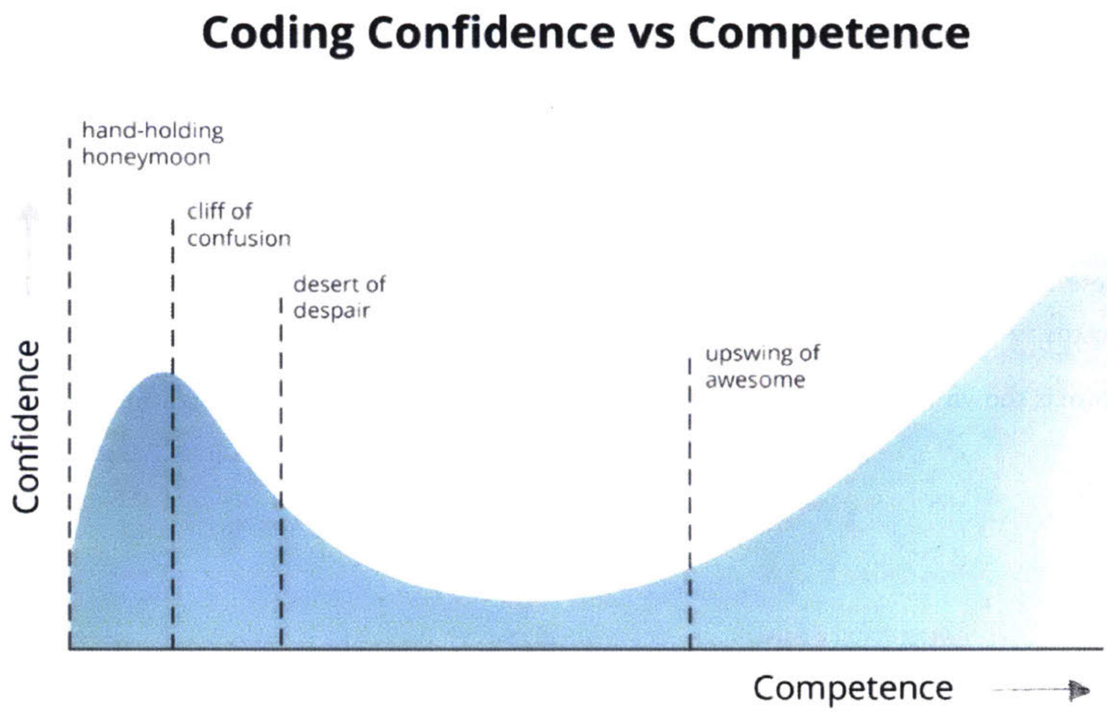

FIGURE 7.1: Short-term intervention has a great impact on self-efficacy, but long-term engagement is needed (graphic modified from [148]).

7.3 Website Implementation

As outlined in chapter 3.4.3.3, a website was to be designed and built to assist and guide learners and provide opportunity to share, interact with, and remix creations. A lot of learning happens during reflection, e.g. while explaining the creation and creative process to others using text, pictures, video and other media. Moreover, social feedback and community are great incentives, especially for adolescent learners. Feature requirements for this website are presented in chapter 3.4.3.3. The focus was easy sharing of creative and hands-on process steps, inspired in part by the websites for LitteBits and Build In Progress (http://buildinprogress.media.mit.edu), and on interaction, inspired in part by the websites for Scratch and social networks in general (e.g Facebook).

The website was implemented using an open-source CMS[8] (Joomla 3.6) with a paid social network component (EasySocial 2.0). "Page" elements were renamed to "projects". Projects can be public or private. One or more project owners are possible, allowing students to have collaborators for each of their projects. Project owners can share pictures, code, videos, as well as updates at any time. Other users can "like" (or become a "fan" of) and comment on public projects or those that were shared with them. These modes of interaction may be useful for developing and fostering 21st century skills in students [149].

A picture is shown in Figure 7.2. The page is publicly available at: http://qwartzi.mit.edu/ideas.

[8] CMS = Content Management System, a system that commonly consist of core files that allow for separating a website's content from its layout, so each can be managed more easily, and new content (e.g. pages, menu items) can be added without the need to change any of the existing pages

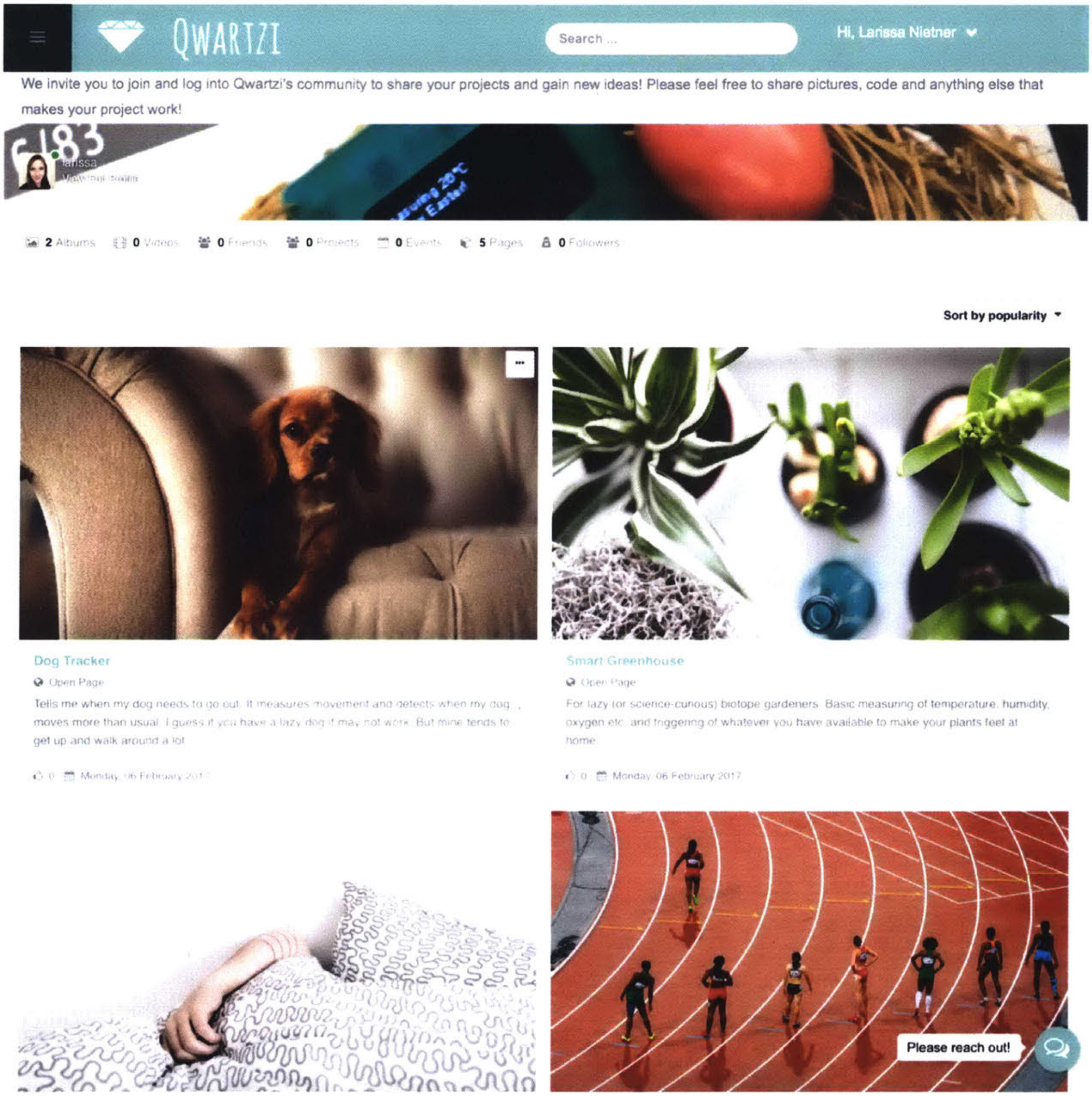

FIGURE 7.2: Website with Project Sharing Platform. The website can be used to share creations and copy from other users.

The website will be complemented with monthly challenges, like "create something for this person, who has autism," to incentivize active participation, reward students for their creative inputs, and provide more opportunity for real-world social impact.

Also, the online sharing network might help reach students that are home-schooled or whose schools do not have the resources to offer product design or coding activities.

7.4 Deployment in Schools

Possible venues for deployment of this toolkit are after-school clubs and classes. While traditional school curricula may not provide for design and engineering learning per se, the presented toolkit might create the opportunity for project-based learning in science or math classes. This could bridge the disciplines and help students to take charge of technical experimentation to experience the real-world impact they desire.

7.4.1 Standards-Compatible Curricula

To reach girls across all spectrums, it is important that the toolkit will be deployed in schools. Starting with a few pilot schools, an after-school club format will provide a testing ground for a curriculum that fosters long-term engagement. A STEAM competition will create excitement around participation. In-class curricula can also be derived, satisfying Next-Generation Science Standards (NGSS).

A possible strapped-down version may open up the arena as a low-cost solution (see Figure 7.3).

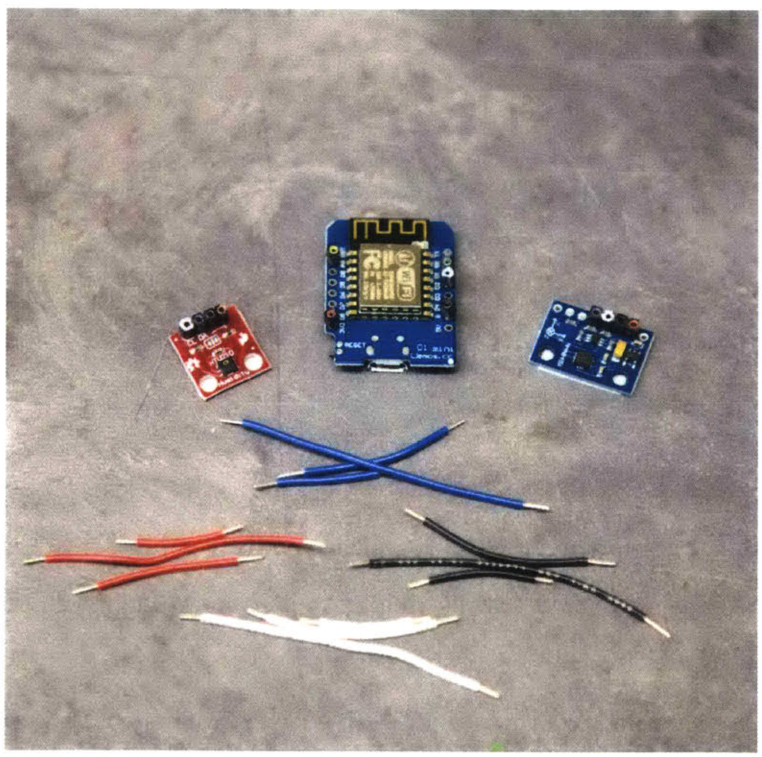

FIGURE 7.3: A possible ultra-low-cost version for reaching a broader audience.

This may also be a way to reach other minority groups. Black, Hispanic, and Native-American ethnicities represent 31% of the US population, but they only make up for 11% of STEM jobs. It will be an important goal to eventually reach all underrepresented groups in design and engineering. It would therefore be favorable if the presented solution also served youth from other minorities in STEM fields, e.g. Hispanic, black, and Native-American youth. Considering Figure 7.4 (shown in chapter 2.1.2.4 and repeated here for convenience), black and Hispanic girls value social impact even more than white girls, so it can be argued that the social impact youth get to experience with this activity may influence ethnical minority girls even more.

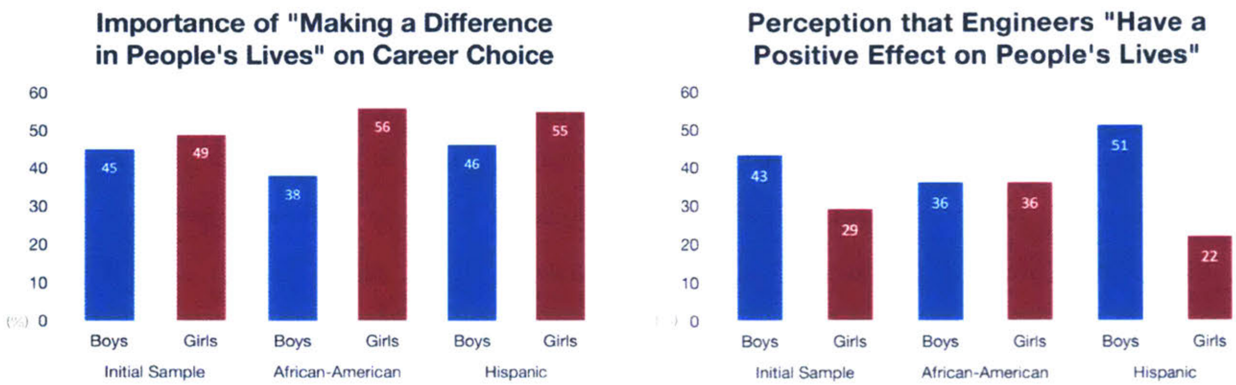

FIGURE 7.4: Teen girls' desire for social impact vs. their perspective on engineering, also showing minorities. Statistically, black and Hispanic girls value social impact even more than white girls. Data from [62].

What holds many young people back from learning about engineering is opportunity. This is especially true for low socio-economic background youth. Many young people don't have the chance or the time to engage in an after-school activity. Some young people have to work part-time jobs to supplement their family's expenses (e.g. rent in the expensive Boston area). Moreover, hands-on after-school activities are not offered in many school districts.

Maybe those young people will have a chance to start a club at their school, using curricula based on the ones presented, that conform with their state's standards. Maybe they can use the toolkit to create solutions that help their communities – such as a drug addict health monitor (idea from a workshop with East End House, Cambridge) or personal safety device. Maybe guidance material will be available in Spanish, so they can explain what they created and how they did it to their parents and siblings, making it all the more meaningful.

7.4.2 A Suitable STEAM Competition Format

FIRST (For Inspiration and Recognition of Science and Technology) is a non-profit organization that inspired thousands of students to form teams to design robots to participate in competitions. It grew from New Hampshire and now has competitions in many countries of the world. While FIRST originally required teams to purchase a kit for about $6,000, other competition tracks have since become available, such as FIRST Lego League, in which student teams obtain Lego Mindstorms Kits to design and build their competition robots (source, source).

The results of this dissertation were of interest to the founders of FIRST. However, it was clarified that a product design track was not planned in the future, in spite of its potential to attract more girls – an issue FIRST has recognized for some time now (source).

Teachers have asked for a STEAM competition format that is conceived with girls' needs and interests in mind. This presented the opportunity to work out a plan for such a competition.

The competition will be an after-school (or in-class) STEAM design project with an annual challenge for teen girls age 13-18. Challenges will focus on creative design or artistic projects with a social function, prompting students to understand their user (design thinking) and reflect on the impact of their creation. The experience of partaking in this challenge with a team should foster 21st century skills and collaborative learning of coding, electronics, engineering, and design.

Although it would exceed the scope of this work, a pilot plan is presented here (see Table 7.1).

TABLE 7.1: STEAM competition milestone overview.

Identify a user, conduct interviews
Brainstorm products, solutions, concepts
Prototype (create sketch models) round 1
Test, get feedback + review
Prototype (create sketch models) round 2
Test, get feedback + review
Create final product model and demonstration video
Present and receive competition results at final symposium!

7.5 Technology Scale-Up

The technical implementation of the toolkit must be adjusted for scale-up to sustainably reach a great number of users. Although the groundwork for future deployment and scale-up is laid, a lot remains to be done to give learners the opportunity this work promises.

In order to let a greater number of students use the program editor at the same time, a more dynamic instance management system will be required. It might be prudent to introduce password-protected access. For example, users may automatically log in with an account they created, to which they can register devices. This way, interference between users would be prevented, whereas thus far it is technically possible to access any device from any instance of the program editor, making it possible for students to "hack" each other's devices (it has not been a problem in any of the workshops, but might be a problem in the future).

Design changes to the hardware will allow for mass-fabrication. For example, by reconciling the main device to a single board, the tedious soldering of thin wires between the microcontroller and display board will become unnecessary. Then, mass-production techniques like SMT board fabrication will be possible. Also, injection molding the cases will be much faster and cheaper than 3D printing them.

Additionally, standard electrical connectors can be used in place of header pins, to make for an easier and more robust assembly.

The design activity may also be complemented with more activity guides, examples, and mechanisms for providing immediate feedback. It was found that providing guidance does not merely consist of asserting structure, but rather providing clarity about the state of objects and tools at any given time to allow the learner discovery in design. Additional guidance can be implemented both in the platform itself and on the website.

An idea for complementing the program editor in a playful and engaging way would be to virtually represent the device. For example, the device and its "needs" (e.g. low battery) may be represented in a way that appeals to empathy, e.g. in a personified way, making the device a relatable protégé of the owner.

Chapter 8

Contribution

The work presented in this thesis encompasses engineering, education research, and social psychology. A new technology was developed consisting of a number of different elements. An overview over the project scope and the interdisciplinary composition of this research is given in Figure 8.1.

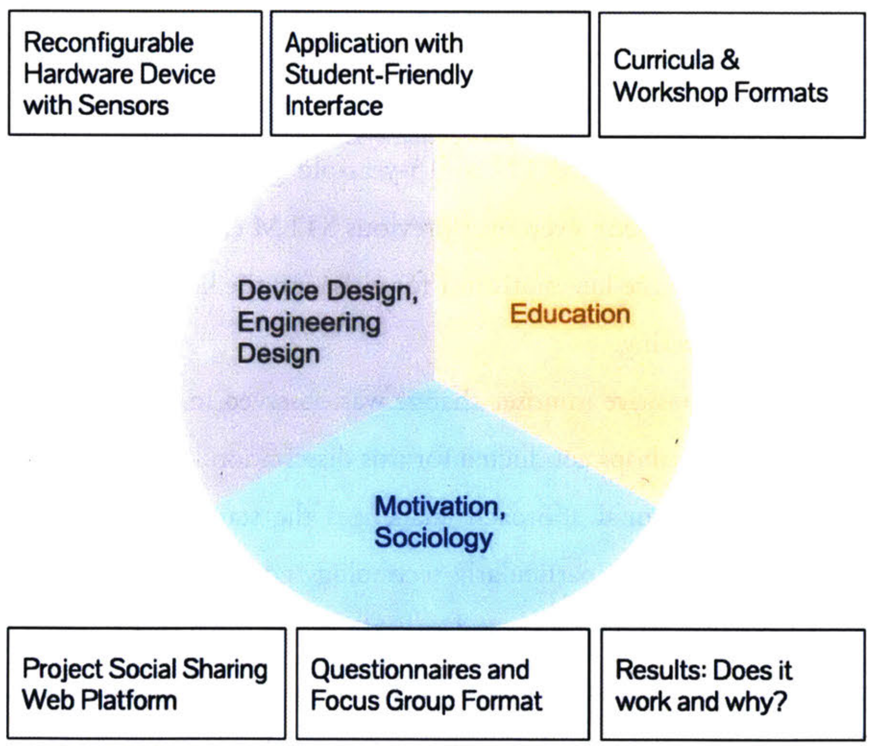

FIGURE 8.1: Scope of this project. An interdisciplinary work between Engineering Design, Education Research and Motivation Research, its deliverables are not limited to the design toolkit itself, but also encompasses certain motivational dimensions.

8.1 Changing STEM Education

This dissertation made a first step towards designing and implementing an engaging STEM learning experience that addresses teen girls' needs.

As a reaction to feedback from experimental workshops, the technical implementation has grown to a modular IoT-solution using state-of-the-art technology. This is the first ever reported use of Node-Red in the classroom.

Curricula were created that are compatible with schools' standards and with after-school-clubs' goals. Design principles were extracted that may inform the design of future STEM learning experiences and educational technologies.

Various research methods were developed and tested, both for early-stage testing of new learning experiences, as well as for objective and in-depth quantification of the success of an educational program. Questionnaires were developed for measuring the (social) efficacy of STEM activities.

The efficacy of the developed learning experience was measured over different dimensions. It was shown that the experience increased 12- to 15-year-old girls' self-efficacy in having impact with engineering to a significant extent, even over previous STEM exposure. This result is very important because this was found to be the key motivator for girls, and the key factor that decides whether a girl sees a connection to engineering.

Finally, a measurable positive mindset change was observed in at least 49 young people over the course of experimental workshops conducted for this dissertation.

Importantly, this educational approach challenges the status quo and many of the persisting stereotypes in STEM education, particularly technology education. "Of course, to create a device, students will first have to learn to solder and to code, so we teach that first, and then they can start bringing in their own ideas," one educator phrased a prevalent approach to lesson planning. The assumptions on which this statement is based are widespread. However, there are two problems with this perspective: not only does this pedagogy create a "valley of death" in which budding STEM interest is nipped by a lack of agency and personal relevance throughout the content learning phase, but this narrative does not reflect today's professional world of engineering and computer science. Technologists of today select from a ubiquitous pool of technology pieces: code libraries, electrical and mechanical components. Who is to say that soldering, lighting up an LED, or compiling Arduino code are the aspects of engineering that should be the first that young people get to experience (when, moreover, hand-soldering is obsolete in nearly all industrial applications, as the majority of soldered connections uses surface-mount technology)? Engineering has many layers, and by depriving young learners of those that translate technology into social impact, we strip away much of what makes it purposeful and intrinsically motivating. Why not lead with the activity of putting existing pieces together into something that solves a real, meaningful problem? Instead of focusing on what engineering *is*, we need to teach young people what engineering is *about*. This is the mission of this toolkit.

This work may also lay the groundwork for a learning communities that may contribute to inviting girls into STEM and increasing the number of middle and high school girls envisioning a technical career. Certainly, a remaining challenge on the road to equality will be that of retention. Still, at many colleges, most engineering students are male, and as McCarthy and Berger state, a classroom filled with males requires that female students feel comfortable with "being fluid in their own gender roles" and can accept being "a bit of an anomaly" as the only female in "a classroom filled with boys" [137]. But by creating a community of socially-oriented future engineers, a step is taken towards a more a diverse and welcoming environment in engineering education.

To offer an additional perspective, it can be reasoned that teaching IoT device design is becoming a new educational requirement. This toolkit offers instructional materials to learners of all backgrounds.

8.2 Changing Who Designs

By inviting all those into the engineering design world who previously didn't see its social impact potential or said about themselves "I am not creative" or "I am not technical", the floor is opened up to a whole new set of ideas and individual perspectives. But the effects of this are two-fold. Over the long term, meaningful STEM exposure and perceived social impact and competency may attract female students into the engineering field, contributing to a diverse workforce. But also, over the short term, many of the inventions seen in the workshops served very small groups: A Lacrosse throw-meter, or an audible activity tracker that speaks both French and English. Notwithstanding empowering the underserved: industry may not develop products this specialized for a long time to come, because the market would simply be too small. But an IoT toolkit, that allows users to create convenient devices with not prior coding experience required, radically opens up the space.

To take a step back and offer a bigger perspective, it can be argued that this work is just a branch in the movement of democratizing engineering. Companies like Autodesk are working towards making CAD accessible to non-engineers, including teenagers. Affordable 3D printing machines have long given the power to create physical objects into the hands of amateurs. And if this does not suffice, the quickly growing number of makerspaces allows almost anyone to design and build using a variety of materials and manufacturing processes. Equally, now, this project creates an ecosystem that lets non-engineers create their own connected sensing devices. All these developments – accessible CAD, 3D printing, makerspaces, and this work on tinkerable IoT devices – contribute to a democratization of design and engineering. In combination, these different elements empower non-engineers to make almost anything; something that would have been unimaginable mere decades ago.

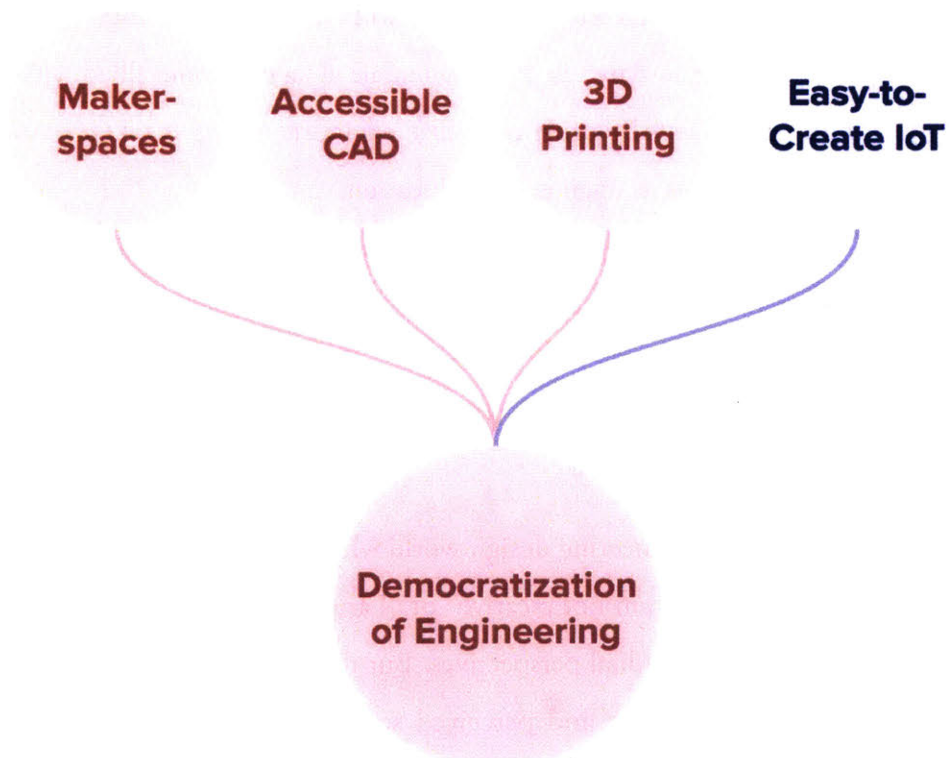

FIGURE 8.2: A scheme for how this project fits into the movement of democratizing engineering. Other branches of this development include the rise of makerspaces, accessible CAD and 3D printing. One of the outcomes of this development is to broaden who participates in innovation, much beyond just engineers.

8.3 Rapid Innovation Device Architecture

This work contributes its part to the ever-growing world of connected devices. A modular hardware platform was created for rapid prototyping of functional IoT products. Within minutes, functional devices can be assembled and programmed. Using pre-programmed microcontroller boards, a variety of applications are possible. The devices used in the workshops support a bandwidth of 4 Hz, but a higher bandwidth would certainly be possible with the same architecture. In its current implementation with accelerometers, pulse and temperature sensors, main applications revolve around wearable devices. And with every additional sensor that is implemented to the platform, the range of possibilities extends. Environmental sensors like ambient pressure, UV and visible light, orientation and location sensors. As sensing technology advances into fields like sensing gas and particles, the range of possible applications will extend even further. Digital sensors can be integrated by adding to the programming of the pre-programmed microcontrollers, and analog sensors of any type can already be readily used with the device as it is.

The rapidness with which connected electrical devices can be prototypes provokes a change in the design process. Whereas creating a prototype device was previously a long process, it is now much easier to simply connect a sensor to a device base microcontroller and create a quick program via drag-and-drop, to gather data shortly after the idea was conceived. This allows for much quicker hardware innovation cycles.

The research methods for complex hardware development, which were presented in this dissertation, also entail methods for testing concepts early on, thus facilitating a rapid (agile) innovation environment even more.

The hardware, software, and online sharing infrastructure are scaled and improved and will be available to the public as "Qwartzi" beyond this research.

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A

Focus Group Questions

A.1 Lead Questions

- Tell me about what you enjoy and don't enjoy in and outside of school.
- Tell me about an activity where you might create something.
- What is your first reaction to this toolkit?
- What would you make with it, if anything?
  - for whom?
  - what makes it meaningful?

A.2 Additional Questions

At beginning of interview:

- tell girls that anyone who is present won't share anything of what they say in conjunction with their identity;
- ask parents if the interview may be audio-recorded

<u>Beginning of interview</u>

- What school do you go to?
- **How do you like school? What are people like?**
- (Are you doing something for Halloween?)
- Which classes do you enjoy?
- What is most challenging (or annoying)?
- **What bothers you most at school, at home, ...?**

Social context

- Do you “fit in” with your school class?
    - Is that important to you?
    - How are you different from your peers?
- Who do you look up to?
- Do you have life dreams?
- **What do you want to be when you grow up?**
- Where do you spend most of your time after school?
- **How do you communicate with your friends? Why?**
- **What do you like to do with your friends? What do you like to talk about with your friends?**
- Do you have a best friend? What’s (s)he like?
- How much time do you spend together, and where?
- Do your friends ever make you gifts? What is important to you, when is it a good gift?
- Do you use things more often that a friend gave to you vs. your parents vs. that you bought yourself?
- **What do you enjoy gifting (and to whom, when, and why)?**
- Do you ever give your friends …
    - techy gifts (e.g. headphones, speakers, iPhone add-ons)?
    - accessories?
    - What’s the difference? (Why is one a “safer bet” than the other?)

Building

- **Do you enjoy building / creating something?**
- **If so, what do you like about it?**
- **How did you get into that; what got you started?**
- Do you like challenges?
- What lets you not give up? What drives you to complete a challenge?

- **Do you create for yourself or for others?** (Why?)
- **Do you create alone or with others?**
- When is doing things as a team fun?
- Do you *enjoy* coding? (Why?)
    - Would you ever wish your creations were more tangible?
- Do you ever use scratch? Do you like it?
    - Makey makey? Little bits?
    - Arduino?
- **What challenge are you stimulated by?**
- **What impact or accomplishment are you stimulated by?**
- **What was your favorite thing you ever built?**
- What is the last thing you made?
- (Can you bring a portfolio?)
- **What kind of devices or applications are you most interested in?**
- **How did you get inspired to create (through toys, TV, etc.)?**
- How important is personalization to you? What [objects] do you personalize and how?
- Did you use Arduinos or other microcontrollers?
- What were you bothered by? What did you like?

<u>"Engineering"</u>

- Do you consider yourself to be tech savvy?
- Do you feel like boys are different from girls? (In STEM subjects?)
- How do you feel about "engineering"? Is that a thing you're curious about?

<u>Style</u>

- What were your last 5 purchases?
- Is "style" important to you?
- Are brand names important to you?
- How do you accessorize? How often?

Using Tech

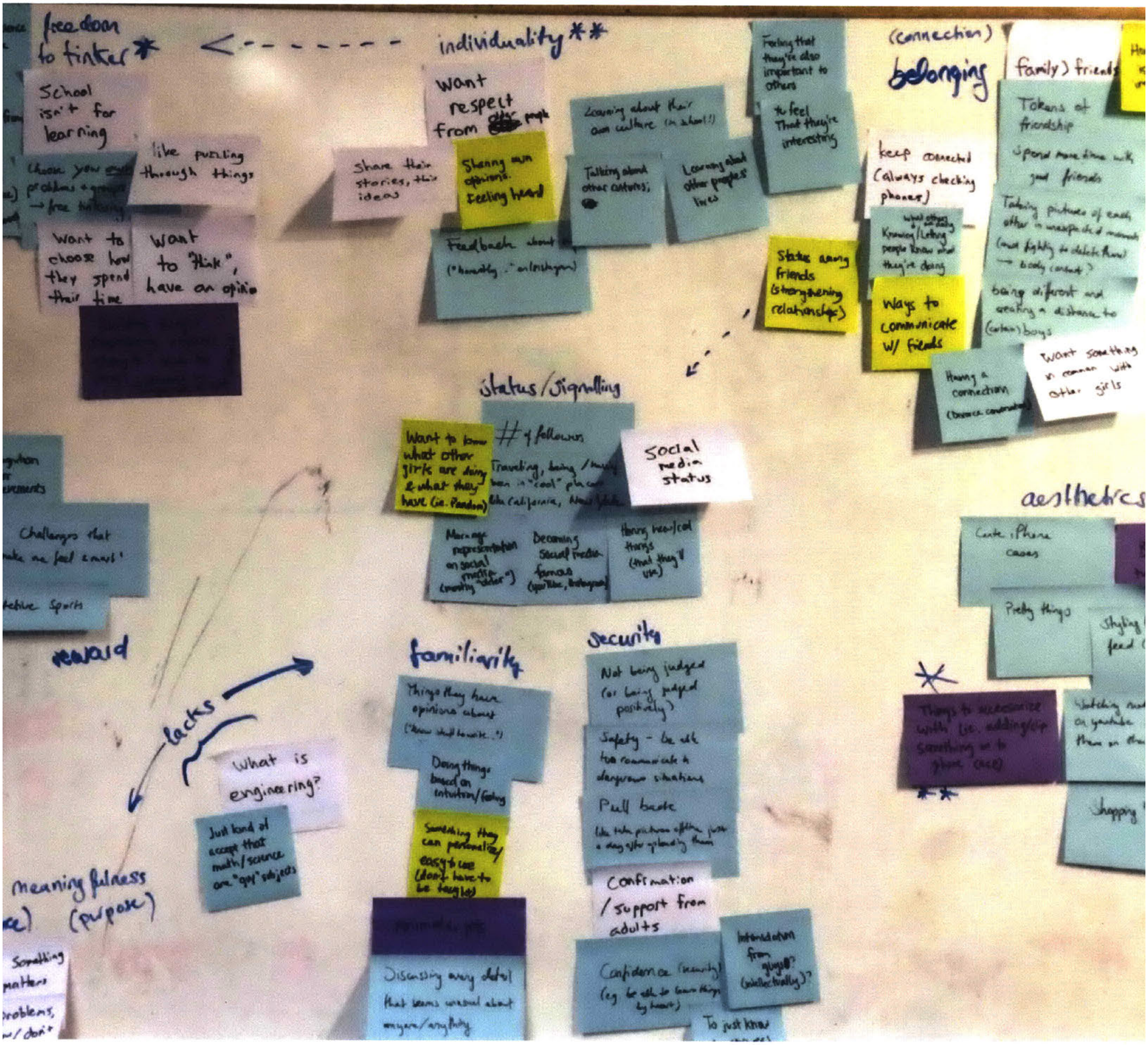
- Do you enjoy using your phone? Why (not)?
- What bothers you most when using your phone?
- How do you choose to get notified about?
- Do you text in class?
- What is your experience with wearables?
    - What do you enjoy? What do you criticize?
    - Fitbit?
    - Apple Watch?
        - **What is right and wrong about the Apple watch (for you)?**
        - **Why would or wouldn't you use it?**
    - Pebble?
    - Misfit (e.g. Shine, Link)
- **Why would you (or anyone) use a smartwatch (or any wearable device)?**
- Can you interact with wearables? (Does that feel geeky?)
- If you built a wearable device, would you wear it yourself?
- What would you want it to do?
- Would you want to get notified about social media interactions? What else?
- What do you use wearables for (vs. your phone)?
- Do you text a lot (or what form of communication do you use)?
- Where do you use wearables?
- How do you feel about:
    - If you press a button, your best friend(s) get a short buzz / LOL / smiley face
    - Wearing watches in general (and why)?

B

Sorted Needs – Raw Results

B.1 Whiteboard Photo of Sorted First Results

An expanded image is on the next page.



freedom to tinker *
individuality **
School isn't for learning
like puzzling through things
Want respect from people
Sharing own opinions. Feeling heard
share their stories, their ideas
Want to choose how they spend their time
want to "think", have an opinion
Feedback about
Learning about their own culture (in school!)
Talking about other cultures;
Learning about other peoples' lives
Feeling that they're also important to others
to feel That they're interesting
(connection)
belonging
family) friends
Tokens of friendship
Spend more time with good friends
Taking pictures of each other
being different and creating a distance to (certain) boys
keep connected (always checking phones)
Status among friends (strengthening relationships)
Ways to communicate w/ friends
Having a connection
Want something in common with other girls
status/signalling
Want to know what other girls are doing & what they have
# of followers
Traveling, being / having been in "cool" places like California, New York
Social media status
Becoming social media famous
aesthetics
Cute iPhone cases
Pretty things
Challenges that make me feel smart
reward
lacks
What is engineering?
Just kind of accept that math/science are "guy" subjects
meaningfulness (purpose)
familiarity
Things they have opinions about
Doing things based on intuition/feeling
Something they can personalize/ easy to use (don't have to be taught)
Discussing every detail that seems unusual about anyone/anything
security
Not being judged (or being judged positively)
Safety - be able to communicate in dangerous situations
Pull back
Confirmation / support from adults
Confidence (security)
Interest from guys? (intellectually)?
To just know
Things to accessorize with
Shopping

C
List of all Experimental Workshops

C.1 Table of all Studies

TABLE C.1: List of all studies, including focus groups and formal experiments

Description	*Date*	*Partner*
Prelim. informal focus groups	July 2014	Local parents
Focus groups	Oct / Nov 2015	Local parents
Girls Day 2016	Mar 2016	MIT Museum
Cardboard study	Apr 2016	MIT Museum
Workshop with modular prototypes	Aug 2016	Science Club for Girls
Workshop with reprogrammable prototypes	Nov 2016	Big Sister of Boston
Secondary study with science club	Nov / Dec 2016	Buckingham Browne and Nichols School
Girls Day 2017	Mar 2017	MIT Museum
Workshop with two groups (male and female instructors, refined device design)	Apr 2017	MIT Museum
Short workshop (no analysis)	May 2017	CATS Academy
Focus group with male and female instructor	June 2017	MIT Edgerton Center

D

Pre- and Post-Questionnaires

D.1 Initial Pre- and Post-Questionnaires

The questionnaires are printed on the following pages. The pre-workshop questionnaire consists of the first two pages, whereas the post-workshop questionnaire consists of all four pages, essentially repeating two pages.

What is your experience with science, engineering or technology?

How much confidence do you have in your ability to ...

	Not confident at all										Absolutely confident
	0	1	2	3	4	5	6	7	8	9	10
Come up with a product that people like and use	O	O	O	O	O	O	O	O	O	O	O
Come up with useful product ideas	O	O	O	O	O	O	O	O	O	O	O
Make a product that has technology, like a thermometer	O	O	O	O	O	O	O	O	O	O	O
Solve math problems, like find the equation for a line	O	O	O	O	O	O	O	O	O	O	O
Solve science problems, like design an experiment for examining 2 factors	O	O	O	O	O	O	O	O	O	O	O
Create technology that has an impact on people's lives	O	O	O	O	O	O	O	O	O	O	O
Obtain skills to be an engineer	O	O	O	O	O	O	O	O	O	O	O
Have a positive impact on people's lives	O	O	O	O	O	O	O	O	O	O	O
Make a difference in people's lives with my engineering skills	O	O	O	O	O	O	O	O	O	O	O

Please state whether you agree / disagree with the following:

	Strongly agree	Agree	Some-what agree	Neither	Some-what disagree	Disagree	Strongly disagree
Product designers can have a positive impact on people's lives	O	O	O	O	O	O	O
Engineers can have a positive impact on people's lives	O	O	O	O	O	O	O
I could see myself as an engineer one day	O	O	O	O	O	O	O
I would enjoy creating technology for people	O	O	O	O	O	O	O
Engineering has a positive impact on my life	O	O	O	O	O	O	O
In my career, I would definitely like to have a positive impact on people's lives	O	O	O	O	O	O	O

How old are you?

What is your first and last name?
(Don't worry - we'll keep this a secret, we just need it to match your answers and to make sure your parents agree with your participation.)

How did you enjoy the session overall? (What did you like; what could have been better?)

How did you enjoy the **activity / technology** used? (What did you like and dislike?)

What can be improved (interacting with it, design, what you can do with it) to make this fun to use?

Would you prefer ...

- if it had a display? (Why?)
- if sensors were inside the case? (Why?)
- if the web interface was much simpler (no coding) ? (Why?)
- a project without the wearable sensors? (Why?)

With your improvements implemented, would you use this outside school? What for?

For each of the following statements, please indicate how true it is for you:

	Strongly agree	Agree	Some-what agree	Neither	Some-what disagree	Disagree	Strongly disagree
I enjoyed doing this activity very much	O	O	O	O	O	O	O
This activity did not hold my attention at all	O	O	O	O	O	O	O
I did pretty well at this	O	O	O	O	O	O	O
After a while I felt pretty competent about this	O	O	O	O	O	O	O
I put a lot of effort into this	O	O	O	O	O	O	O
It was important to me to do well at this task	O	O	O	O	O	O	O
I was free to create what I wanted	O	O	O	O	O	O	O
I think I could make something valuable with this	O	O	O	O	O	O	O
I would like to do this again (honest answer)	O	O	O	O	O	O	O
I could have a big impact designing wearables	O	O	O	O	O	O	O

D.2 Pre- and Post-Questionnaires after Revision

The revised questionnaires are printed on the following pages. The pre-workshop questionnaire is on the first page, followed by two pages containing the post-workshop questionnaire.

Why did you come to this workshop?

What is your previous **experience with science, engineering or technology**?

How sure are you that you can do the following things:	Could not do at all 0	1	2	3	4	5	6	7	8	9	Could definitely do 10
Solve math problems, like calculate the equation for a line	O	O	O	O	O	O	O	O	O	O	O
Design a scientific experiment to test the influence of a factor	O	O	O	O	O	O	O	O	O	O	O
Make hardware with technology, like a thermometer	O	O	O	O	O	O	O	O	O	O	O
Create a product that people would like and use	O	O	O	O	O	O	O	O	O	O	O
Come up with ideas for useful technical things	O	O	O	O	O	O	O	O	O	O	O
Make a difference in people's lives with technical solutions I come up with	O	O	O	O	O	O	O	O	O	O	O

Do you agree / disagree with these statements?	Strongly agree	Agree	Some-what agree	Neither	Some-what disagree	Disagree	Strongly disagree
People who design hardware can have an impact on people's lives	O	O	O	O	O	O	O
Engineering can have a big impact on people's lives	O	O	O	O	O	O	O
I could see myself as an engineer one day	O	O	O	O	O	O	O
I would enjoy creating technology for people	O	O	O	O	O	O	O

How **old** are you?

What is your first and last **name**?
(Don't worry - we'll keep this a secret, we just need it to match your answers and to make sure your parents agree you participate.)

What is your first and last name?
(We'll keep this a secret)

How did you enjoy the **session**?

How did you enjoy the **activity** / technology used?

What did you make?

What was **fun / cool / meaningful** about making hardware?

What can be **improved** (**design, editor, sensors, what you can do with it, device shape, guidance**)?

How would your experience have been different if ...

- sensors were all built-in to the device?
- just the editor (no device) ?
- the device had a built-in battery?

With your improvements implemented, would you use this outside school (free time, clubs, etc.)? What for?

How sure are you that you can do the following things:	Could not do at all 0	1	2	3	4	5	6	7	8	9	Could definitely do 10
Solve math problems, like calculate the equation for a line	O	O	O	O	O	O	O	O	O	O	O
Design a scientific experiment to test the influence of a factor	O	O	O	O	O	O	O	O	O	O	O
Make hardware with technology, like a thermometer	O	O	O	O	O	O	O	O	O	O	O
Create a product that people would like and use	O	O	O	O	O	O	O	O	O	O	O
Come up with ideas for useful technical things	O	O	O	O	O	O	O	O	O	O	O
Make a difference in people's lives with technical solutions I come up with	O	O	O	O	O	O	O	O	O	O	O

Do you agree / disagree with these statements?	Strongly agree	Agree	Some-what agree	Neither	Some-what disagree	Disagree	Strongly disagree
People who design hardware can have an impact on people's lives	O	O	O	O	O	O	O
Engineering can have a big impact on people's lives	O	O	O	O	O	O	O
I could see myself as an engineer one day	O	O	O	O	O	O	O
I would enjoy creating technology for people	O	O	O	O	O	O	O

Please indicate how true it is for you:	Strongly agree	Agree	Some-what agree	Neither	Some-what disagree	Disagree	Strongly disagree
I enjoyed doing this activity very much	O	O	O	O	O	O	O
This felt engaging	O	O	O	O	O	O	O
I did pretty well at this	O	O	O	O	O	O	O
I was free to create something I care about	O	O	O	O	O	O	O
I think I could make something valuable with this	O	O	O	O	O	O	O
I would like to do this again	O	O	O	O	O	O	O
I learned valuable skills	O	O	O	O	O	O	O
I learned some of what engineers do	O	O	O	O	O	O	O

E

Additional Experimental Results

E.1 Group of mostly boys, extensive prior exposure to STEM

The self-efficacy results of the control group are summarized in Table . As explained in the previous section, a notable change in self-efficacy was not expected in the control group.

TABLE E.1: Self-efficacy change in the control group, a science club (12.9 years average age).

Self-efficacy questions (11-point scale)	*Average change*	*Std. dev.*
Come up with a product that people like and use	**-1.0**	1.83
Come up with useful product ideas	**-0.8**	1.69
Realize a product that has technology, like a thermometer	**-0.2**	2.13
Solve math problems, like find the equation for a line	**0.5**	1.22
Solve science problems, like design an experiment that looks at 2 different factors	**0.3**	1.90
Create technology that has an impact on people's lives	**-0.3**	2.07
Obtain skills to be an engineer	**0.0**	2.88

F

Analytical Methods

F.1 MATLAB Commands: Confidence Interval for the Mean

To determine the confidence intervals from paired data, MATLAB's *bootci* command was used with arguments for number of samples (100,000), statistical property for which to determine confidence intervals (the mean, denoted by @mean), and the name of the data table:

```
>> bootci(100000, @mean, pairedData)
```

Multi-column matrices allow for calculating several confidence intervals at once.

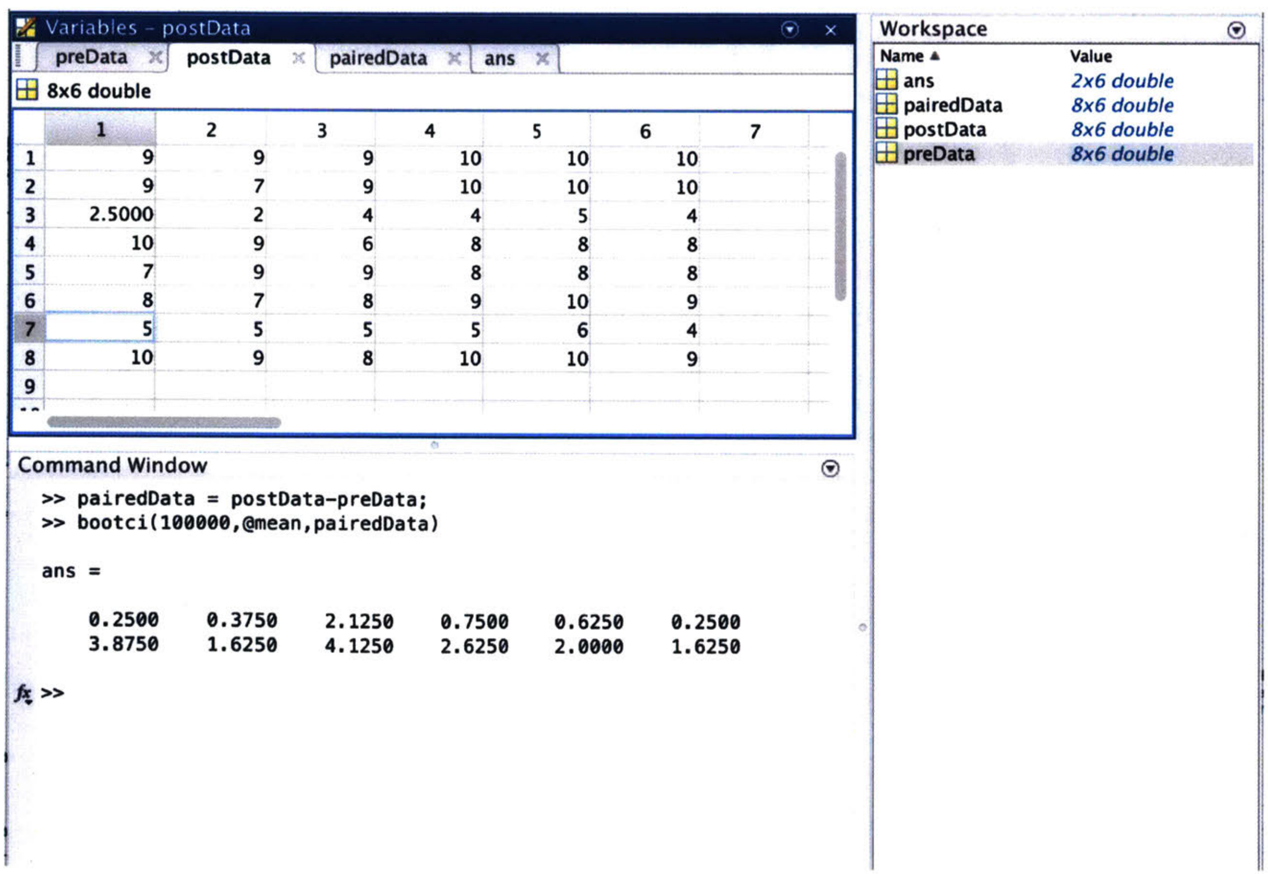


FIGURE F.1: MATLAB *bootci* command to determine the mean of multiple data sets at once.

F.2 MATLAB Commands: Confidence Interval for Correlation

To determine the confidence intervals for correlation coefficients, MATLAB's *bootci* command was used again, with arguments for number of samples (10,000), statistical property for which to determine confidence intervals (the coefficient of correlation, denoted by @corr), and the names of the data sets to be correlated (pre-workshop values and difference values). The following example shows this for the pre-workshop and difference values for "Come up with ideas for useful technical things":

```
>> ci=bootci(10000,@corr,startComeUp,diffComeUp)
```

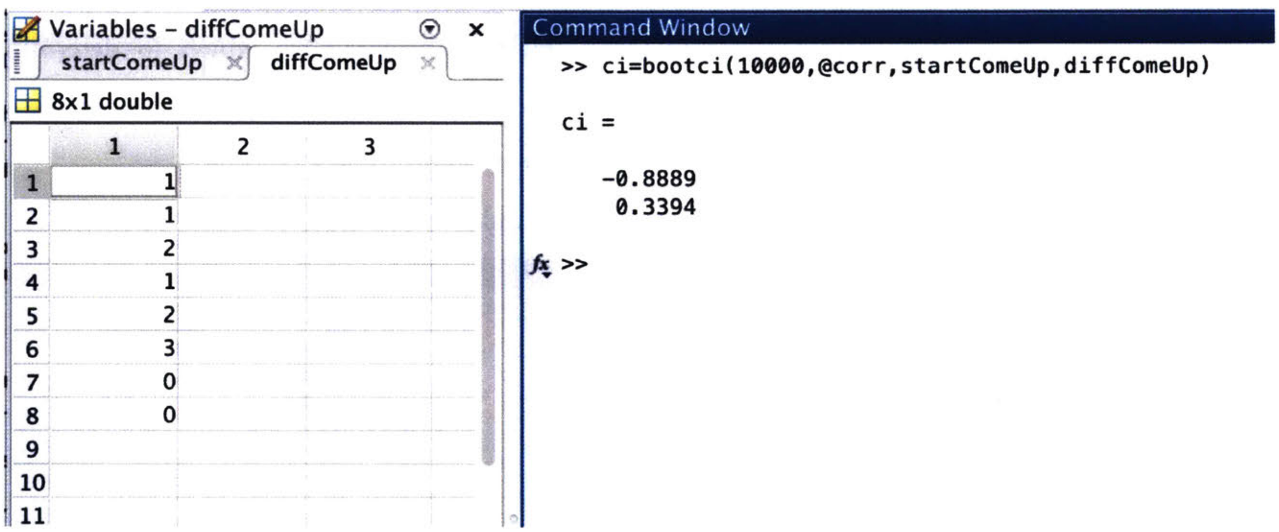


FIGURE F.2: MATLAB *bootci* command to determine the coefficient of correlation.

G

Guidebook

G.1 Guidebook Copy

A complete copy of the guide booklet supplied with each kit is printed in the following.


QWARTZI

1. CONNECT SENSOR TO DEVICE
2. POWER WITH USB
3. CONNECT DEVICE TO INTERNET
4. GO TO THE EDITOR AT NAME.EDITOR.QWARTZI.COM

AND START CREATING!

GETTING STARTED

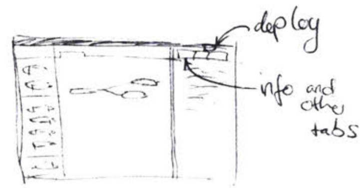
Take out your device, sensor(s), and USB cord!

To make your smart device, plug in the sensor on your device (match colors). Power it up with the USB cord.

To connect to the internet, you should be within range of a wifi network. If you have never connected to the wifi network you want to use, you have to teach your Qwartzi device the network and password. To do that, find the wifi-network with your device's name, log on, and follow the instructions on the window that opens.

Now open your program editor (name.editor.qwartzi.com) and start creating!

Always deploy after changes. For detailed info about each node (instructions and examples), select the node and check out the info tab.



If you use an iPad or touch screen device:
To get quick info about the node types, touch a node in the left panel (instead of hovering with a cursor)

To delete stuff in your editor, push for 2 seconds until you get the delete option (instead of delete button)

GETTING STARTED

Let's start with an example!

Connect a virtual button to a debug node by dragging them onto the screen and wiring them together. Now make the code real by clicking the red deploy button in the top right corner!

You just wrote a program! Test is by pushing the red tab on the virtual button. What does it say?

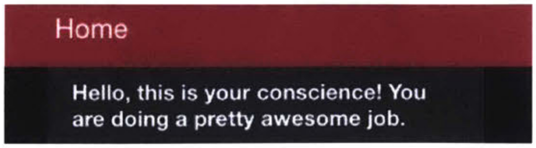
You can edit the virtual button by double-clicking it. You could change what it will say. Remember to deploy after you've made changes!

Now let's try with a sensor. Your Qwartzi should have a sensor (be careful not to break wires off), be plugged into USB for power, and show a measurement on the display. If you're not connecting, try unplugging the USB to restart.

In your editor, drag the sensor node in. Open it the node, edit the name so it matches your device, and deploy!

Design your App

You can make a web-app with an interface so people can interact with what you create. It can have visual inputs and outputs and you can even give it a voice!



Check out the dashboard nodes. Audio, chart, gauge, etc. are outputs. Button, slider, switch, etc. are inputs, so you can process your user's input in your program. Create an app by dragging any dashboard nodes into your editor and double-click it to edit. Click the pen icon to create a group (this will be a page in your app) and a tab (this will be a column).

Once you deploy, your app will be on ***name.app.qwartzi.com***.

The node descriptions will give you detail about which dashboard node is good for numerical data, text, etc.

To edit the layout of your app, go to the "dashboard" tab on the right sidebar (by the info tab). It in turn has 3 tabs: layout, theme, and site. Layout is for rearranging elements by dragging (to delete anything, click edit and delete). Always hit "Deploy" after any edits.

Example: Connect a sensor input to a gauge!
Another example: Connect a virtual button to a text output or voice output!

Note: audio out not work on iOS browsers.

Fun fact: Your app could be turned into an actual iOS or Android app (using a webview)!

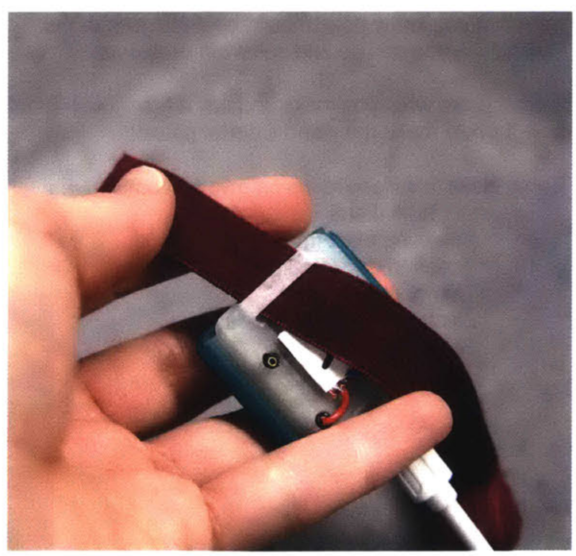
Making It Wearable

Qwartzi may not be an Apple Watch, but you can reinvent, repurpose or style it and come up with wearable technology that the world hasn't seen before. Design for people or any other living being!

The device has loops or slots for attaching it.

You can use elastic band, tape, any type of jewelry, glue velcro to it ... anything!

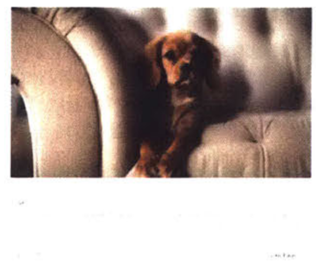
If you have a 3D printer and like designing your own case, you can do that too! You can download the shape of a 3D printed case for the Qwartzi device from *qwartzi.com* and redesign it to fit you needs.



Share and Make Followers

If you ever run out of project ideas, check out the Ideas platform on the qwartzi.com website.

And once you have something to share, definitely join and share with others. You may find many fans and followers!



Stuff You Can make

Now that you know how to build cool things with the Qwartzi kit, you can go and solve big problems!

Please share what you make and say a few words about how it could make the world a better place.

Some ideas (also: see Ideas on qwartzi.com):

- DIY fitbit (hard)
- Speaking plant (medium)
- Tweeting dog (medium)
- Thermometer (easy)
- Electronic high striker (easy)
- Safety device (hard)

Visit http://qwartzi.com for ideas,

guides and ways to reach us!

Thank You for Supporting our Cause!