Do-It-Yourself Cellphones: An Investigation into the Possibilities and Limits of High-Tech DIY

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ABSTRACT
This paper describes our do-it-yourself cellphone and our use of it to investigate the possibilities and limits of high-tech DIY practice. We describe our autobiographical approach – making the phone and using it in our daily lives – and our work disseminating the cellphone in workshops and online. This informs a discussion of the implications of technology for DIY practice. We suggest an understanding of DIY as an individual's ability to combine existing technologies into a desired product, enabled and limited by ecosystems of industrial actors and individuals. We distinguish different pathways into high-tech DIY practice, consider the relationship between prototyping and production, and discuss the effect of technology on DIY's relevance and tools, and on notions of transparency. We conclude by reflecting on the relationship between DIY and empowerment: the extent to which making devices gives people control over the technology in their lives.

Author Keywords
Digital Fabrication; Electronics; DIY; Cellphone; Microcontrollers; Toolkits; Prototyping

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J.6 Computer-Aided Engineering

INTRODUCTION
Neil Gershenfeld, a leading visionary of the personal fabrication movement, tells us that it's now possible for an individual to "make almost anything" [6]. In many respects, this is true. Digital fabrication machines enable precise, one-off production of a diversity of forms in a variety of materials. Combined with the increasing power and accessibility of embedded computation, individuals can create complex electronic devices in small quantities or as one-off pieces. The design files for these objects can be shared online, enabling their reproduction and adaption to others' needs. Locations like FabLabs and maker spaces provide access to machines and like-minded individuals. Online services provide access to more sophisticated machines and processes. All of this is a huge change from the capital investments, big companies, and mass markets of traditional manufacturing.

Still, there's a big gap between having access to the technology and actually building devices for use in one's daily life. Our research seeks to investigate this gap, exploring both "the myth and the mess" of personal fabrication (to borrow a phrase from Dourish and Bell's book on ubiquitous computing [3]). We're interested in individual's use of digital fabrication and embedded computation to make electronic devices, a practice we refer to as *high-tech DIY*. For example, how does this practice relate to and differ from other forms of DIY? What determines the extent to which people are able to make sophisticated devices for use in their daily lives? How can we introduce people to these practices and to what difficulties and limitations will they encounter? What tools or technologies would allow them to go further? To what extent and in what ways does making a DIY device empower people in their lives and in their relationships with technology?

This paper explores these questions through our experience in using digital fabrication to produce what is perhaps the quintessential device of our day: the cellphone. This is a deliberate attempt to push the limits of DIY practice in order to better understand its possibilities and limitations. The requirements and constraints of mobile phones – in terms of functionality, size, battery life, usability, and more – make them a particularly enlightening case study. A cellphone is something that most of us carry with us every day, rely on for many purposes, and have a complex relationship with. And yet, cellphones (at least in a Western context) lack the rich DIY heritage of, say, early radios or personal computers. As such, it seems important to ask what will happen when we try to make cellphones for ourselves. To what extent can we even build a phone that will function well enough for us to use it in our daily life? What parts of the design space will we and others be able to explore – and what will prevent us from going further? How much will people be able to understand of a device that's composed of sophisticated and often opaque components and designed using complex tools?

We've taken multiple approaches to this investigation. The first is an autobiographical method, in which the first author designed, made, and used multiple iterations of a DIY cellphone. This process, including more than nine months in which these phones have served as the author's primary phone, has addressed two main research themes: (1) approaches to and constraints on developing a complex DIY device and (2) the experience of using a DIY device in daily life. Second, the author conducted two workshops in which oth-

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ers made the phones: one focused on designers, the other including members of the general public. These workshops explored the extent to which participants were able to meaningfully engage with the process of building a device for themselves and the value they were able to derive from it. Finally, the cellphone has attracted interest from others, both friends of the authors and strangers who saw the project online. We draw on their experiences to discuss some lessons for the dissemination of DIY devices.

These activities have yielded insights about technology, design, and people, revealing both opportunities and challenges. They show how new technology requires more nuanced notions of DIY – notions that acknowledge the complex networks of actors and layers of technology that go into making a modern device. In such ecosystems, DIY is about the ability to put together available parts and processes into a desired product – rather than the knowledge of how to make everything for oneself. High-tech devices can provide new relevance and motivation for DIY practice but only if DIY tools and toolkits can keep pace with technological development. Further, the complexity of these devices reveals DIY as a deep and multi-faceted process, only some parts of which may be possible to explore in a given activity or with a particular audience. Digital fabrication and embedded computation turn DIY into an ever more digital activity, increasing the importance of software and interfaces as an enabling and limiting factor in DIY practice. The ease-of-use and functionality of a CAD tool, for example, may impose more constraints than the fabrication process itself. Access to source code for communicating with an electronic component may be as important as access to the component itself. In short, the cellphone starts to reveal the ways in which technology transforms DIY practice.

In the next section, we discuss related work; then, we present a short overview of the DIY cellphone. This is followed by a discussion of our personal experience making and using the phone. Then we describe the two workshops and other dissemination. These experiences inform the discussion, which explores in-depth the implications of new technology for DIY practice. Finally, we conclude with a more general discussion about the relationship between technology, DIY, and empowerment.

RELATED WORK

Here, we discuss related work on electronics prototyping platforms, digital fabrication, and DIY.

DIY electronics and prototyping platforms.

Electronics prototyping and toolkits have a long history, both within and outside of the HCI community. Mitchel Resnick and collaborators have developed a series of projects to introduce programming and engineering to children ([21], [22]). These research projects helped to inspire the Lego Mindstorms products and PicoCrickets. Other toolkits have focused more specifically on designers, like Phidgets [8]. Popular commercial products include Basic Stamp, Arduino, and the Raspberry Pi. Some platforms, like d.tools [9], combine electronics modules with tools to help in the creation of on-screen interfaces. More recently, some projects – like .NET Gadgeteer [28] – have started to look at the combination of an electronics toolkit with digital fabrication. Other researchers have taken a more general look at the role of prototyping in the design process [14]. In this work, we're interested in going beyond prototypes to looking at ways to help people assemble finished devices for use in their daily lives. In this way, we're inspired by tools like Fritzing [11], that help people translate electronic prototypes into fabricated circuit boards.

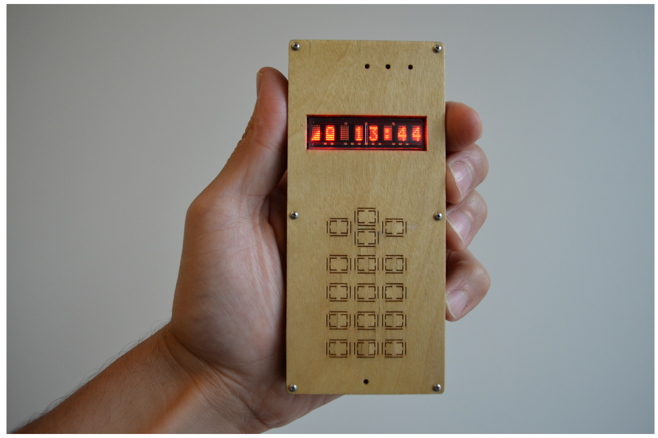

Figure 1. The DIY cellphone.

Digital fabrication and human-computer interaction.

In recent years, a variety of research projects have looked at the intersection of digital fabrication and human-computer interaction, a topic summarized in a workshop at last year's CHI [16]. Some have focused on creating new interfaces for computer-aided design or fabrication. These include a number of systems for real-time, interactive control of fabrication machines ([4], [19]). Others provide tangible or software interfaces for computer modeling for fabrication ([5], [10], [24]). Other projects look at ways to use digital fabrication to create interfaces that integrate with various forms of sensing or actuation ([25], [29]). Still others have created new fabrication machines with interactive capabilities ([29], [30]). We're interested in combining digital fabrication with electronics to create final products, an approach similar to that explored in our previous work ([17], [18]).

DIY and Technology Practice

Another strand of HCI research has looked at the effect of technology on DIY and craft practices, both traditional and technological ([2]). For example, [13] surveyed contributors to online DIY communities, while [27] examines maker culture more broadly. Other work has focused specifically on repair as a form of DIY and creativity ([15]). Other researchers have looked at technology and DIY practice within specific domains, such as craft [1], environmental sensing [12], furniture hacking [23], or knitting and gardening [7].

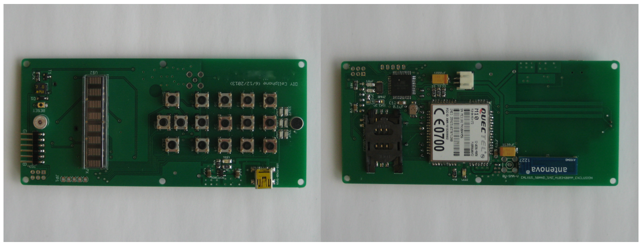

Figure 2. The circuit board (top and bottom).

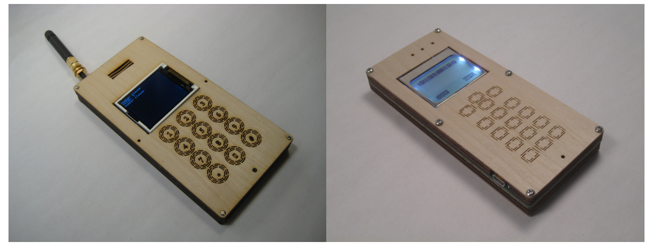

Figure 3. First generation prototype and second generation w/ LCD.

THE DIY CELLPHONE

The DIY cellphone is an attempt to satisfy two somewhat contradictory objectives: it should be as easy as possible to individually assemble by hand; and it should be functional enough to serve as one's primary phone. The phone's electronics and enclosure have been iteratively designed to satisfy these objectives. For the electronics, this requires balancing the overall size and functionality of the device against the difficulty of soldering the components. For the enclosure, the challenge has been to create a robust, attractive form that can be produced using digital fabrication, minimizing the time, cost, and number of processes required.

In its current form, the DIY cellphone makes and receives phone calls and text messages, stores up to 250 phone numbers and names, shows the time, and serves as an alarm clock. It connects to GSM networks (like AT&T and T-Mobile in the United States) and includes a socket for a standard, full-size SIM card. The phone is powered by a 3.7 volt, 1000 milli-amp hour rechargeable lithium polymer (LiPo) battery and rechargeable via a mini-USB port. In total, there are a little over 60 individual components on the board, including 16 buttons, a microphone and speaker, a magnetic buzzer for generating ring tones and the alarm, and either a black and white LCD display (84x48 pixels) or an 8-character LED matrix (where each character is a 5x7 grid of LEDs). The phone uses the same GSM module (the Quectel M10) and antenna as those found on the Arduino GSM Shield; these components handle the major functionality of connecting to the cellular network and processing audio input and output. The phone's firmware is a ~1000 line Arduino program running on an ATmega1284P micrcontroller; it controls the user interface and communicates with the GSM modules, using the Arduino GSM library, custom extensions to it, and other Arduino libraries. All the components can be individually ordered from three suppliers (Digi-Key, SparkFun, or the Arduino store). The total cost of the components (in the quantities required to make a single phone) is around $105 for the LCD version, $135 for the LED matrix version. The cost of the circuit board varies from around $10 to $60 each, depending on the desired quantity and turn-around time.

A variety of enclosures have been designed for the phone, both by the author and others. The standard one consists of two halves sandwiching the PCB, which is visible from the side. Each half is made from laser-cut 0.25" plywood covered with laser-cut veneer. The halves are held together with small bolts.

The phone is open-source, with design files for both the electronic circuit and enclosure available online,[1] along with the source code for the Arduino-based firmware and libraries.[2] The circuit was designed in Eagle, the enclosure in Inkscape.

DESIGN FOR PERSONAL MANUFACTURING AND USE

Through the process of designing, making, and using DIY cellphones, we hoped to derive more general lessons about the possibilities and limits of do-it-yourself technology. In this, we were inspired by autobiographical approaches (e.g. [20]). In particular we were interested in the opportunities and constraints of available technology and in the experience and meaning of using devices that we'd designed ourselves.

I went through a number of iterations in making the DIY cellphone. (Note: in this section, "I" refers to the first author.) These started with a breadboard prototype, then a first-generation proof-of-concept (which could make and receive calls but not much else), then multiple iterations of the second generation (described in the previous section). These second generation prototypes have served as my main phone for the past nine months. To facilitate learning from the process, I kept a rough diary of my experiences with the phone, both making and use. Reviewing these notes and reflecting on my experiences yields some practical insights.

Component Availability Enables and Limits DIY

Picking the right electronic components was the core of the technical design work and highlights some of the main opportunities and challenges of making DIY devices. (Laying out the circuit boards, assembling the prototypes, and writing the software took time, but was fairly deterministic.) On the one hand, it is only the availability of increasingly sophisticated components that made it possible for me to build a phone at all. On the other hand, my choice of components was surprisingly limited, given that I want to hand-solder the boards, limit the overall size, cost, and complexity of the resulting circuit, and only use components that other people will be able to get.

The GSM module was perhaps the most complicated component. There are not many modules available for individual purchase (at least in the U.S., where the authors are based), and those that are often have a connector that it is difficult or impossible to solder by hand. Luckily, the module on the Arduino GSM shield (the Quectel M10) is easier to solder and I was able to work with Arduino both to receive samples and to

[1] `https://github.com/damellis/cellphone2hw`

[2] `https://github.com/damellis/cellphone2`

make the module publicly available for individual purchase. The only other source I've found for the module is the Chinese e-commerce site AliExpress. This module may not be a long-term solution, however, as the GSM networks it relies on are slowly being phased out, at least by AT&T and T-Mobile in the U.S. It's not clear if a suitable replacement exists for use with newer 3G or LTE networks, without which it may be impossible to create a DIY cellphone.

The display and speakers were two other components with limited options. While there are many displays available to hobbyists, the LCD I used initially seemed to break after about a month of use. Other LCDs seemed even less robust, leading me to switch to an LED matrix, for which I could find only a single satisfactory option. Similarly, given my constraints on size, electrical resistance, and solder-ability, I could only locate a single viable speaker.

These examples (the GSM module, display, and speaker) highlight the extent to component availability constrains high-tech DIY. Despite the large number of electronic parts available to hobbyists, there may be few options satisfying specific functional requirements. On the other hand, only the sophistication of these parts enables the creation of high-tech DIY devices.

Open Ecosystems Enable Bricolage

The process of designing and building the various versions of the phone hasn't necessarily required specific deep technical expertise. Instead, it's been more of a process of bricolage: assembling the device from existing resources and information. For example, the antenna design was borrowed from the Arduino GSM shield (by literally copying the original Eagle file) but didn't require me to learn anything about radio frequency (RF) circuit design. Surprisingly for me, every version of the phone has connected to the cellular network and seemed to get reasonable reception, despite a lack of any specific RF testing or expertise on my part.

Other parts of the circuit's design have been borrowed from various other sources. The GSM module's datasheet described the requirements for its connection to the SIM socket, microphone, and speaker. The LiPo charging chip was selected because it's the one that SparkFun uses on their boards (and has performed reasonably in practice). Its datasheet suggests the PCB footprint I've adopted to enable adequate heat dissipation.

It's not just the hardware that draws on existing resources. The phone's software uses a variety of open-source libraries, enabled by its use of an Arduino-compatible microcontroller. For example, in various prototypes I've tried out a total of four different displays and was able to find an existing library (or more than one) for each. In many cases, I needed to understand or modify the source code to the libraries I used, though, which wouldn't have been possible with proprietary code.

Both the hardware and software, then, have been pieced together from various sources. This can be a slow and difficult process, of course, but it doesn't require the expertise or low-level knowledge that would be needed to design the phone from scratch. It does rely, however, on access to a variety of information and open-source designs, both hardware and software.

The Joys and Frustrations of Using a DIY Phone

In retrospect, the version of the phone that I first start using was very rough. It had sharp corners, large bolts extending out the back, a hole in the back for a programming header, and many missing features in the software. While it had a phone book, it wouldn't show people's names when they called. There was no way to generate the DTMF tones needed to interact with automated menus and, consequently, no way to enter the password to check my voicemail. There was no way to change the volume or check the battery life.

In large part, my willingness to tolerate all these shortcomings was the result of the excitement I felt at being able to start using the phone in my daily life. The initial prototype of the second generation phone went into my pocket immediately after I screwed it together, a process that was repeated with every subsequent iteration. Typically, I'd intend these as prototypes to be refined before I started using them – but, inevitably, as soon as they were finished, they became my primary phone. This was true even in one case when I had finished the circuit board but not the case, so I carried the bare PCB for a couple of days before finishing the enclosure.

This excitement was sometimes shared by others seeing me use the phone. Even people that knew I was working on DIY cellphones were often surprised to see me actually pull one out of my pocket. They would express astonishment that was this was the phone I had been previously talking to or texting them with. I was actually conscious to keep the phone in my pocket most of the time to avoid conversations with strangers about it, but was pleasantly surprised by the attention it received from the waiters in a variety of restaurants. Friends who had seen the phone would often encourage me to show it to others.

At other times, the phone led to friendly teasing from friends, for example, about the fact that I couldn't use it to look up something on the web. One friend joked "what, do I have to call you now?" when I went a weekend without receiving an email he had sent me, and knowing that the phone doesn't sound an alert when I get a text message. On another occasion, my aunt called to wish me a happy birthday, and the call dropped a couple of times. She gave me a hard time about it, although it wasn't clear if the problem was my phone, the connectivity in the spot I was standing, or on her end. Friends would chide me for reading about new iPhones, as if I were cheating on my phone.

Any problems with the phone were a source of intense stress. The frustration with a non-working device seemed increased because I knew that I had no one else blame: I designed it, built it, and was the one using it. For example, the LCD on early iterations of the phone would became unreliable, I would compulsively check to see if it would turn on, and developed elaborate tricks involving pressing on various spots of the display as I turned it on. Once, my phone was continuously crashing, even when I removed and reinserted the battery; I was pre-occupied until I could get to my computer and figure out the cause (an overly-long text message).

In short, the current state (working or not) of the latest prototype could become a proxy for my feelings towards the whole endeavor: excitement and satisfaction when everything worked, stress and frustration when anything was wrong. I have to remind myself that certain problems (like not having a friend's number in my phone book or forgetting my charger) have nothing to do with the DIY cellphone per se but could happen with any device. Now that the device is relatively stable, it's become less of an emotional experience – but the process of getting it to that point has been intense and personal.

DISSEMINATION

In order to help other build the DIY cellphone, we've conducted two workshops, helped friends to make the device, and published detailed instructions on our website.

Workshop 1: Designers

As an initial effort to understand how others might respond to the process of making or modifying the cellphone, we invited colleagues and friends with experience in design and technology to attend a workshop. Nine people participated, three female and six male. Their ages ranges from 21 to 36; six were white, two black, and one Asian. On a pre-workshop survey, many of the participants self-reported an expertise in design but only some experience with electronics and programming. Participants had some experience with soldering, less with microcontroller programming, and even less with circuit board design. All reported regular smartphone use and liking their phones.

The workshop started with an opening discussion. Then participants brainstormed and sketched a concept for a phone that would be ideal for either themselves or someone they knew. Most of the rest of the first day was spent soldering the phones together. In theory, the second day was meant to be used for modifying the circuit or designing and making an enclosure. In practice, we had to finish programming and debugging that day. Some people had other obligations as well, and could only attend for part of the time. Still, everyone was able to successfully assemble the electronics and program the firmware. After completing the assembly and debugging, some participants used their cellphone circuit boards (without enclosures) to call friends or experimented with calling each other from various locations in the building. The workshop ended with a closing discussion, including thoughts from participants on the directions they would take the DIY cellphones if they continued to work on them.

Two participants did create custom enclosures for the phone, although both did so in advance of the workshop itself. One enclosure was modeled in SolidWorks and 3d-printed on a MakerBot Replicator. It consisted of seven parts (top, bottom, keypad, and plugs to cover the screws) and required about five hours in total to print, including two iterations of the bottom and keypad. The other enclosure had a bottom half of wood, which was also modeled in SolidWorks and CNC milled on

Figure 4. Variants created by workshop partipants.

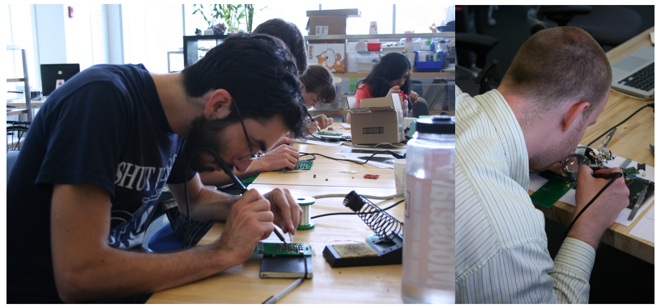

Figure 5. Workshop participants assembling their phones.

the ShopBot. The fabrication took about five hours (including two iterations), after approximately the same amount of time for modeling. The top half of the enclosure was created by placing silkworms on top of the circuit board and allowing them to spin a silk covering, a process which was only somewhat successful.

Workshop 2: With the Public

For this workshop, we wanted to work with a more general audience to see how they would respond to the process of making a cellphone for themselves. We recruited using fliers in local coffee-shops and other locations. Five participants found out about the workshop in this way, six others joined through word-of-mouth from the authors. Participants were charged a $150 materials fee. Three of the participants were female, eight male. Their ages ranged from 24 to 45. Professions varied, although many participants had experience in an area involving engineering or technology but not specifically electronics, like mechanical engineering, computer science, or graphic design. Participants reported less extensive use of cellphones and expressed less positive feelings towards them than the participants in the previous workshop.

This workshop was two days long (1 to 6 pm on a Saturday and Sunday) and deliberately focused on assembling the DIY cellphone in its existing form. The only customization was selecting a graphic to be laser-etched into the veneer on the back of the phone. After an opening discussion, each participant received a PCB and the necessary electronic components, and most of the first day was spent soldering the boards together. The second day consisted of programming the boards and, mostly, debugging various problems. These issues took a variety of forms, including one unexpected problem: the buzzers of nine of the eleven phones failed to ring when an incoming call was received. This was eventually identified (after the workshop) as a result of a difference

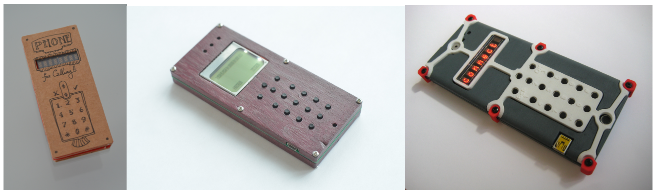

Figure 6. Phones made by friends.

in the firmware between two batches of GSM modules. Many participants (six of the eleven) returned after the workshop to continue to troubleshoot or to implement a workaround to get their buzzers to work. Some returned multiple times to continue to debug and would coordinate their visits to work on their phones together. Eventually, all but one participant was able to complete a functional phone.

While many participants reported a desire to use their DIY cellphones in their daily lives, a variety of practical obstacles have interfered. At least two participants are still lacking a SIM card from a GSM carrier. Another reported that the phone doesn't get good reception in their apartment. Two mentioned that the lack of a silent mode would be an obstacle to adoption.

Other Dissemination

In addition to the workshops, we've begun to disseminate the DIY cellphone in other ways. We've documented the phone online so that others can make it and worked with friends to build their own. This has yielded additional insights about the possibilities for and obstacles to getting the phone out into the world.

Some people have built their own phones with little or no help from us beyond the information posted on our website. Others have asked questions over email and then made the phone on their own. We find these examples meaningful as an indication that the components and processes required to create the phone are, at least for some, independently accessible. This suggests that there is in fact value in designing and sharing the hardware and software for these DIY devices.

In other cases, people have encountered various obstacles to making the phone, pointing out some of the limitations of this sort of distributed production. Some have reported difficulty getting some of the necessary parts in Europe, including the small (M0) screws used to hold the enclosure together. (In response, the design has since been updated to allow for the use of slightly larger M2 screws as well.) Others reported high costs to order a single PCB, or were uncertain about how to do so. (In response, we've improved the directions on our site for ordering a circuit board from an online manufacturer.) These examples highlight the importance of having others (in different places with different resources) try to replicate a device as part of the process of refining its design.

I've also worked with friends to make their own DIY cellphones. This has included several custom enclosures, including one CNC-milled from solid, purple-heart wood, another hand-cut from cardboard, and a third assembled from multiple 3d-printed pieces. Two friends have used the phones in their daily lives, at least temporarily. One seemed undaunted by usability issues, commenting, for example, that the lack of labels on the buttons isn't a problem. Another made requests for new features, like battery-life and signal strength indicators that were later implemented. Both have encountered practical obstacles that have prevented more in-depth use: one doesn't get good reception at home, the other hasn't found the time to make a necessary repair. With friends, as with participants in the workshop, organizing a dedicated time to get together and work on the phone has helped them fit the activity into their lives.

DISCUSSION

Reflecting on the experiences and comments of the people involved in these dissemination activities, we discuss some of the broader implications of the DIY cellphone.

High-Tech DIY Exists in an Ecosystem

With modern industrial supply chains, companies depend on complex systems of third-party parts and knowledge to produce devices. Our experience with the cellphone shows that similar ecosystems exist in DIY practice. The phone builds on components, materials, and processes that are produced at an industrial scale and embody deep, domain-specific expertise. Intermediate actors (like Arduino, SparkFun, or BatchPCB) make these high-tech parts and processes available to individuals. The DIY cellphone, in turn, draws on – and is limited by – the elements that these actors make available. This ecosystem suggests a nuanced notion of DIY, one that consists of the ability of individuals to create devices from the parts, resources, and processes available – rather than their ability to do everything themselves, from scratch.

Participants in the workshops seemed to share this perspective, commenting on their new-found understanding of the way in which devices are assembled from existing parts:

"When I'm choosing a phone, I'm choosing the phone based on what I see, how it looks, I never thought about where the speaker might be, what's the speaker like underneath it, a speaker to me is this set of holes, but then there's this speaker component inside that. I don't know what it looks like in my phone but I know what it looks like in this other phone [the DIY cellphone]. All the different elements, I know what they look like and what they are." (Workshop 1, Participant 1)

"It's cool that you can treat this all as a black box. You can pull out components and you can make a phone that works with stuff you can buy at home, off-the-shelf. You don't have to know how the part works to know the part is working. You don't have to know how the GSM works but how to connect it." (W2-P3)

This perspective (of DIY within an ecosystem) highlights the extent to which DIY practice depends on the decisions of actors, like industrial manufacturers or hobbyist services, that may or may not have an interest in supporting it. For example, while we were able to find the components necessary to build a functional phone, we had few choices available. Furthermore, we're not able to access many of the technologies in modern smartphones – and probably couldn't work with them even if we could get them. The decisions of industrial and commercial actors has significant potential to change the possibilities for DIY practice. The availability of new hand-solderable components could dramatically expand the possibilities for DIY devices, as could easier access to automated assembly processes. Conversely, the discontinuation of essential components or changes to required infrastructure (like the cellular network) could prevent continued making or use of DIY devices.

Consequently, effecting changes in these supply chains can expand the possibilities for DIY practice as much as the creation of new tools or toolkits or the production of new educational resources. Our experiences with the phone suggests some ways that individuals can effect changes in these ecosystems. By working with Arduino to make the GSM module available, for example, we greatly expanded the number of people that could build the phone. By making the phone's hardware and software available online as open-source, we enabled others to build a phone without designing it themselves. Similarly, we were enabled by the decisions of others to open-source libraries for talking to various electronic components. These examples show that while industrial and commercial entities may shape much of the ecosystem surrounding high-tech DIY, it's still possible for individuals to make meaningful changes in the technologies available for DIY practice.

DIY Technology Supports Multiple Forms of Engagement

A single device, especially one as complex as a cellphone, provides for many different kinds and levels of engagement with DIY practice. For example, some workshop participants were most interested in building a device they could use in their daily life; others wanted to understand how a modern device works. Some wanted to experiment with new interaction design possibilities, like alternative form factors and interfaces, or simply ways to re-engage people with actually talking on the phone. Others were seeking an alternative to buying a phone from a big company. In these different perspectives, we see some of the diversity of activities and interests that can fit within an undertaking like making DIY cellphones.

Our efforts at dissemination have shown some different aspects of the process that people have or haven't engaged with. Specifically, while people have explored different possibilities for the DIY cellphone's enclosure, including a variety of materials and fabrication processes, almost none have modified the circuit itself. In part, this seems to reflect people's previous skills, which have tended to be stronger in design than electronics. Still, many of the workshop participants and others who have made the phone have significant experience with electronics prototyping. Other factors discouraging the experimentation with the electronics may be the seemingly complete nature of the existing cellphone design, the lack of available expansion points on the circuit, the time required to design and fabricate a new circuit board, or simply the greater appeal of creating an enclosure, with its opportunity for aesthetic exploration and personalization.

This emphasizes the importance of being deliberate about the intended audience or outcomes of a DIY process. Even within a specific set of tools and products – like assembling electronic components into a cellphone – there are opportunities for many different workshop structures and emphases. For example, in holding another workshop for designers, we would emphasize the exploration of different form factors and interfaces, a prototyping process that suggests a very different structure from a workshop targeted at individuals interested in producing a device for daily use. (We discuss this tension more in the following section.) Both of these would be very different from a workshop aimed at teaching people about electronics or cellular communication technology.

Across all of these different entry points, it's important to consider social factors. Hosting workshops provides an opportunity for people to come together, learn from the instructor and each other, observe each other's work, etc. Some workshop participants attended with people they knew, suggesting that perhaps they wouldn't have come without the social connection. Our friends, too, seemed to prefer to make the phone together with others, making it a social occasion as well as a DIY activity – a connection seem in some, but not all, forms of non-technical DIY [7].

In addition to different types of engagement, the complexity of the cellphone as a device highlights the importance of providing for different levels and durations of involvement. Assembling the device can provide motivation for further exploration. In the words of participants:

"I think the workshop's definitely long enough to assemble the stuff that you've designed, but I think then, once you've done that, it takes time for that to sink into people's brains and then be able to think about not just how they would want to customize it but the ways in which they would be able to. Cause at the beginning of yesterday morning, you can have ideas about the kind of phone that you want, but now I have a better idea of how that might be manifested: what things might be easier to include or not include." (W1-P2)

"I think that definitely I don't want to stop at the cellphone, now I want to make more things. This has definitely motivated me to try making other stuff and not just stop here." (W2-P5)

These quotes highlight the importance of not just finding ways to engage people initially but also helping them to progress to more in-depth and meaningful forms of high-tech DIY practice.

Bridging the Gap Between Prototyping and Production

The cellphone's constraints on form and function highlight some of the tensions between prototyping (rapid exploration of the design space) and production (robust, reproducible devices). In optimizing the circuit, we've limited its flexibility as a prototyping platform. The use of a single, unified circuit board soldered directly to off-the-shelf electronic components helps to contain the phone's size and increase its robustness, but a modular toolkit would allow for more variation in form-factor and interface. The latter was much requested by the designers in the first workshop. On the other hand, prototyping tools may not always be appropriate for production use; as a participant in the first workshop pointed out, an Arduino board plus the Arduino GSM shield is even larger and less flexible than the DIY cellphone's PCB.

Our experience with the phone suggests some approaches that could enable an easier transition between prototype electronics and production devices. The regular pin spacing of the LED matrix, for example, enabled it to be tested in a breadboard and then soldered directly into the final PCB. Regular pin spacing on other components would make it easier for them to function in both prototypes and final products. Another option is illustrated by the Quectel module on the Arduino GSM shield. The existence of the shield enables prototyping, but the module itself can be hand-soldered, allowing the same component (and associated software) to be used in both prototype and product. Furthermore, the module itself a high-level encapsulation of functionality like that found in many toolkits, but it's in a form that's robust and optimized enough to permit its use in production devices.

Open-source also facilitates the transition between prototype and production. Open-sourcing a toolkit's hardware allows the design of a prototyping module to serve as the basis for part of a production circuit (as with the cellphone's borrowing of the antenna design from the GSM shield). Better hobbyist software for routing circuit boards could facilitate mashups of existing open designs or adapting of circuits to new components or designs. Open-source software also helps, allowing for the adaptation of prototyping libraries or examples to production use, as, for example, in our changes to the LED matrix library and additions to the GSM library. If we had used proprietary libraries for prototyping and encountered similar bugs or missing features, we would have to had to re-implement the libraries for production use. Furthermore, it might not be feasible to purchase proprietary software for each production device, even if the cost were acceptable as part of the prototyping process.

Digital fabrication helps close the gap between prototyping and production, by minimizing the time and effort required to go from a reproducible digital design to a physical object that can be experimented with. With direct access to fabrication machines, it may be possible to try multiple iterations of a design in a day – and then immediately put those prototypes into use. Of course, different processes have different speeds but, in general, digital fabrication allows for faster iteration than production processes which are completely separate from the relevant prototyping techniques.

The experience of the few people who have used the DIY cellphone in their daily lives suggests some interesting lessons for the requirements of a production DIY device. In general, these people (including the first author) seemed willing to accept tradeoffs in functionality (e.g. versus a smartphone) and ease-of-use (like the the lack of labels on the buttons) but not in robustness or reliability. For example, the limited lifespan of the initial LCD was problematic but the limited resolution of the LED matrix, while limiting, is acceptable. Similarly, while the failure to store text messages after they're read reduces ease-of-use, it's less of a problem than the failure to get reception in someone's home (a reliability issue).

Modern Technology Gives Relevance to DIY Practice

Talking with the participants in the workshops made it clear that building cellphones appeals to people and motivations not present for simpler devices or more general-purpose toolkits. As one person put it in an email after building the cellphone independently:

"I have had an Arduino Uno board for months, and I've fiddled around with it a little. However, until this cellphone project, I have not felt inspired to really dig in and test the limits of this platform. Now, I am completely captivated... I anticipate a long and very enjoyable journey down the perverbial rabbit hole."

The relevance was also reflected in the excitement of workshop participants at successfully completing their phones, an excitement far beyond what we've encountered in previous workshops on other DIY devices (e.g. radios or speakers). This makes sense when we consider how ubiquitous cellphones are in our daily lives and how little understanding most people (at least in our Western society) have of how they work or what they're made of. As one participant said:

"I like that you grabbed our attention and forced us to slow down and say this is how you build a thing you use every single day. It's just, I guess you know the DIY movement is saying don't take everything for granted, see how it actually works." (W2-P3)

For a DIY experience to affect someone in this way, it seems important for it to engage with the things that people encounter in their daily lives. In the realm of technology, the rapid change in consumer devices means that the devices people want to make are likely to change rapidly as well. The DIY cellphone, for example, may be more advanced than a DIY radio but it's a lot simpler than today's smartphones. For those of us interested in supporting or researching DIY practice, new technology is thus both an opportunity and a challenge. If we can create tools and experiences for creating modern devices, we can provide DIY with increased appeal and value – but, unless we keep up, DIY will offer fewer and fewer possibilities for the devices that people use in their daily lives.

If we can help DIY practice keep pace with technological development, however, our experience suggests that it will continue to have meaningful parts of the design space to explore – spaces left largely unexploited by industry but still of interest to designers and members of the general public. In the cellphone industry in the developed world, the tremendous efforts of many huge companies has been largely focused on a narrow segment of devices: powerful, general-purpose smartphones. Going into the workshop, we expected that participants would be interested in pushing the DIY cellphone in that direction. Instead, multiple participants in both workshops expressed interest in simpler, special purpose devices, whether for use in their own lives, for someone else they knew, or as a design exploration. In addition, the enclosures we and others have designed for the phone showcase very different materials and aesthetics from those found in most commercial devices – whether wood, cardboard, or even silk. This suggests that regardless of the resources an industry invests, there are factors that may make certain kinds of functionality or aesthetics better suited for DIY production.

High-Tech DIY Practice Relies on Software

Just as the products of DIY practice need to keep up with modern technology to stay relevant, the tools for DIY practice need to keep up in order to make modern technology accessible. The cellphone workshops shows that even when a technology is accessible, the tools for working with it may not be. A circuit board, for example, can be ordered by anyone with an internet connection and a credit card – but the tools for modifying them were not suited to the skills of the workshop participants or the level of abstraction at which they were interested in working. In many kinds of physical making, there is a long heritage of tools that have evolved to support the construction of specific types of functionality or aesthetics. As DIY moves into high-tech realms like CAD and embedded software, it becomes an increasingly digital practice. This requires increasing attention to the nature of these digital tools and their adaptation to the various domains and audiences of DIY. There is an opportunity for HCI research and practice to develop new software tools and interfaces that increase the accessibility of design tools for sophisticated circuits and digitally-fabricated forms.

Technology Requires New Conceptions of Transparency

The workshop participants' understanding of the cellphone demonstrates the changing nature of transparency as it relates to modern electronics. By opening up a cellphone and allowing participants to assemble one for themselves, the workshops gave them an understanding of its overall composition and components. This traditional approach to transparency, however, breaks down when it comes to the microcontroller and GSM module, both of which are complex assemblages that can't be deconstructed physically. Instead, transparency of these components depends on access to information, like datasheets and source code. This suggests that notions of openness and transparency from the software world will be increasingly relevant for DIY devices. It also means that transparency is increasingly dependent on decisions made by manufacturers that may not be interested in or supportive of DIY practice.

CONCLUSION: TECHNOLOGY, DIY, EMPOWERMENT

After all this, some fundamental questions remain: So what? Does this actually give anyone control over the technology in their lives? Even if someone invests the time to design and build their own device, aren't they still dependent on technology from big companies? Is there any chance for DIY to replace mass production in even a small fraction of high-tech devices?

At the core of these questions is the relationship between DIY and empowerment, as applied to technology – specifically, the extent to which making something for oneself (DIY) gives someone the ability and confidence to control the technology in their life (empowerment). This relates to broader conversations about the rhetoric and reality of DIY and maker activities (e.g. [26]). There are clearly limits: even of the small group that have assembled a phone, few have used it in their daily life. For those few, this is just one of many devices they interact with. For all the workshop participants, having assembled a phone doesn't mean that they have the knowledge or motivation to design one themselves. Even if they did, the functionality of the cellphone is, to a large extent, limited by the decisions of entities that individuals have little control over. All in all, despite our extensive efforts, we've made little obvious impact on people's use of technology.

Still, building the cellphone has helped people make steps towards taking control over the technology in their lives in at least three important ways:

1. *Having a Choice to Produce Technology.* Through the workshops and other dissemination, we've shown people that it is possible to make a cellphone for oneself instead of buying one. Even if someone doesn't end up doing so, there's power in just knowing that such a thing is possible. Here, we see parallels to craft and DIY in other domains, like knitting or woodworking, in which, even if someone still buys most of the products (like clothing or furniture) that they use, DIY gives them control in the form of a choice about whether to make or buy any particular artifact.
2. *Understanding How Devices are Put Together.* In making the cellphone, people opened up what is, to most, a black box – something taken for granted. Understanding the way a cellphone is assembled from existing parts, and the ecosystem that those parts exist within, provides a valuable perspective on the technology in people's lives. It's also an important first step towards re-thinking those devices and the ways they're put together.
3. *Questioning the Control of Technology.* Perhaps most importantly, we hope that by giving people a perspective on the possibilities and limits of DIY technology, we can encourage them to reflect on the questions we're considering here: to what extent do they have control of the technology in their daily lives? Do they want to live in a world in which only big companies have access to the technology needed to make a modern device? Understanding the limits of the available DIY possibilities may spur people to pursuing other (e.g. political or economic) approaches to technological empowerment.

So, when we ask whether DIY leads to empowerment in the form of control over the technology in our lives, the immediate answer may be no, not directly. However, in helping people to understand how their devices come to be and the ways that process might be different, we offer them new choices in their relationship with technology and an understanding of the limits on those choices – both important steps towards empowerment.

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